The Value of Urban Ponds for Odonata and Plant Biodiversity

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I dedicate this thesis to my father, Jules Perron, who is my biggest inspiration. I love you dad.

Abstract

Urbanization involves the conversion of natural areas to impervious surfaces, which can lead to an increase in the frequency and severity of flood events in cities. To mitigate flood risk, stormwater ponds are constructed to manage urban runoff. Stormwater ponds can also be colonized by wildlife, but their suitability as habitat is disputed due to potential toxicological risks. This study assessed the suitability of stormwater ponds as habitat for the bioindicators Odonata (dragonflies and damselflies) and determined environmental factors that impact their community structure. Odonata (adults, nymphs and exuviae) were sampled at 41 stormwater ponds and 10 natural reference ponds across the National Capital Region of Canada, with a subset of ponds sampled over four years (2015-2018). Plant communities, water quality and surrounding land cover were analyzed at each pond to determine their impacts on Odonata community structure. Overall, stormwater ponds had lower Odonata abundance and a greater variation in species richness and community structure compared to natural ponds but had comparable dragonfly reproduction rates. Plants were the most significant driver of Odonata communities, as stormwater ponds with a high richness of native wetland plants had higher Odonata abundance and community structures similar to natural ponds. Water quality was the second most important driver of Odonata communities with dragonflies showing greater sensitivity to urban contaminants than damselflies. While stormwater ponds had higher concentrations of trace elements than natural ponds (e.g. Ni, V, As), concentrations were generally below toxic levels for all elements except copper and chloride, the latter likely an input from winter road salting. Surrounding land cover was the least important factor affecting Odonata communities. In conclusion, this research demonstrated the importance of local-scale factors related to plants and water quality in sustaining Odonata communities and specifies recommendations for stormwater pond design and maintenance that enhance urban biodiversity.

Résumé

Avec le développement urbain, la conversion des espaces naturels à des surfaces imperméables modifie le cycle hydrologique naturel en augmentant la fréquence et l'intensité des inondations dans les villes. Une façon de contrôler les inondations est de construire des étangs artificiels qui collectent les eaux pluviales et servent à protéger la qualité de l'eau des systèmes en aval. Ces étangs urbains sont également colonisés par la faune, mais leur capacité de fournir un habitat propice à soutenir la biodiversité est débattue dans la littérature scientifique. De nombreux risques toxicologiques peuvent être associés à ces systèmes. Cette thèse a examiné la valeur des étangs urbains comme habitat pour un groupe de bioindicateurs, l'ordre Odonata, qui englobe les libellules et les demoiselles. Les facteurs qui contrôlent leur diversité et capacité de reproduction ont aussi été pris en considération. Odonata (les adultes, naïades et exuvies) ont été échantillonnés dans 41 étangs urbains et 10 étangs naturels dans la région de la capitale nationale du Canada, avec un sous-ensemble d'étangs échantillonnés pendant quatre ans (2015-2018). Les étangs naturels ont été utilisés en tant que systèmes de référence. Les communautés de plantes, la qualité de l'eau et la couverture terrestre des environs ont été analysées à chaque étang afin de déterminer leurs effets sur la structure des communautés des odonates. Dans l'ensemble, les étangs urbains comprenaient moins d'individus que les étangs naturels et une grande variation dans la richesse des espèces et la structure des communautés d'odonates mais semblent permettre une reproduction de libellules comparable aux étangs naturels. La végétation avait la plus forte influence sur les odonates; les étangs avec beaucoup d'espèces de plantes indigènes aux zones humides ont soutenu des abondances plus élevées et des communautés plus semblables aux étangs naturels. La qualité de l'eau était le deuxième facteur le plus important, les libellules étant plus sensibles aux contaminants urbains comparés aux demoiselles. Les étangs urbains avaient des concentrations plus élevées de plusieurs éléments comparés aux étangs naturels (ex. Ni, V, As), mais les étangs urbains posent de faibles risques toxicologiques. La seule exception est potentiellement le chlorure provenant du salage des routes en hiver, ainsi que le cuivre. Les caractéristiques du paysage aux alentours des étangs étaient moins importantes pour les communautés d'odonates. Cette recherche démontre l'importance des facteurs locaux en relation des plantes et de la qualité d'eau pour les communautés d'odonates. En conclusion, cette recherche a permis de déterminer les caractéristiques environnementales des étangs urbains qui peuvent être améliorées enfin d'encourager la biodiversité urbaine.

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Chapter 1: General Introduction

1.1 Biodiversity

Biodiversity, encompassing the variation of life on earth, is critical for the maintenance of ecosystem functions and the provision of ecosystem services (Millennium Ecosystem Assessment 2005). Despite its importance, biodiversity is declining at an unparalleled rate, resulting in the sixth mass extinction in geological history (Barnosky et al. 2011). While a decline in vertebrate species has been comprehensively documented, invertebrate species are underrepresented in the conservation literature (Donaldson et al. 2016). This absence is problematic because invertebrates represent the largest percentage of the world's known species, with over 80 times more invertebrate species than vertebrates (Scheffers et al. 2012). Invertebrates are also important players in the maintenance of ecosystem functions (Wilson 1987) and contribute trillions of dollars annually in ecosystem services worldwide (e.g. Postel and Carpenter 1997). Still, many invertebrate species are facing extinction, with decreases in local populations and shifts in species composition due to several threats of anthropogenic origin (Donaldson et al. 2016).

1.2 Threats to biodiversity

Humans are predominantly responsible for the ongoing rapid decline in biodiversity, both directly and indirectly (Dirzo et al. 2014). Freshwater ecosystems are among the most threatened environments globally due to human population growth and increased urbanization in watersheds (Abell 2002; Vörösmarty et al. 2010; Reid et al. 2019). In North America, the extinction risk of freshwater species is estimated to be five times greater than that of terrestrial species (Ricciardi and Rasmussen 1999). Freshwater invertebrates are specifically threatened by pollution, water diversions, development, agriculture and aquaculture, species exploitation, climate change and invasive species (Collen et al. 2012; Donaldson et al. 2016). In particular, land use change from natural areas to urban areas causes disturbances that are stressors for many species (Grimm et al. 2008).

Cities consume large amounts of resources while producing extensive waste and as a result tend to be associated with ecosystems of poor environmental quality (Sanderson et al. 2002). As urbanization increases, the species richness of vertebrates and invertebrates appears to decrease (McKinney 2008). In contrast, plant species richness appears to increase at intermediate levels of urbanization as a consequence of the establishment of non-native species in cities (McKinney 2008). With this increase there is a loss of indigenous plant species in city centers (Standley 2003; DeCandido et al. 2004; Tait et al. 2005). Urbanization thus causes shifts in the community composition of animals and plants (McKinney 2008). While the focus of conservation research is primarily on species at risk of extinction, it is also important to conduct research that advances our understanding of broad changes in population sizes and species assemblages given their critical role in ecosystem functions (Ceballos and Ehrlich 2002; Gaston and Fuller 2007).

1.3 Natural spaces in cities

Urban biodiversity plays a pivotal role in the sustainability of cities by providing a wide range of ecological and economic services (McKinney 2008). There is growing recognition that some degree of "naturalization" in cities is important for society (Boada Juncà et al. 2016). Urban "greenspaces" (e.g. gardens, parks) have been extensively researched and appear to provide many benefits to urban communities (e.g. physical and psychological health, Fuller et al. 2007). Greenspaces can also be important habitats for species in cities (Goulson et al. 2002). In comparison to greenspaces, the benefits provided to urban areas by aquatic environments, or “bluespaces”, has received less attention (Higgins et al. 2019). Incorporating bluespaces into urbanized areas may be a significant way to connect city inhabitants with nature as well as providing potential opportunities for biodiversity conservation. The presence of aquatic environments in cities can also contribute to microclimate regulation and mitigation of urban heat island effects (Gunawardena et al. 2017), nutrient cycling (Vanni 2002) and flood control (Boyer and Polasky 2004; Moore and Hunt 2012).

1.4 Constructed pond systems in cities

Wetland ecosystems have suffered major losses in parallel with the expansion and proliferation of urban areas (Boyer and Polasky 2004). It is estimated that approximately 50% of the world’s wetlands have been lost and that 87% have been degraded, mostly in the 20th and 21st century (Xu et al. 2019); urbanization and land use change are leading causes of this loss and degradation (for a review see Hu et al. 2017). This loss is a major concern as studies have shown that wetlands have the capacity to produce 47% of the ecosystem services valued on a global scale (Costanza et al. 1997; Xu et al. 2019). Wetlands and aquatic-terrestrial ecotones in general provide an array of economic and ecological benefits, including biodiversity conservation, flood attenuation, nutrient retention (including carbon), water filtration (purification) and recreational and cultural uses (Keddy 2010).

As a result of urbanization, natural land surfaces are replaced with impervious (impermeable) surfaces. This loss in natural permeable surfaces in urban areas increases the proportion of precipitation that becomes runoff (Livingston and McCarron 1992). Stormwater runoff has become a major issue facing cities, leading to frequent and at times catastrophic flooding (Schueler 1992). As a way to mitigate flooding, cities across the world (particularly in North America and Europe) have adopted the construction of shallow artificial ponds, also known as stormwater management ponds (Marsalek and Chocat 2002; Scher and Thiéry 2005).

The construction of stormwater ponds begins with the creation of hydric conditions through the excavation of soils and alteration of hydrology to achieve a lentic condition (Noon 1996). The pond is usually created in an irregular shape and is 1.5 to 2 m deep (Schueler 1987). Because stormwater runoff can generate high sediment loading, more recent designs include an adjacent section to the pond, called the forebay, to retain sediments that can later be removed (Marsalek and Chocat 2002). Regardless of design differences between ponds, their two primary functions are flood control and water filtration (Schueler 1992). Stormwater ponds typically improve the quality of urban runoff through various chemical, physical and biological processes (Schueler 1992; Weiss et al. 2006). The main process that removes the majority of urban contaminants is physical sedimentation, which includes the settling of sediment particles and the trapping of sediments by wetland vegetation (Li et al. 2007). Contaminants can thus accumulate in the pond environment, potentially degrading the water quality for aquatic life (Helfield and Diamond 1997). Contaminants that are typically present in urban runoff include nutrients (e.g. $NO3^-$), trace metals and metalloids (e.g. Zn, Cu, Pb, As), Cl^- (in temperate regions due to road de-icing salts) as well as a suite of organic pollutants (Paul and Meyer 2001; Frost et al. 2015).

While stormwater ponds are built for flood and water quality protection, recent studies have suggested they may be suitable habitats for wetland species, especially given the loss and degradation of natural wetland areas (Hassall and Anderson 2015). Some research has concluded that benthic macroinvertebrate richness and diversity does not significantly differ between stormwater ponds and “natural” or unmanaged urban ponds (Table 1.1, Hassall and Anderson

2015). However, there is a concern that because stormwater ponds can accumulate contaminants, they may pose a risk to wildlife and thus are poor habitats (Helfield and Diamond 1997). Toxicological studies suggest that wildlife should be deterred from inhabiting these systems due to the risk of contaminant exposure (Table 1.1, Wren et al. 1997; Bishop et al. 2000a, b). Overall, the use of stormwater ponds as a habitat for species in cities is an ongoing debate in the scientific literature: approximately one third of peer reviewed studies on macroinvertebrates conclude that stormwater ponds provide poor quality habitat for wildlife, while the remaining literature suggests that stormwater ponds provide good quality habitat that is similar to habitat provided by reference or unmanaged systems (Table 1.1). This topic is an emerging area of research interest, as most of the literature has been published within the last decade (Table 1.1). One order of aquatic macroinvertebrates that has been important for ecological research is Odonata.

1.5 Odonata as biological indicators

Odonata are well-established biological indicators of aquatic ecosystem health and have been successfully used to study wetland integrity and environmental change in North America (Foote and Rice Hornung 2005; Kutcher and Bried 2014). The Odonata order is comprised of two main suborders: Anisoptera (dragonflies) and Zygoptera (damselflies). They are ancient insects with their earliest progenitors (the Meganisoptera) dating back approximately 320 million years ago (Hutchins et al. 2003) and the first fossil records of Odonata dating back 250 million years (Clarke 1973). Odonata are well understood taxonomically, with approximately 5,900 species described (Zhang 2011). They are geographically widespread, abundant under a range of environmental conditions and present in nearly all freshwater systems (Clark and Samways 1996; Corbet 1999; Silva et al. 2010). Species can be exclusive to pond, riverine or lacustrine habitats (Bracken and Lewis 2008). Dragonflies in particular are large and conspicuous as flying adults; they can be easily identified through their distinct coloration and behaviour, even by a non-expert (Smith et al. 2007).

Odonata are ideal indicators of wetland habitat quality as they have a bipartite lifecycle (aquatic and terrestrial life stage) and are dependent on a land/water interface (Corbet 1999; Butler and deMaynadier 2008). They are key members of aquatic and terrestrial food webs as both predators (being voracious consumers of small flying insects) and prey (for fish, frogs and birds) (Morse 1971; Rehfeldt 1990; Corbet 1999; Šigutová et al. 2015). Odonata can therefore reflect the health of other trophic levels (Briers and Biggs 2003). Odonata provide ecosystem services (i.e. mosquito control, see Sebastian et al. 1990; ecotourism, see Lemelin 2007) and are considered flagship species for conservation as charismatic and empathic species (Lemelin 2009).

1.6 Odonata lifecycle requirements

Odonata are hemimetabolous insects (undergo incomplete metamorphosis). Their life history includes an aquatic stage (where most of their lifecycle is spent) and an adult aerial/terrestrial stage (Corbet 1999). Odonata, particularly dragonflies, have high dispersal abilities with some species migrating long distances, as seen with green darners (*Anax junius*) that fly hundreds of kilometres in a migratory season (Wikelski et al. 2006). Odonata actively select their breeding habitats based on visual cues (Wildermuth 1992), in particular the presence of water and the presence of vegetation, which can be detected by their photoreceptory responses of reflective polarization (Wildermuth 1998; Ward and Mill 2005).

Adult Odonata require vegetation as it creates microhabitats that enable thermoregulation, roosting and sheltering (Corbet 1999). Adult Odonata can be categorized based on their thermoregulatory abilities as either fliers or perchers (Corbet 1962). Although all odonates are ectothermic, fliers are also endothermic through their use of flight muscles to generate metabolic heat (May 1978). In contrast, perchers seek an optimal environment to regulate their body temperature through microhabitat and perch selection (i.e. plants) (Corbet 1962; May 1978; Hykel et al. 2020). Adult odonates also rely on vegetation to provide sheltered roosting sites (Corbet 1999). The choice of a favorable roosting site is based on the plant's physical structure, but this preference appears to vary among species. For example, the Southern damselfly (*Coenagrion mercuriale*), an endangered damselfly in the United Kingdom, favors tussock-forming vegetation, potentially because this type of vegetation offers increased protection from weather and predators (Purse and Thompson 2009).

There are two modes of oviposition in the order Odonata: exophytic (eggs are freely laid in water) and endophytic (eggs are laid directly inside a substrate i.e. inside plant tissue) (Westfall and May 1996; Corbet 1999). All damselflies lay their eggs endophytically while most dragonflies lay their eggs exophytically (except for the family Aeshnidae) (Corbet 1999; Needham et al. 2000). When prospecting a potential habitat, Odonata demonstrate an exceptional ability to detect oviposition sites related to vegetation (e.g. Waage 1978; Martens 1993) and have shown preference for specific plant taxa used for oviposition (Guillermo-Ferreira and Del-Claro 2011). Damselflies select plant species with similar physical properties for oviposition, specifically plants with thin cuticle layers and spongy parenchyma, which may efficiently protect the eggs during development (Purse and Thompson 2009). In temperate regions, it is common for species who lay eggs endophytically, such as the Northern spreadwing (*Lestes disjunctus*) to successfully overwinter in the egg stage from the protection provided by the plant tissues (Sawchyn and Gillott 1974).

Once eggs hatch, Odonata spend the majority of their life in aquatic habitats as nymphs (Corbet 1999). Odonata nymphs are affected by a range of physio-chemical variables in water (e.g. Wichard and Komnick 1974; Cannings and Cannings 1987; Rychła et al. 2011; Suhling et al. 2015). In addition to water chemistry, the presence and abundance of aquatic plants (macrophytes) could affect predator-prey relations for the nymph. Macrophytes provide structural heterogeneity to aquatic environments altering biological interactions among species; the presence of macrophytes reduces predation risk of Odonata nymphs (Remsburg and Turner 2009). Once the nymph is ready to emerge as an adult, Odonata directly depend on vegetation as a substrate for emergence (Bried et al. 2018). The angle of the support is important because most species require a vertical angle to successfully emerge, besides the family Gomphidae (Anisoptera) that can emerge on horizontal surfaces (Corbet 1999). The distance travelled by nymphs to seek emergence substrates is minimized with denser and more diverse bank vegetation (Boda et al. 2015).

Thus, there are several factors that could potentially influence Odonata communities in urban constructed pond systems. As described above, Odonata have an ontogenetic linkage to plants (summarized in Table 1.2), which may prove to be an important habitat feature of stormwater ponds. Water chemistry could be important particularly for aquatic life stages, whereas surrounding vegetation, landscape features and connectivity to other water bodies may be important for adults for thermoregulation, roosting, foraging and dispersal.

1.7 Thesis objectives

Studying ecological processes in urban environments is an important emerging field of ecological research as urbanization is a growing global threat to biodiversity (McKinney 2002). The main objectives of this thesis were: (1) to evaluate the use and quality of stormwater ponds as habitat for Odonata and (2) to identify potential drivers of Odonata biodiversity at stormwater ponds. The study design entailed comparing constructed stormwater ponds and natural ponds at a total of 51 sites across the National Capital Region of Canada (NCRC) for Odonata and plant biodiversity, pond water chemistry and catchment/surrounding land cover over one sampling season, along with a more intense sampling of a subset of five ponds over four sampling seasons. The stormwater ponds in the NCRC are varied in age (1- 36 years since construction), have a range of water chemistries due to differences in the percent imperviousness of their catchments (8-74%) as well as other site specific and land cover differences.

1.8 Thesis organization

This thesis includes six chapters. Chapter 2 addressed the first thesis objective and tested the hypothesis that stormwater ponds are as "attractive" to the terrestrial life stage of Odonata (flying adults) as natural reference ponds. The first hypothesis was that stormwater ponds would attract fewer Odonata than natural ponds and in particular fewer damselflies because of their reportedly greater sensitivity to disturbance (Dolný et al. 2012; Monteiro Júnior et al. 2015; Miguel et al. 2017). The second hypothesis was that attributes of plant communities would explain variation in Odonata community structure at stormwater ponds, as Odonata require plants through several life stages and tend to select breeding habitats based on aquatic plant communities. This chapter has been published in the journal *Biodiversity and Conservation* (Perron and Pick 2020).

Chapter 3 focused on the effects of pond water quality on the aquatic life stages of Odonata (nymphs). Given that stormwater ponds typically have higher concentrations of urban contaminants than natural ponds, I predicted lower nymph abundance, species richness and diversity in stormwater ponds. In this chapter, key water chemistry variables that appeared to impact dragonfly and damselfly nymph diversity at the community level were identified. This chapter has been published in the journal *Environmental Pollution*.

Chapter 4 examined evidence of successful reproduction of Odonata at stormwater ponds in comparison to natural ponds. Even if stormwater ponds attract adult Odonata, nymphs may not be able to tolerate poor water quality such that emergence to the adult stage is compromised. As a result, stormwater ponds could represent ecological traps for dragonfly species. A community-level method to analyze the "trap potential" was developed using the presence of adult dragonfly species and evidence of their successful reproduction (abundance and species richness of exuviae, the last instar exoskeleton).

Chapter 5 addressed the second major objective of the thesis and examined the contributions of three major environmental features (plant communities, water quality and landscape features) on driving patterns in dragonfly and damselfly community structure. The differences in the importance of each feature was examined for adult and for nymph life stages. I predicted that adult dragonflies would be the most strongly associated with surrounding landscape features, as dragonflies have high dispersal abilities. In contrast, adult damselflies would be most closely associated with plants as all species require plants for oviposition. Finally, both dragonfly and damselfly nymphs would be more closely associated with water quality as nymphs are the aquatic stage of Odonata and the longest life stage in the odonate lifecycle.

Finally, Chapter 6 summarized the major results, original findings and contributions to ecological theory of this thesis. In addition, management recommendations are provided that may serve to enhance the ecological services of stormwater ponds, specifically the enhancement of urban biodiversity, which contributes to urban sustainability.

Table 1.1

Summary of studies on urban stormwater ponds as habitats for macroinvertebrates (including Odonata) with sample sizes, locales and overall trends. Table indicates whether the author(s) concluded stormwater ponds could be suitable macroinvertebrate habitat or if ponds ultimately provide poor habitat.

Study	**Stormwater pond type**	**Reference pond type**	**Location**	**Organisms**	**Overall Biodiversity Effects**	**Odonata trends**	**Authors conclusion**
Helfield and Diamond (1997)	n=1 (case study, hypothetical)	N/A	Canada	Mentions macroinvertebrates will be affected	• Review, no empirical data	no data	poor habitat
Wren et al. (1997)	Risk assessment	N/A	Canada	Mentions macroinvertebrates will be affected	• Risk assessment, review of toxicological assays (no empirical data)	no data	poor habitat
Bishop et al. (2000a, b)	n=15 stormwater ponds (mostly residential, but 3 commercial/ industrial)	n=1 natural wetland	Canada	Macroinvertebrates	• Fewer taxa in stormwater ponds than the one natural wetland • Many ponds dominated by one taxon • Two stormwater ponds had similar communities to the one natural wetland	• Coenagrionidae dominated three stormwater ponds (20-57%) • *Pantala* sp. dominated the one natural wetland (23%)	poor habitat
Karouna-Renier and Sparling (2001); Casey et al. (2006)	n=18 stormwater ponds (residential, commercial and industrial)	n=2 ponds with minimal runoff input	United States of America	Macroinvertebrates	• Bioaccumulation of metals higher, at some instances, in invertebrates from stormwater ponds (especially commercial ponds) but bioaccumulation levels were below toxicological thresholds (for Zn, Cu, Pb)	• Bioaccumulation of Cu and Zn in Odonata highest in commercial ponds	good habitat (below toxicological thresholds of some metals)
Scher and Thiéry (2005)	n=6 stormwater ponds	n=1 natural pond	France	Odonata	• Differences among stormwater ponds themselves (not much comparison to the control site)	• Attracted uncommon species of Odonata	good habitat
Le Viol et al. (2009)	n=25 highway stormwater ponds	n=18 surrounding ponds (do not receive runoff)	France	Macroinvertebrates (Coleoptera, Heteroptera, Odonata and Gastropoda)	• No difference in number of families • Higher Simpson's diversity in highway ponds • No difference in community structure • Higher abundance of small/short-lived macroinvertebrates at highway ponds	• No difference in Odonata communities • Higher abundance of Coenagrionidae in highway ponds	good habitat
Woodcock et al. (2010)	n=6 stormwater ponds (residential)	n=5 natural wetlands (rural)	Canada	Macroinvertebrates	• No difference in total richness, abundance and total biomass • Differences in invertebrate community structure and invertebrate biomass turnover • More fast-growing species in stormwater ponds	• No difference in Odonata secondary production (the product of population biomass and individual growth rate)	poor habitat (not comparable to reference)
Herrmann (2012)	n=1 stormwater pond (residential) over 2 years	N/A	Sweden	Macroinvertebrates	• 50 taxa found • Initial high abundance of beetles (first few months of being waterlogged) • Species richness decreased through time	• Odonata had low abundances and species richness through study • Except for *Ischnura elegans* with high abundances in the last year of the study	good habitat

Table 1.1 (cont'd)

Study	Stormwater pond type	Reference pond type	Location	Organisms	Overall Biodiversity Effects	Odonata trends	Authors conclusion
Lunde and Resh (2012)	n=18 stormwater ponds	n=20 rural ponds	United States of America	Macroinvertebrates	• Index of biotic integrity was lower in urban ponds	• Odonata was included in the group EOT (Ephemeroptera, Odonata, Trichoptera) and this index decreased as urbanization increased	no comment as the goal was to simply develop an index
Moore and Hunt (2012)	n=20 stormwater ponds	n=20 stormwater wetlands (40% or more macrophyte cover)	United States of America	Macroinvertebrates	• Similar Shannon-Weiner diversity between stormwater ponds and stormwater wetlands • Higher richness in stormwater ponds • Community composition differed (more collectors in ponds and more scrapers in wetlands)	• Higher abundance of Aeshnidae and Coenagrionidae in ponds with dense littoral vegetation • Similar proportion of Odonata in ponds and wetlands	good habitat (both types)
Briers (2014)	n=4 stormwater ponds over 5 years	N/A	Scotland	Macroinvertebrates	• Decline in species richness over the years • No difference in Shannon-Weiner diversity through time • Piloue's eveness increased over the years • Significant differences in species composition between the sites	• No change in species richness, diversity of eveness for Odonata through time	good habitat
Hassall and Anderson (2015)	n=20 stormwater ponds	n=10 natural wetlands/lakes	Canada	Macroinvertebrates	• No difference in biological communities • No difference in number of taxa found • No difference in Shannon-Weiner diversity	• No Aeshnidae or Gomphidae in stormwater ponds • Similar frequency of Libellulidae and Coenagrionidae	good habitat
Mackintosh et al. (2015)	n=16 stormwater ponds	n=4 natural wetlands	Australia	Macroinvertebrates	• Tolerant taxa dominated regardless of amount of imperviousness surfaces in vicinity	no data	good habitat (if managed properly)
Noble and Hassall (2015)	n=4 Overflow ponds (while there were other types of ponds studied)	n= 11 urban ponds managed for biodiversity	England	Macroinvertebrates	• No difference in ASPT (Average Score Per Taxon) values • No difference between macroinvertebrate richness	no data	poor habitat (all ponds in study)
Stephansen et al. (2014)	n=9 stormwater ponds	n=11 shallow natural lakes	Denmark	Macroinvertebrates	• Similar taxonomic richness • Invertebrates from ponds had the highest bioaccumulation • Similar species composition between most ponds and lakes • Highway ponds had different communities than other stormwater ponds and lakes	• Coenagrionidae was the most present taxa in ponds and lakes	good habitat
Hill et al. (2017)	n=240 urban ponds (but only some stormwater ponds)	n=782 non-urban ponds	United Kingdom	Macroinvertebrates	• Similar family level gamma-diversity • Higher family-level richness in urban ponds • Similar species level gamma-diversity • No difference in alpha species diversity species and family richness • Differences in family and species-level community structure • Large variation in diversity between the urban ponds	• Libellulidae and Aeshnidae occurred at similar frequencies at both pond types	good habitat
Greenway (2017)	n=2 stormwater ponds (residential)	n=1 natural wetland downstream	Australia	Macroinvertebrates	• Greater macroinvertebrate richness	• Similar species richness of damselfly nymphs in stormwater ponds and natural downstream wetland	good habitat

Table 1.1 (cont'd)

Study	Stormwater pond type	Reference pond type	Location	Organisms	Overall Biodiversity Effects	Odonata trends	Authors conclusion
Holtmann et al. (2018)	n=35 stormwater ponds	n=35 next pond in vicinity (regardless of origin)	Germany	Odonata	• Higher species richness and abundance in stormwater ponds	• Higher adult and exvuviae species richness and densities in stormwater pond than control ponds • More threatened species found in stormwater ponds	good habitat
Johansson et al. (2019)	n=18 stormwater ponds	no reference site	Sweden	Odonata	• Range in species richness and composition between the ponds	• Range of 3 to 20 species at each pond	good habitat
Sun et al. (2019)	n=12 stormwater ponds	no reference site	Norway	Macroinvertebrates	• 175 macroinvertebrate taxa identified in study	• Red-listed damselfly *Coenagrion lunulatum* found in stormwater ponds • *Aeshna cyanea* and *Coenagrion pulchellum* correlated with the number of neighboring ponds	good habitat for tolerant taxa

Table 1.2. Odonata associations with plants throughout their hemimetabolous lifecycle, for each life stage with key references cited.

Life Stage	Behaviour /Function	Role of Vegetation	Key References
Adult	Habitat Selection	Macrophytes (particularly bank, floating and submerged plants) as visual cues for habitat selection	(Samways and Steytler 1996) (Ward and Mill 2005)
	Thermoregulation	Microhabitat created by plants (sunny versus shady) that help maintain metabolic activity	(May 1976) (Corbet and May 2008) (Remsburg et al. 2008)
	Shelter/Roosting sites	Resting perch and/or to provide shelter from unfavorable weather conditions	(O'Farrell 1971) (Rouquette and Thompson 2007) (Hykel et al. 2020)
	Oviposition (egg laying)	Plant tissues for endophytic oviposition	(Westfall and May 1996) (Purse and Thompson 2009)
Egg	Protection	Plant tissues protect eggs from predation/desiccation	(Sawchyn and Gillott 1974) (Fincke 1986)
Nymph	Emergence	Plants as vertical substrates required to emerge from last instar into adult	(Boda et al. 2015) (Bried et al. 2018)
	Predator-Prey interactions	Microhabitat created by plants act as refuge areas	(Johansson 2000) (Remsburg and Turner 2009) (Hossie and Murray 2010)

Chapter 2: Stormwater ponds as habitat for Odonata in urban areas: the importance of obligate wetland plant species

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2.1 Abstract

Urbanization significantly alters hydrological regimes in cities by reducing infiltration rates and increasing runoff. Stormwater ponds have been constructed in North American cities to mitigate the effects of increased urban runoff by dampening floods and filtering out contaminants. However, these ponds may also provide habitat for wetland species in cities. This study aimed at determining the significance of stormwater ponds as attractive habitats for the adult stages of Odonata (dragonflies and damselflies), widely considered bioindicators of aquatic and wetland ecosystem health. A total of 41 urban stormwater ponds and ten rural natural ponds were sampled across the National Capital Region of Canada. On average, stormwater ponds had fewer species and lower abundance of dragonflies but, in contrast, more species of damselflies. Stormwater ponds had a higher total plant species richness because of a higher number of non-native species. However, some stormwater ponds had similar odonate and plant species assemblages to natural ponds. The variation in odonate abundance and species composition was largely explained by plant community composition and significantly linked to the presence of specific obligate wetland plant species. Overall, this study highlights the importance of wetland features in cities and points to design elements of stormwater ponds that could be implemented to enhance biodiversity and ecosystem services.

Keywords ponds; dragonflies; damselflies; biodiversity; urban ecology; plant communities

2.2 Introduction

Urbanization leads to the loss of habitat through the replacement of natural areas with impervious surfaces. Impervious surfaces in turn produce more runoff, increasing the incidence of flooding and reducing water quality (Paul and Meyer 2001; Brabec et al. 2002). One way to manage urban runoff is through the construction of shallow open-water systems, notably stormwater ponds. In North American cities, the construction of stormwater ponds is proliferating as they are mandatory, in several jurisdictions, under building legislations (e.g. Ontario Ministry of the Environment 2003; Alberta Environment and Sustainable Resource Development 2013). These ponds are engineered to mimic the ecological services of natural wetlands related to flood attenuation and water filtration (Shutes et al. 1997; Villarreal et al. 2004). Since urban areas lack natural wildlife habitat, wetland species tend to colonize stormwater ponds (Bishop et al. 2000a).

Stormwater ponds thus present an opportunity for wetland species to establish in cities, but to what extent these ponds are suitable habitat remains unclear. Some studies suggest that stormwater ponds contribute to biodiversity (e.g. Hassall and Anderson 2015; Hill et al. 2017, Holtmann et al. 2018) while others suggest more negative impacts (e.g. Bishop et al. 2000a, b; Noble and Hassall 2015). Concerns over the quality of habitat for wildlife have been raised based on the assumption that stormwater ponds are sinks for contaminants (Helfield and Diamond 1997). Concerns have also been raised over the possibility that stormwater ponds are "ecological traps" (Sievers et al. 2018). Wildlife may be attracted to these ponds and select them over other source habitats; reproduction may be affected due to poor environmental quality potentially leading to declines in regional populations (Battin 2004). In contrast, other studies suggest that the wetland habitat associated with stormwater ponds in cities outweighs the risk of contaminant exposure, if properly managed (Sparling et al. 2004). As a first step, the evaluation of *in situ* diversity patterns at stormwater ponds is needed to determine the use of man-made urban ponds as secondary habitat and how they contribute to the conservation of species in urban areas (Bried and Samways 2015).

In this study, biodiversity patterns were compared in a range of stormwater ponds to determine if and how community structure differs from natural ponds. I focused on adult stages of Odonata, class: Insecta, suborders: Anisoptera (dragonflies) and Zygoptera (damselflies), as measures of biodiversity. Odonates are easily identified through their distinct coloration and are flagship species for conservation (Corbet 1999; Lemelin 2007). They are widespread and abundant under a range of environmental conditions (Clark and Samways 1996; Smith et al. 2007; Silva et al. 2010). To complete their lifecycle, odonates require a land/water interface and as a result can be ideal indicators of wetland habitats (e.g. Foote and Rice Hornung 2005; Kutcher and Bried 2014). Overall, odonates are sensitive indicators of disturbance and anthropogenic impacts in aquatic environments (Butler and deMaynadier 2008; Dolný et al. 2012; Kutcher and Bried 2014). Although, the presence of adult odonates does not necessarily indicate reproductive success of the species, adults are good indicators of habitat selection (Wildermuth 1992; Corbet 1999).

I also chose to focus on plant biodiversity because odonates require plants for many life-history stages. Adult odonates select habitats based on a set of visual cues (Wildermuth 1992; Osborn and Samways 1996), mainly the presence of water and macrophytes, particularly emergent vegetation (Dunkle 1976; Wildermuth 1998; Ward and Mill 2005). All damselflies and some dragonfly species require macrophytes for oviposition, laying their eggs directly in plant tissues (Sawchyn and Gillott 1974; Corbet 1999; Purse and Thompson 2009). Plants also serve as vertical substrates for successful emergence from the nymph aquatic stage into the adult aerial stage (Boda et al. 2015; Bried et al. 2018). Furthermore, plants offer refuge for resting and roosting odonates (Askew 1982; Rouquette and Thompson 2007) and provide microclimates for thermoregulation at the adult stage (Remsburg et al. 2008; Kortello and Ham 2010).

As a first step, I tested the hypothesis that stormwater ponds would be less attractive to adult Odonata than natural ponds, given that stormwater ponds are potentially contaminated and more disturbed environments than natural ponds. I predicted lower abundance and fewer species of adult Odonata at stormwater ponds compared to natural ponds. Secondly, I hypothesized that attributes of plant communities would explain variation in Odonata community structure at stormwater ponds given the role of wetland plants in Odonata lifecycles. I predicted positive relationships between diversity/abundance of adult Odonata and species richness of wetland plants and related indices and that stormwater pond plant community assemblages will be related to adult Odonata community assemblages.

2.3 Methods

2.3.1 Study sites

A total of 41 stormwater ponds (Fig. 2.1) were selected out of over 100 constructed ponds currently found across the National Capital Region of Canada (NCRC), which encompasses the cities of Ottawa, Ontario and Gatineau, Québec (Table S2.1 for pond characteristics). Stormwater ponds held a permanent body of water and were 1 to 2 m in average depth. Ten natural (non-constructed) ponds were selected from undeveloped areas in the NCRC, with little to no impervious surfaces in the catchment area. Although more than ten natural ponds would be desirable, few fit the above selection criteria or could be legally accessed. Fig. S2.1

provides an example of differences in surrounding land cover types between stormwater ponds and natural ponds. All study ponds chosen were approximately one hectare in size in order to minimize species-area effects. In addition, ponds were at least 1 km away from rivers or lakes to avoid population overlap with riverine and/or lacustrine odonate species (Dolný et al. 2014).

The stormwater ponds ranged in age from one to 36 years post construction (Table S2.1). A total of 38 stormwater ponds and five natural ponds were sampled in the summer of 2015; three additional stormwater ponds and five additional natural ponds were sampled in the summer of 2016 to increase the range in age of stormwater ponds and the sample size of natural ponds. Stormwater ponds were located in residential areas and/or associated with small scale developments such as strip malls; the percent of impervious surfaces in catchment basins ranged from 8.3 to 74.3% (average of 44%). Both summers had similar weather conditions and were relatively hot and dry (Fig. S2.2); 2015 had slightly more precipitation.

2.3.2 Odonata sampling and metrics of community structure

Adult dragonflies (Anisoptera) and damselflies (Zygoptera) were identified and enumerated twice at each site (as suggested by Oertli et al. 2005) in late spring/early summer (2015: 13/06-26/07, 2016: 16/06-05/07) and late summer (2015: 27/07-28/08, 2016: 01/08-09/08) to ensure the likelihood of encountering all early and late emerging species. Adult odonates were observed on at least partly sunny days (cloudy days were excluded) between 10:00 am and 4:00 pm in temperatures above 16ºC to ensure they were active and easily identified. Furthermore, observations only took place when wind speeds were below 30 km/h in order to observe species in flight; extra care was taken to search for sheltering individuals if wind conditions were above 10 km/h (methods following Butler and deMaynadier 2008). A 60-minute survey at each pond was conducted by systematically walking along the pond perimeter (as in Bried et al. 2007; Kadoya et al. 2008). Circuits around the pond were performed starting from the waters' edge and moving progressively further from the edge as time permitted depending on the length of the perimeter. Information on species and their respective flight periods was obtained from a regional taxonomic list (Bracken and Lewis 2008). The maximum abundance observed in a given pond circuit was used to avoid the possibility of double-counting individuals between circuits. Individuals were identified to species and if certain individuals could not be identified by eye or binoculars, they were caught with a sweep net. In this instance, the chronometer was stopped until the species was accurately identified with a hand lens and field guide (Jones et al. 2013). Pictures and voucher specimens were obtained to confirm identifications of cryptic species. Species richness, abundance and Shannon-Weiner diversity were calculated for each pond. In addition, I calculated the ratios between Libellulidae/other Anisoptera and Coenagrionidae/other Zygoptera (Šigutová et al. 2019) to determine if there were any relationships to disturbance as measured by the percent of impervious surface cover in the catchment basins of stormwater ponds. In cases where there was an abundance of zero for the denominator, abundance was set at one to allow for the calculation of a ratio.

Odonata were also sampled as described above at a subset of stormwater ponds (n=5) over a four-year period (2015-2018), by the same observer to determine if similar species were present from year to year.

2.3.3 Plant sampling, metrics of community structure and conservation value

Plant communities were sampled twice, once in early summer (2015: 02/06-24/07, 2016: 27/06-07/07) and once in late summer (2015: 26/07-28/08, 2016: 02/08-11/08) to ensure detection and identification of the majority of species (early and late flowering) at each pond. Plants were sampled using interrupted belt transects perpendicular to the waters' edge. Three 1 m-wide transects were sampled at each pond starting at the submerged aquatic vegetation and extending towards higher bank vegetation (Dalton et al. 2015). Transects were at least 10 m away from any infrastructure (e.g. pond outlet grates) to avoid zones of high disturbance, which would affect the establishment of vegetation. The first transect was randomly placed at the pond, and the two other transects were evenly distanced along the perimeter. Four 1 m^2 quadrats in each transect were sampled, one in water to include submerged macrophyte species. At a few sites, where the littoral vegetation band was too narrow for three transects (i.e. <4 m), more transects were established to complete a total of 12 quadrats at each pond. All transects were sampled in early summer and resampled in late summer (total of 24 quadrats per pond).

Within each quadrat, vascular plants were identified to species (with <1% identified to genus). Difficult graminoid species were collected and pressed for subsequent identification. Taxonomic references included Dore and McNeill (1980), Marie-Victorin et al. (2002), Barkworth et al. (2007), Brouillet et al. (2010) and Voss and Reznicek (2012). A voucher collection was preserved in the University of Ottawa herbarium (OTT). The presence and percent cover were recorded for each species and an average cover was calculated for each species at each site for analyses. Plants were also categorized based on their broad functional guilds (i.e. submerged plants, narrow leaved emergent, etc., adapted from Golet 1976).

Four metrics of plant community structure were calculated including total species richness, species richness of obligate wetland plants, species richness of native plants and the Floristic Quality Index (FQI) (Oldham et al. 1995). The FQI was calculated by scoring all native plants a coefficient of conservatism, assigned by Oldham et al. (1995), that ranges between 0 and

10 (0-3: common species found in a variety of environments, including disturbed areas, 4-6: tolerant of moderately disturbed areas but associated with only certain plant communities, 7-8: plants in advanced successional stages with low disturbances, and 9-10: plants with very specialized habitat requirements, usually seen in pristine conditions). The FQI was calculated by averaging the coefficients of conservatism of all native species at a site and dividing the average by the square root of the total number of native plant species for that site (Oldham et al. 1995). Examples of the use of the FQI in ecological and conservation studies include Bried et al. (2013) and Dalton et al. (2015). In addition, each individual species was assigned a wetness index between -5 (obligate wetland) and 5 (obligate upland) following Oldham et al. (1995). Obligate wetland species refers to plants that occur 99% of the time in wetlands naturally and obligate upland species have less than a 1% probability of occurring in wetlands naturally. The designation of native species versus non-native species were listed according to Oldham et al. (1995).

2.3.4 Statistical analyses

The residuals of variables associated with odonate and plant diversity were checked for normality using the Shapiro-Wilks test from the *stats* package (R Core Team 2017) and transformed accordingly (requiring log or square root transformations).

To test whether the proximity among certain sites biased the Odonata and plant community metrics in stormwater and natural ponds, I quantified the non-independence within clustered sites using a linear mixed-effect model framework with the *stats* package. In particular, a number of natural ponds were clustered in one area (n= 6), whereas the remaining natural (n= 4) and man-made (n= 41) ponds were scattered across the landscape. Thus, for the linear mixed-models, a random effect variable was created that coded clustered natural ponds (B), scattered natural ponds (A) and scattered manmade ponds (C). The intra-class correlation (ICC), which is the ratio of the among group variation (or random effect variance) to the within group variation (or error), was then calculated to: (1) determine the importance of this random effect, and thus whether response values within each group (A, B or C) were more similar than among the groups, and (2) obtain the effective sample size (i.e. the sample size after correcting for any pseudo-replication due to non-independence). Differences in the response variables among spatially clustered natural ponds (B) and scattered natural ponds (A) were also compared to those of stormwater ponds (C) by nesting the random effect by pond type (urban versus natural). Models with and without the random factors were compared using the Akaike information criterion corrected for small sample sizes (AICc). In all cases, the ICC was small and the most parsimonious models (lowest AICc) did not include the random effect, indicating that spatial clustering did not affect the odonate or plant metrics significantly.

Boxplots, created with the *graphics* package (R Core Team 2017), were used to visualize differences between measures of odonate community structure (total and suborder species richness, total and suborder abundance and total Shannon-Weiner diversity index) and measures of plant community structure (total species richness, obligate wetland plant species richness, native plant species richness and the FQI). Simple pairwise comparisons were used to test differences between stormwater and natural ponds (independent t-test, Mann-Whitney-U test, or Welch's test, from the *stats* package, depending on the distribution and the variances of the data).

Pearson's correlations were used to test for relationships between pond age and biodiversity measures and to test for relationships between plant community metrics and odonate community metrics in stormwater ponds. Linear regressions were used to test the strengths (adjusted R^2) and significance of these relationships ($p<0.05$) in stormwater ponds using the *stats* package.

Pond area did not have any significant relationships with total odonate species richness ($p=0.10$) or abundance ($p=0.14$), dragonfly (Anisoptera) species richness ($p=0.23$) or abundance ($p=0.99$), damselfly (Zygoptera) species richness ($p=0.25$) or abundance ($p=0.11$). Length of pond perimeter also did not have any significant relationships with total odonate species richness ($p=0.43$) or abundance ($p=0.13$), dragonfly species richness ($p=0.49$) or abundance ($p=0.79$), damselfly species richness ($p=0.70$) or abundance ($p=0.063$).

Prior to multivariate analyses, I tested for potential effects of spatial autocorrelation on Odonata community composition. Spatial autocorrelation was present in the dragonfly communities ($p=0.008$), thus for ordination analyses, the dragonfly community data were detrended of any broad-scale spatial trends to examine finer scale relationships between dragonfly communities and plant communities. Spatial autocorrelation was not present in the damselfly communities ($p=0.087$).

A transformation-based redundancy analysis (tb-RDA), using Hellinger transformation (plotted in scaling type 2) (Legendre and Anderson 1999; Legendre and Gallagher 2001) with the *vegan* package (Oksanen et al. 2018), was performed to determine relationships between plant species composition and the detrended dragonfly species composition. The analysis was repeated for plant species composition and damselfly species composition. Only the dominant plant species were retained for analyses, which included 50 out of the 297 species present (found at 5 or more sites with an average cover greater than 6%). Also, rare odonate species that were seen at a single instance at a single site were removed to avoid undue weighting in ordination analyses. The significance of specific plant species ($p<0.05$) as well as the coefficients of determination (adjusted R^2) for each redundancy model was determined through stepwise forward regression with permutation (= 9,999). The redundancy (RDA) axes and models were tested for significance ($p<0.05$) and plotted in two-dimensional space. A tb-RDA was also performed to determine relationships between the average cover of plant functional guilds and the detrended dragonfly species composition as well as for plant functional guilds and damselfly species composition. All statistical analyses were conducted in R and RStudio (version 0.99.902, 3.4.2 and 1.1.456).

2.4 Results

2.4.1 Stormwater pond versus natural pond biodiversity

A total of 13,579 individual odonates were identified across seven families (Calopterygidae, Lestidae, Coenagrionidae, Aeshnidae, Gomphidae, Corduliidae and Libellulidae). A total of 52 species were identified out of the 123 species known locally. Out of the 52 identified species, 42 were pond species, representing over 63% (42 out of 66) of the known pond species in the area, with the other species identified in this study being more characteristic of slow-moving waters (habitat information from Bracken and Lewis 2008). Stormwater and natural ponds shared a large pool of similar odonate species: approximately 70% of species observed were present in both environments (Table S2.2). There was no significant difference in total odonate species richness (Fig. S2.3a, W=165.5, p=0.54) or Shannon-Weiner diversity (Fig. S2.3c, t=-0.16, p=0.87**)** between stormwater and natural ponds. However, stormwater ponds had significantly less total abundance of odonates in comparison to natural ponds (Fig. S2.3b, t=-2.17, p=0.04).

When odonate suborders were analyzed separately, several differences became apparent. A total of 3,636 individuals belonged to the Anisoptera (dragonflies) suborder and 9,943 to the Zygoptera (damselflies) suborder. In comparison to the natural ponds, stormwater ponds had a significantly lower dragonfly species richness (Fig. 2.2a, t=2.33, p=0.003), yet a significantly higher damselfly species richness (Fig. 2.2b, W=329.5, p=0.024). Dragonfly abundance was also significantly lower in stormwater ponds (Fig. 2.2c, t=8.88, p<0.001), whereas damselfly abundance was not significantly different (Fig. 2.2d, t=0.424, p=0.673). There was no relationship between Libellulidae/other Anisoptera as well as Coenagrionidae/other Zygoptera ratios with impervious surface cover in the catchment basin of stormwater ponds (Fig. S2.4).

Odonata were sampled at a subset of stormwater ponds over four years. The overall community structure of Odonata was similar between years (based on rank abundance slopes) with the exception of the pond with the least amount of suitable habitat (shoreline with steep rock walls and little vegetation). The dominant species (those with abundances that collectively represented over 75% of the total) were similar from year to year, although their specific ranking varied (e.g. Fig. S2.5).

A total of 297 species of plants were identified, with stormwater ponds sharing approximately 29% (85/297) of the same plant species with natural ponds. There was a higher total species richness and higher variation in richness of plants in stormwater ponds compared to natural ponds (Fig. 2.3a, t=2.67, p=0.010). On average, stormwater ponds had significantly fewer obligate wetland plant species (Fig. 2.3b, t=-5.57, p<0.001). However, some individual stormwater ponds had comparable obligate wetland plant species richness to the natural ponds. Stormwater ponds also had a lower percentage of native plants (average of 57%) than natural ponds, (average of 86%) (t=-15.38, p<0.001) but stormwater ponds had comparable overall native plant species richness to natural ponds (Fig. 2.3c, t=-1.48, p=0.145). The FQI was significantly lower in stormwater ponds (Fig. 2.3d, t=-8.39, p<0.001), with an average value of 14.83, compared to an average FQI of 26.98 at the natural sites. However, four stormwater ponds had FQI values over 20 and were comparable to the natural ponds.

I also considered whether stormwater pond age affected biodiversity patterns. There was no significant relationship between pond age and total odonate species richness (R^2=0.05, p=0.08), abundance (R^2=0.04, p=0.10) or Shannon-Weiner diversity (R^2=-0.01, p=0.45), and no relationship with dragonfly species richness (R^2=0.01, p=0.22) and abundance (R^2=-0.00, p=0.41) or damselfly species richness (R^2=0.02, p=0.18) and abundance (R^2=0.04, p=0.11). There was no significant relationship between pond age and plant species richness (R^2=0.00, p=0.30), obligate wetland plant species richness (R^2=-0.03, p=0.97) or the FQI (R^2= -0.00, p=0.36). However, there was a significant positive relationship between stormwater pond age and the percent of native plant species (Fig. S2.6, R^2=0.24, p<0.001).

2.4.2 Plant-Odonata associations

The plant community metrics, including total plant species richness (R^2=0.03, p=0.10), obligate wetland plant species richness (Fig. S2.7a, R^2=0.053, p=0.079), native plant species richness (Fig. S2.7c, R^2=-0.001, p=0.33) and the FQI (Fig. S2.7e, R^2=0.014, p=0.22) were not significantly related to total odonate species richness. In contrast, odonate abundance was significantly related to plant species richness (R^2=0.08, p=0.045), obligate wetland plant species richness (Fig. S2.7b, R^2=0.279, p<0.001) and the FQI (Fig. S2.7f, R^2=0.126, p=0.013), but was not related to the native plant species richness (Fig. S2.7d, R^2=0.03, p=0.14).

When suborders were analyzed separately, no relationships between plant metrics and dragonfly (Anisoptera) or damselfly (Zygoptera) species richness were found (Fig. S2.8). However, dragonfly abundance was significantly related to all four plant community metrics, while damselfly abundance was significantly related to only two of the metrics. Dragonfly abundance was positively related to total plant species richness (R^2=0.137, p=0.001), while damselfly abundance was not (R^2=0.039, p=0.11). Obligate wetland plant species richness explained the most variation in odonate abundance out of all four plant community metrics, explaining over 36% of the variation in dragonfly abundance (Fig. 2.4a, R^2=0.366, p<0.001) and over 20% of the variation in damselfly abundance (Fig. 2.4b, R^2=0.205, p=0.002). Dragonfly abundance was positively related to species richness of native plants (Fig. 2.4c, R^2=0.182, p=0.003), but damselfly abundance was not (Fig. 2.4d, R^2=0.002, p=0.31). Dragonfly abundance was significantly higher in stormwater ponds with high floristic quality (Fig. 2.4e, R^2=0.257, p<0.001); damselfly abundance followed the same relationship but with much less variation explained (Fig. 2.4f, R^2=0.076, p=0.045). When the response of the two suborders were directly compared, there was a significant decrease in the abundance of damselflies relative to dragonflies as the species richness of obligate wetland plants increased (R^2=0.187, p<0.001) and the floristic quality of the pond increased (Fig. S2.9, R^2=0.285, p<0.001).

The cover of plant functional guilds did not explain a large amount of the variation in dragonfly or damselfly community structure. Upland herbaceous plants (p=0.002) explained only a small amount of the variation (5.6%) in dragonfly communities and were not associated with any particular dragonfly species (Fig. S2.10). Upland herbaceous plants (p=0.002) and wetland herbaceous plants (p=0.004) explained slightly more variation (16.4%) in damselfly communities but again plant functional guilds were not associated with any particular damselfly species (Fig.

S2.11). A more detailed trait-based analysis of the 297 plant species would be required to fully test for the presence of relationships between Odonata and plant structural complexity.

Odonate community composition was closely associated with plant species composition. A total of 25.5% of the variation in dragonfly community composition could be explained by nine plant species (Fig. 2.5, Table 2.1). The amount of variation explained in damselfly community composition by plant community composition was higher, with a total of 40.4% of damselfly communities explained by 12 plant species (Fig. 2.6, Table 2.1). Obligate wetland plant species was the most common plant type influencing both dragonfly and damselfly species composition (Table 2.1).

Dragonfly species composition was significantly related to one free-floating species, two species of wetland sedges and six species of herbaceous plants (Table 2.1). One dragonfly species, *Leucorrhinia intacta*, was most dominant in stormwater ponds and associated with a mix of wetland and upland herbaceous species (Fig. 2.5). In contrast, *Leucorrhinia frigida* was dominant in a number of natural ponds and closely associated with a species of wetland sedge (Fig. 2.5).

Damselfly species composition was significantly related to one robust-emergent plant species, two species of sedges, one wetland fern, six species of herbaceous plants, one tall shrub and one deciduous tree (Table 2.1). In particular, Lestidae were related to plant species that provide shade (*Fraxinus americana* and *Alnus incana*) and were mostly present in natural ponds. In stormwater ponds, one species of damselfly, *Ischnura verticalis*, was highly dominant and was not associated with wetland plant species, but rather did well in ponds with a high abundance of upland plant species (Fig. 2.6). *Nehalennia irene* was dominant in a number of natural ponds as well as certain stormwater ponds and was significantly associated with obligate wetland plants present in both urban and natural environments (Fig. 2.6).

2.5 Discussion

2.5.1 Abundance and diversity in stormwater ponds versus natural ponds

Based on the literature describing contrasting effects of disturbance on the two suborders of Odonata (Dolný et al. 2012; Monteiro Júnior et al. 2015; Miguel et al. 2017), I expected that there would be more dragonflies and fewer damselflies at the stormwater ponds. However, I found the opposite: fewer dragonflies and no significant difference in damselfly abundance in stormwater ponds when compared to natural ponds within the same region (Fig. 2.2c, d). In addition, dragonfly species richness was lower, whereas damselfly species richness was higher at the stormwater ponds (Fig. 2.2a, b). The previous studies suggesting that dragonflies are more tolerant of habitat disturbance and degradation compared to damselflies were all conducted in tropical ecosystems, especially in streams (Dolný et al. 2012; Monteiro Júnior et al. 2015; Luke et al. 2017; Miguel et al. 2017). However, for a river in South Africa, Samways and Steytler (1996) noted that dragonflies had narrower requirements for macrophyte cover and sun exposure than damselflies. My results are in keeping with the latter study and suggest that damselflies can withstand a wider range of environmental conditions compared to dragonflies. With respect to family-level trends, a recent study found that the relative abundances of Libellulidae (dragonfly) and Coenagrionidae (damselfly) increased with forestry disturbances (as a categorical variable) (Šigutová et al. 2019). I did not find such family-level relationships with urbanization (percent imperviousness of the pond catchment); urbanization may represent a very different type of disturbance.

In terms of the plant communities, stormwater ponds had a higher overall plant species richness in comparison to natural ponds (Fig. 2.3a). This was largely explained by the high number of non-native species, which comprised, on average, nearly half of the plant taxa present. In contrast, the natural ponds had few non-native plant species and overall plant communities with higher conservation value (Floristic Quality Index). In a literature review, McKinney (2008) found that terrestrial plant species richness increases at intermediate levels of urbanization as a result of the increased presence of exotic plants in urban centers. With respect to wetland habitats, Magee et al. (1999) showed that sites dominated by industrial/commercial or agricultural land-use in a 100 m radius were more susceptible to invasive plant species than areas surrounded by undeveloped land. Stormwater ponds generally offered less available wetland habitat than natural ponds, with a lower richness of obligate wetland plant species (Fig. 2.3b). This is consistent with studies of cedar swamps where stormwater runoff lead to declines in the species richness of obligate wetland plants in receiving wetlands (Ehrenfeld and Schneider 1991; Ehrenfeld and Schneider 1993).

Across the ponds, there was considerable variation in Odonata composition along with variation in plant community structure (Fig. 2.5, Fig. 2.6). The species *Leucorrhinia proxima*, *Leucorrhinia frigida* and *Sympetrum internum* as well as all *Lestes* sp. were more common at the natural ponds (Fig. 2.5, Fig. 2.6); there were three species exclusive to the natural ponds: *Lestes forcipatus*, *Enallagma aspersum* and *Aeshna tuberculifera* (scarce, rare and uncommon species for the region respectively, Bracken and Lewis 2008, Table S2.2). Whereas, *Enallagma ebrium*, *Enallagma civile*, *Ischnura verticalis*, *Anax junius*, *Libellula luctuosa*, *Libellula pulchella*, *Plathemis lydia* and *Leucorrhinia intacta* were more common at the stormwater ponds (Fig. 2.5, Fig. 2.6). One species of dragonfly, *Leucorrhinia intacta*, and one species of damselfly, *Ischnura* *verticalis*, in particular were characteristic of stormwater ponds that were the most dissimilar from the natural ponds (Fig. 2.5, Fig. 2.6). Both species are considered generalist species (Wolf and Waltz 1988; Butler and deMaynadier 2008). *Leucorrhinia intacta* lays eggs exophytically (freely into the water) and adults prefer habitats with little emergent vegetation due to a high risk of predation associated with their mode of oviposition (Wolf and Waltz 1988). *Ischnura verticalis* has been associated with high nutrient concentrations in water (Catling 2005) and a European species from the same genus (*I. elegans)* has also been found to favour ponds with high disturbance levels (Goertzen and Suhling 2013). Nevertheless, several stormwater ponds had comparable odonate and plant communities to natural ponds as reflected in their proximate location in ordination space (Fig. 2.5, Fig. 2.6). This suggests that stormwater ponds can potentially provide comparable habitats to natural ponds.

2.5.2 Plant-Odonata relationships

I hypothesized that plant communities would be predictors of Odonata community structure in stormwater ponds, as odonates require plants throughout their life history. This hypothesis was largely supported given several significant relationships between Odonata and plant communities in the stormwater ponds (Fig. 2.4, 2.5 and 2.6). As anticipated, I found that adult odonates were most abundant in stormwater ponds where plant communities were comparable to natural ponds (Fig 2.4a, e). Obligate wetland plant species richness was the strongest predictor of Odonata abundance, explaining over 36% of the variation in dragonfly abundance and over 20% of the variation in damselfly abundance (Fig. 2.4a, b).

Compared to dragonflies, damselflies were more closely associated with specific plant species rather than with community level metrics (such as total plant species richness, obligate wetland plant species richness, native plant species richness and FQI). Wetland sedges and many herbaceous species likely have the characteristics suitable for damselflies to lay their eggs endophytically. Plant tissues protect eggs from predation, desiccation and extremes in weather (Corbet 1999). There is evidence, based on individual species of damselflies, that specific plant species may be selected for oviposition (Lambret et al. 2018). Purse and Thompson (2009) found that *Coenagrion mercuriale*, a damselfly in the United Kingdom, selected herbaceous plant species with similar physical properties (thin cuticle layers) for oviposition. Plant species that were used less for oviposition had strengthening tissues making it more difficult for egg insertion. The distribution of a damselfly (*Oxyagrion microstigma*) in Brazil was largely determined by a specific plant genus (*Eleocharis*) shown to be most suitable for oviposition and typically defended by males (Guillermo-Ferreira and Del-Claro 2011).

Plant characteristics that may influence habitat selection by odonates are also related to the provisioning of perches and thermoregulation. In particular, upland and wetland herbaceous plants may be acting as important perches for adult odonates and their density is also important (Remsburg et al. 2008). Plants that provide a dense canopy create microclimates in the shade. Unlike dragonflies that have better self-regulating thermoregulatory systems, damselflies (particularly Lestidae) seek shade to regulate their body temperature (May 1978; McKay and Herman 2008). From this study, *Lestes* spp. were associated with white ash (*Fraxinus americana*) and speckled alder (*Alnus incana*) (Fig. 2.6), both species that provide a canopy and shade.

2.5.3 Stormwater ponds as "attractive" habitats

My results support the general hypothesis that adult odonate habitat selection is based on the presence and structure of wetland plant communities. However, this does not mean that urban stormwater pond systems are necessarily good habitats for Odonata; the presence of adult odonates alone is not indicative of reproductive output and oviposition does not guarantee successful offspring (Raebel et al. 2010). Stormwater ponds are engineered to retain and improve the quality of downstream waters; they are susceptible to urban pollution and tend to have poorer water quality than natural systems (Frost et al. 2015). If adult odonates are choosing stormwater ponds based on plant communities but the habitat is too poor for aquatic life stages (nymphs), these ponds may be ecological traps (Battin 2004; Harabiš and Dolný 2012). Odonata may be quite vulnerable to ecological traps as adults have been observed ovipositing in environments completely unsuitable for egg and nymphal development such as gravestones with reflective surfaces (Horváth et al. 2007). To determine if stormwater ponds are in fact acting as ecological traps for odonates it would be necessary to demonstrate that: (1) stormwater ponds are being selected over other available habitats of higher overall quality, and (2) adult odonates are reproducing in stormwater ponds but egg and/or nymph development is impaired, hindering odonate emergence rates (nymph to adult).

2.5.4 Value of stormwater ponds for urban biodiversity

Understanding the value of stormwater ponds as wildlife habitat in cities and the potential drivers of biodiversity is important as urbanization is expected to continue to increase globally (Hassall 2014). My results show that there is a wide variation in the diversity patterns between stormwater ponds themselves, with some ponds having very poor diversity and others providing comparable habitats to natural ponds, at least for adult odonate and wetland plant communities. A diversity of obligate wetland plants appears important in sustaining and enhancing adult Odonata abundance. Stormwater pond design should promote the establishment of high-quality plant communities, which would in turn increase wetland habitat for other species and ecological services in cities. Management recommendations could include ensuring the planting of native wetland species and providing an appropriate bank slope for the establishment of wetland plant communities. As cities continue to expand and multiply, stormwater ponds may prove to be important for wetland plant and odonate conservation, but only if properly designed and managed.

See Appendix A for Supplementary Material

Table 2.1

Relationships between Anisoptera (dragonfly) species composition and plant species composition (Fig. 2.5) and Zygoptera (damselfly) species composition and plant species composition (Fig. 2.6) describing the plant species that were significantly associated with Odonata species composition (p<0.05) as determined from transformation based-redundancy analyses (tb-rda) (with Hellinger transformation). Plant species (with tb-rda abbreviations) are described in terms of functional guilds, origin and wetland zonation (based on Oldham et al. 1995) with corresponding p-values. *ns means that the relationship was not significant (p>0.05).

Plant Species	Abbreviation	Functional Guild	Origin	Wetland Zonation	Anisoptera p-value	Zygoptera p-value
Lemna minor	LEMMINO	Free-floating	Native	Obligate wetland	0.030	ns
Sagittaria latifolia	SAGLATI	Robust Emergent	Native	Obligate wetland	ns	0.045
Eleocharis acicularis	ELEACIC	Sedge	Native	Obligate wetland	0.005	ns
Eleocharis palustris	ELEPALU	Sedge	Native	Obligate wetland	ns	0.010
Schoenoplectus tabernaemontani	SCHTABE	Sedge	Native	Obligate wetland	0.010	0.010
Galium palustre	GALPALU	Herbaceous	Native	Obligate wetland	0.015	ns
Lysimachia terrestris	LYSTERR	Herbaceous	Native	Obligate wetland	0.015	0.040
Alnus incana	ALNINCA	Tall shrub	Native	Obligate wetland	ns	0.010
Thelypteris palustris	THEPALU	Fern	Native	Facultative wetland	ns	0.010
Symphyotrichum lanceolatum	SYMLANC	Herbaceous	Native	Facultative wetland	0.020	0.040
Fraxinus americana	FRAAMER	Deciduous Tree	Native	Facultative upland	ns	0.025
Galium triflorum	GALTRIL	Herbaceous	Native	Facultative upland	ns	0.025
Melilotus albus	MELALBA	Herbaceous	Non-native	Facultative upland	0.005	0.030
Oenothera biennis	OENBIEN	Herbaceous	Native	Facultative upland	0.015	ns
Solidago canadensis	SOLCANA	Herbaceous	Native	Facultative upland	0.015	0.040
Vicia cracca	VICCRAC	Herbaceous	Non-native	Obligate upland	ns	0.005

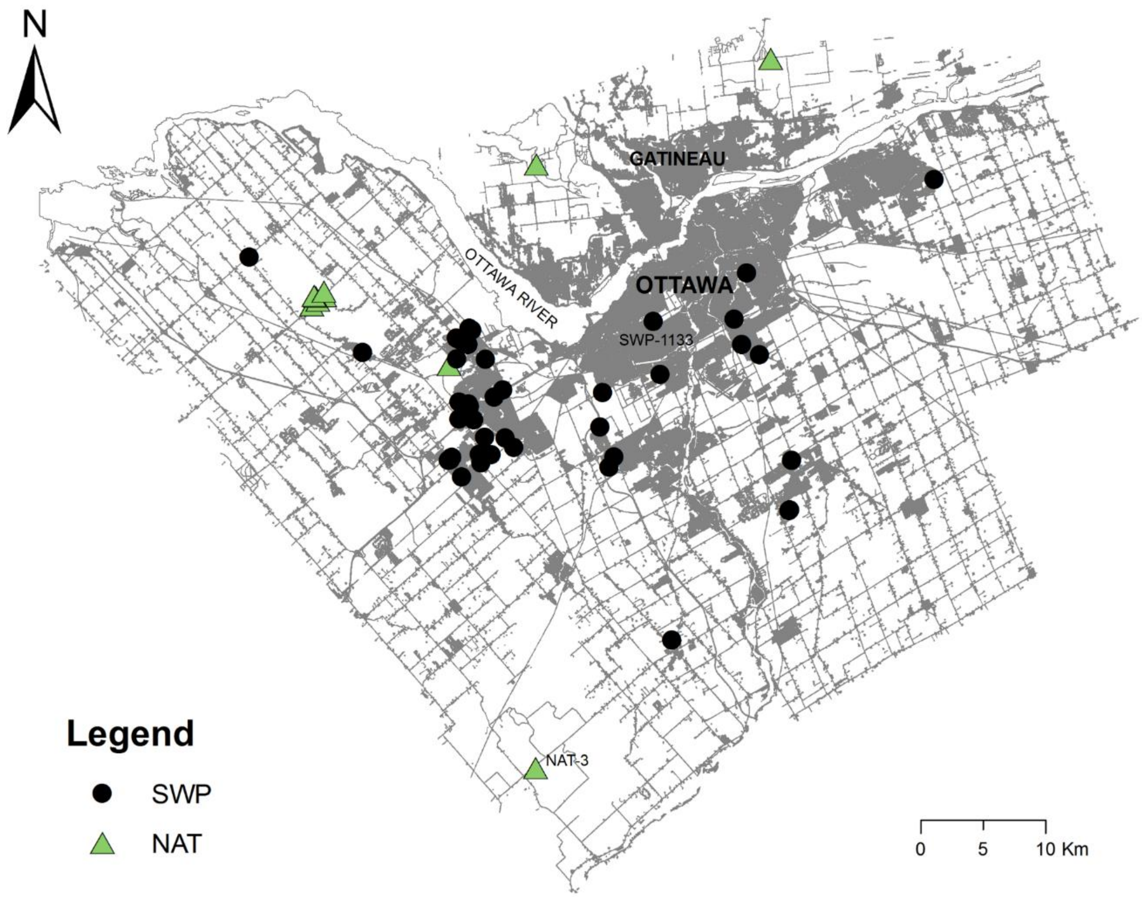

Figure 2.1 Urban stormwater ponds (SWP, n=41, black circles) and natural ponds (NAT, n=10, green triangles) sampled for Odonata and plant community structure in the National Capital Region of Canada (NCRC). Grey areas represent impervious surfaces. Data were obtained from the City of Ottawa, Ontario (2011) and Environmental Systems Research Institute (2009) World Imagery for areas of Gatineau, Québec. All data were updated to reflect 2015 conditions.

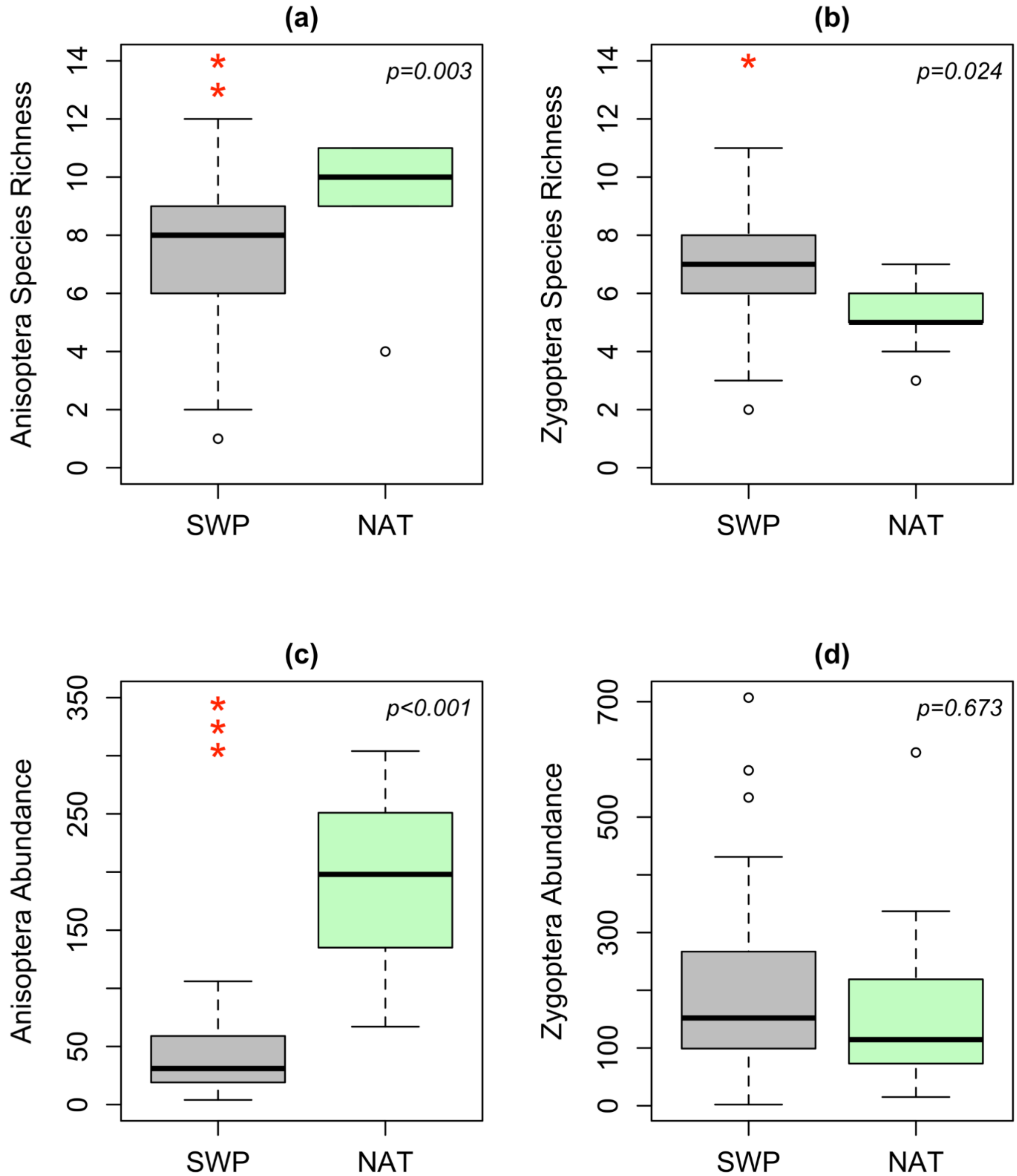

Figure 2.2 Comparisons of Odonata suborder community structure in urban stormwater ponds (SWP, n=41) versus natural ponds (NAT, n=10): (a) Anisoptera (dragonfly) species richness, (b) Zygoptera (damselfly) species richness, (c) Anisoptera abundance and (d) Zygoptera abundance.

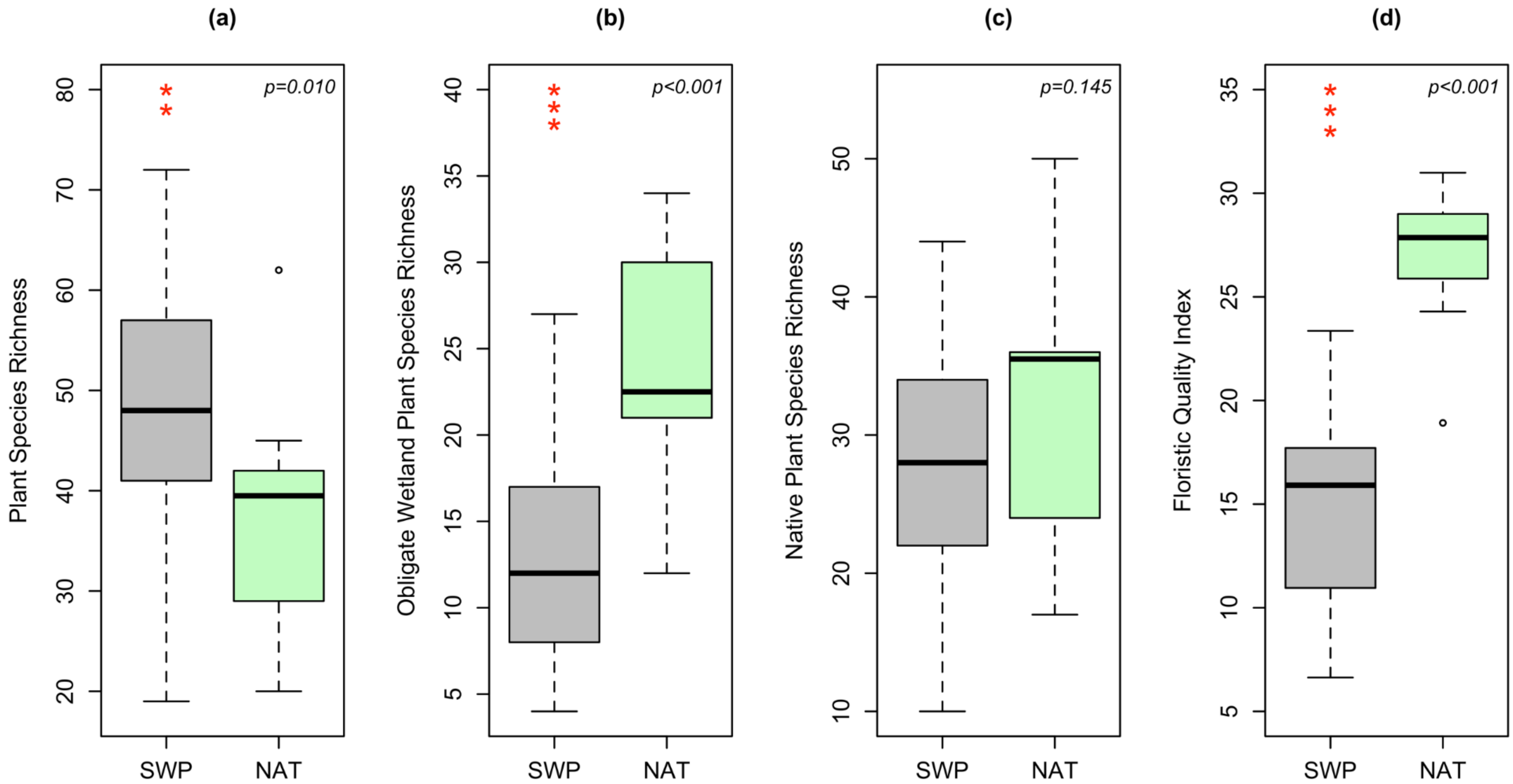

Figure 2.3 Comparisons of plant community metrics in urban stormwater ponds (SWP, n=41) versus natural ponds (NAT, n=10): (a) plant species richness, (b) obligate wetland plant species richness, (c) native plant species richness and (d) Floristic Quality Index.

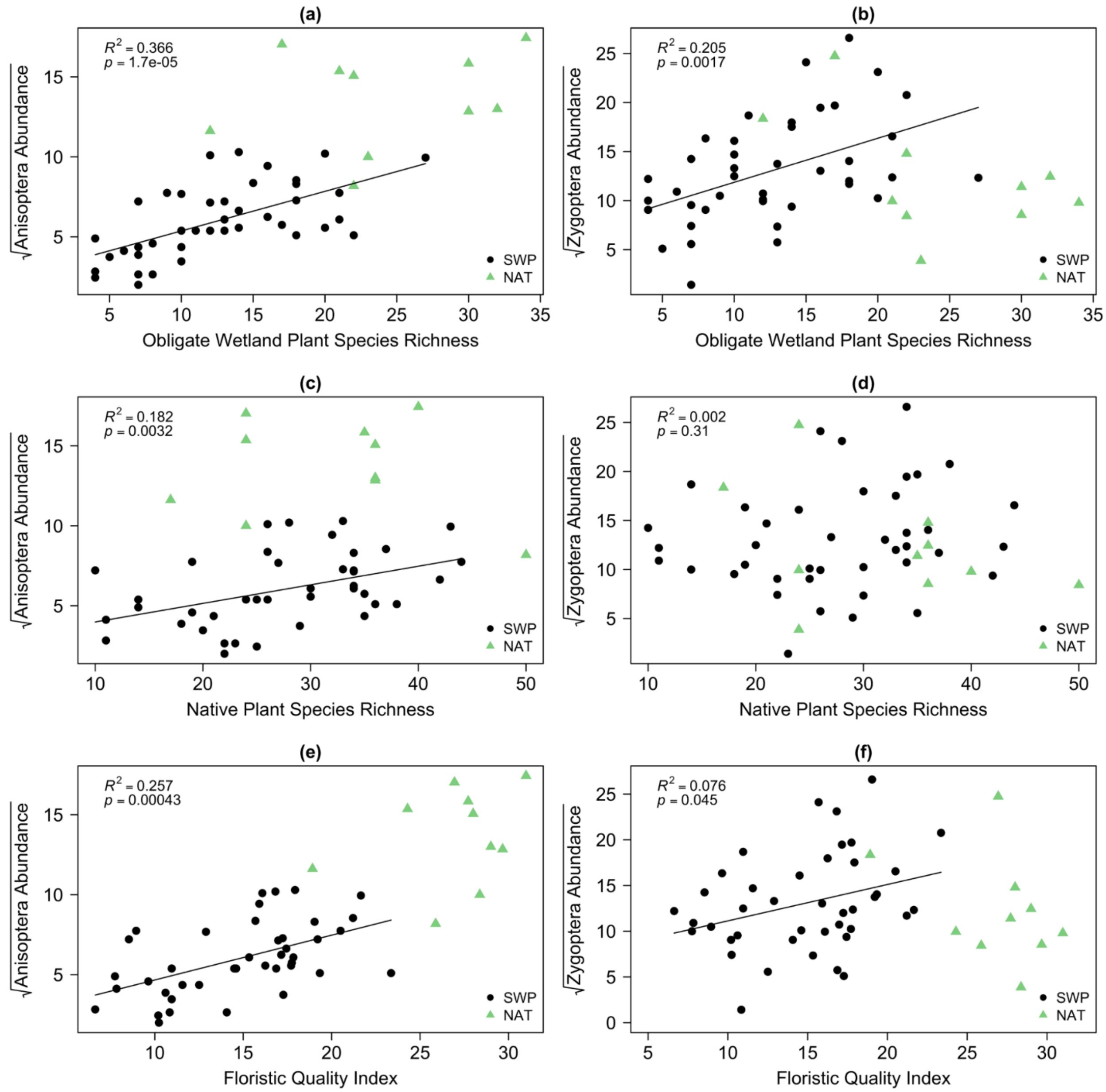

Figure 2.4 Relationships between Odonata suborder abundance and plant metrics in urban stormwater ponds. Regression models based on stormwater ponds exclusively (SWP, n=41, black circles) with natural ponds (NAT, n=10, green triangles) indicated for reference only: (a) Anisoptera (dragonfly) abundance in relation to obligate wetland plant species richness, (b) Zygoptera (damselfly) abundance in relation to obligate wetland plant species richness, (c) Anisoptera abundance in relation to native plant species richness, (d) Zygoptera abundance in relation to native plant species richness, (e) Anisoptera abundance in relation to the Floristic Quality Index, (f) Zygoptera abundance in relation to the Floristic Quality Index. Plant metrics were assigned based on Oldham et al. (1995).

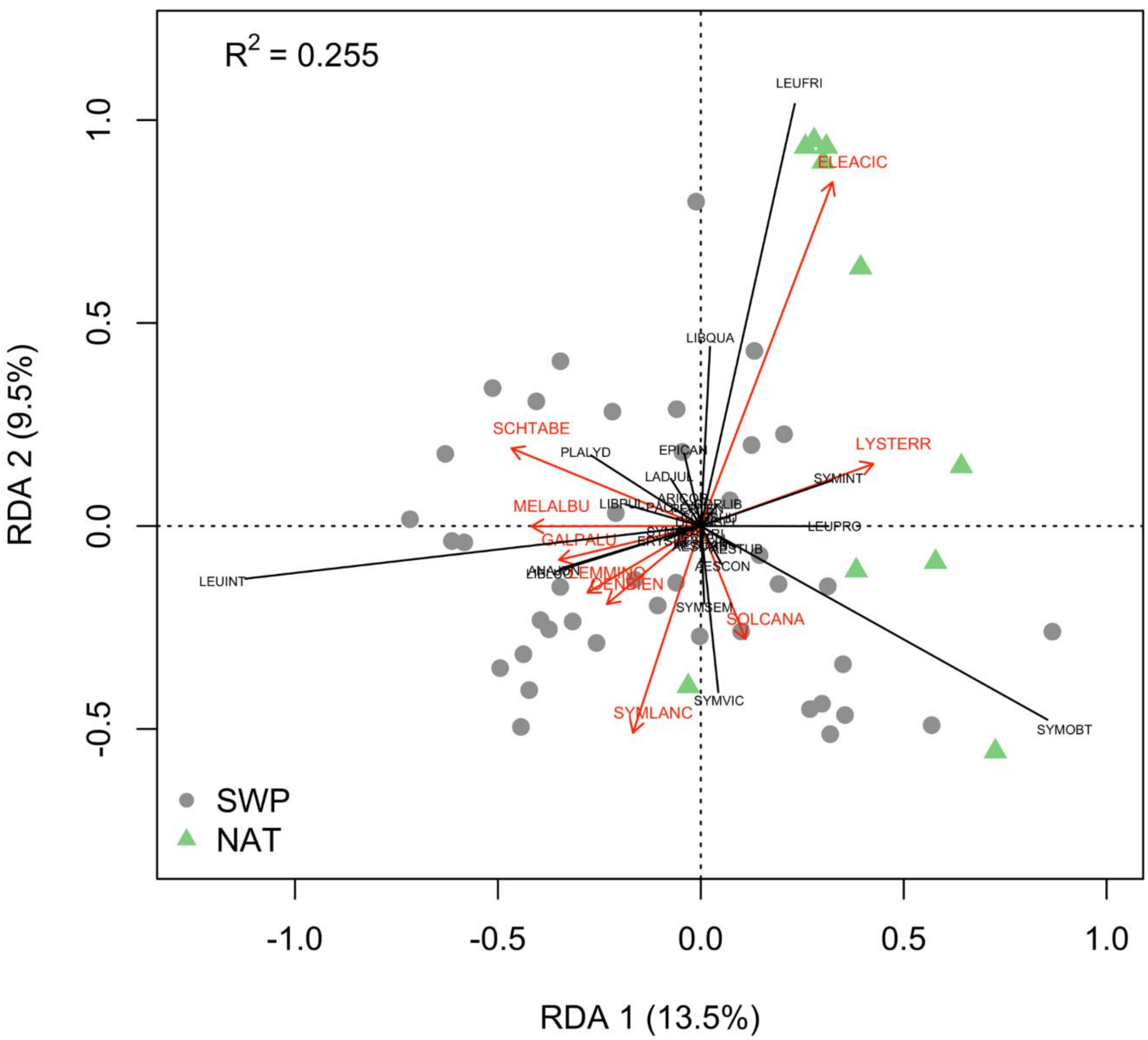

Figure 2.5 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between Anisoptera (dragonfly) species composition (represented by black vectors without arrows) and the average cover of significant ($p<0.05$) plant species (represented by red vectors with arrows) at urban stormwater ponds (SWP, n=41) in grey circles and natural ponds (NAT, n=10) in green triangles. Data plotted in scaling type 2, appropriate for interpreting distance among communities. Table 2.1 lists plant abbreviations and *p*-values.

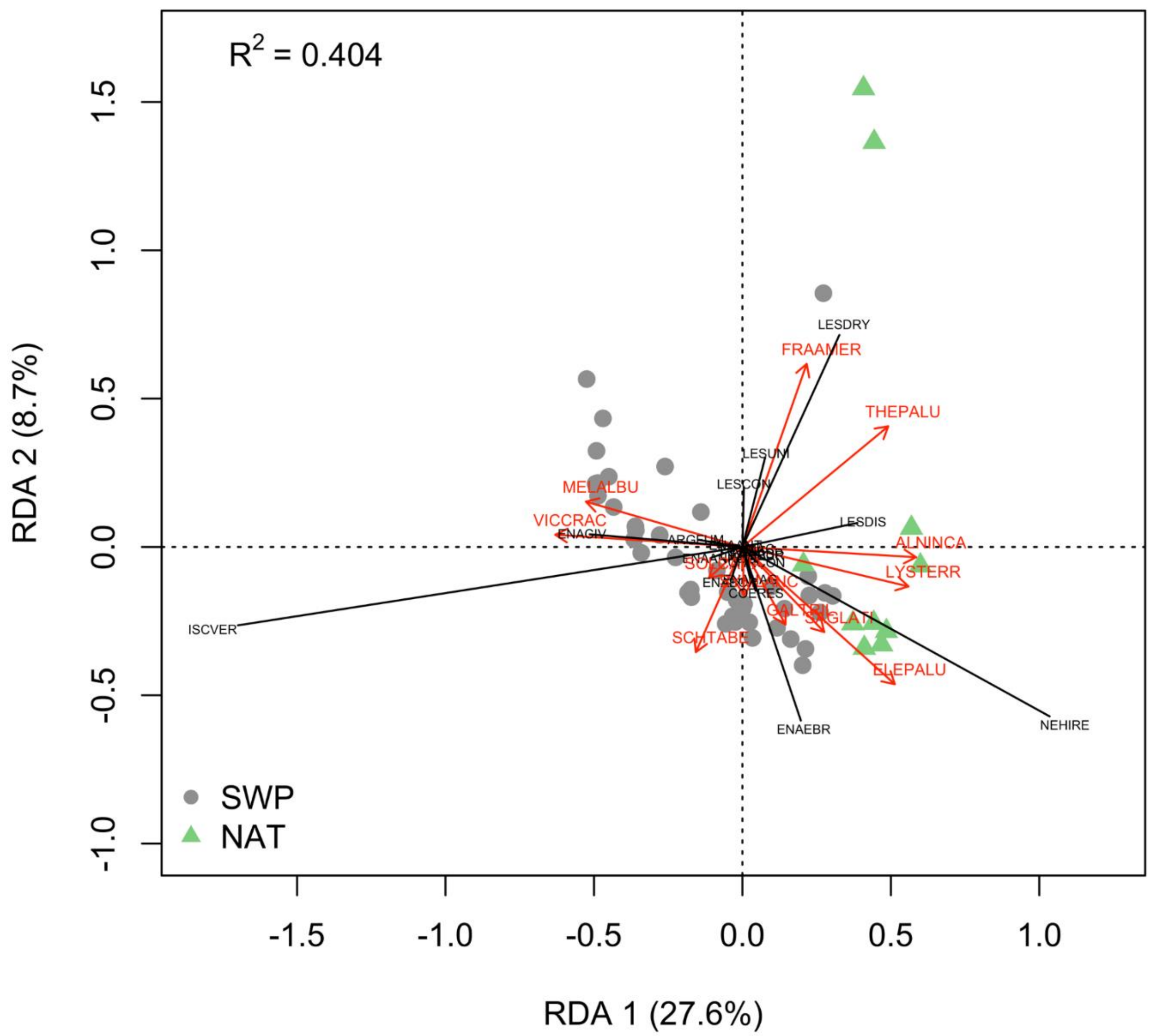

Figure 2.6 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between Zygoptera (damselfly) species composition (represented by black vectors without arrows) and the average cover of significant ($p<0.05$) plant species (represented by red vectors with arrows) at urban stormwater ponds (SWP, n=41) in grey circles and natural ponds (NAT, n=10) in green triangles. Data plotted in scaling type 2, appropriate for interpreting distance among communities. Table 2.1 lists plant abbreviations and *p*-values.

Chapter 3: Water quality effects on dragonfly and damselfly nymph communities: a comparison of urban and natural ponds

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3.1 Abstract

Cities are increasingly using constructed ponds to mitigate flooding and downstream water pollution from urban runoff. As a result, these stormwater ponds can have poor water quality, yet they can also attract wildlife. In this study, the effects of water quality on dragonflies and damselflies (Odonata) were determined in stormwater ponds (n=41) and natural reference ponds (n=10) of similar size across the National Capital Region of Canada. A total of 38 chemical/physical water quality variables along with Odonata nymph abundance and taxonomic composition were sampled at each pond. Chloride concentrations exceeded the guideline for the protection of aquatic life at over two-thirds of the stormwater ponds. Among all the metals tested, only Cu exceeded guidelines at many stormwater ponds. Both dragonfly and damselfly nymphs were on average less abundant in the stormwater ponds in comparison to the natural ponds. Ponds with high concentrations of chloride and metals typically had lower dragonfly abundance. Dragonfly community structure was significantly influenced by high chloride (or conductivity), which likely originates from winter road salting. In contrast, damselfly community structure in the stormwater ponds was similar to that found in natural ponds, with nutrients and metals explaining a small percent of variation in community structure. A water quality index developed to assess habitats for the protection of aquatic life did not significantly explain Odonata abundance or measures of diversity and may not be suitable in assessing pond habitat quality. To improve pond habitats within cities, efforts should be directed at reducing the amount of impervious surface and road salt usage within catchment basins.

Keywords stormwater ponds; Odonata; chloride; trace metals; nutrients; water quality index

3.2 Introduction

Urbanization has striking effects on the natural hydrological cycle (Paul and Meyer 2001). As land is developed and natural permeable surfaces are replaced with impermeable surfaces, the amount of precipitation that becomes surface water runoff can increase from 10% to 55% (Livingston and McCarron 1992). This becomes both an economic and environmental problem because higher runoff increases the frequency and severity of flooding events as well as the transport of contaminants into aquatic systems (Marsalek et al. 2005). To mitigate the impacts of urban runoff, many cities in North America and Europe have adopted constructed pond systems (Marsalek et al. 2005; Scher and Thiéry 2005), also known as stormwater management ponds. These ponds are engineered for two main functions: (1) to capture urban runoff and to release it at a slower rate into the environment to reduce the risk of major flooding and (2) to filter out sediments and contaminants found in urban runoff in order to improve the quality of water released back into natural systems (Schueler 1992; Marsalek et al. 2005).

Contamination of urban runoff originates principally from building surfaces, industrial activities, traffic and vehicular erosion, road maintenance, fertilizers and construction residues (Davis et al. 2001; Eriksson et al. 2007; Tixier et al. 2011). Contaminants can be removed from surface waters in stormwater ponds through physical sedimentation, natural filtration, plant adsorption and assimilation, microbial processes and decomposition as well as chemical immobilization (Schueler 1992; Weiss et al. 2006). Stormwater management ponds can effectively remove up to 75% of total suspended solids, 45% of total phosphorus and total nitrogen, 15% of lead and 75% of zinc along with other trace elements (Schueler 1992). Thus, water exiting stormwater ponds is typically of higher quality than the inflow water.

A concern that arises with stormwater ponds is that they are often colonized by wildlife, particularly since natural wetland systems are rare in urban areas (Bishop et al. 2000a,b). Studies have shown that urban ponds can harbour a diversity of plants and macroinvertebrates (Bishop et al. 2000a; Hassall and Anderson 2015). Hill et al. (2017) compared a number of urban ponds with non-urban ponds and found a wide variation in macroinvertebrate community structure among urban ponds, with the urban "pondscape" contributing similarly to gamma diversity as non-urban ponds. However, whether stormwater ponds are suitable habitat for urban wildlife remains unclear; alternatively, these ponds may pose toxicological risks because of high contaminant levels (Helfield and Diamond 1997; Bishop et al. 2000b), particularly from significant inputs of trace metals in stormwater runoff (Frost et al. 2015). In addition, winter road salting in temperate regions (usually in the form of NaCl) can lead to high concentrations of chloride and high conductivity which may challenge the osmotic tolerance of organisms (Hart et al. 1991; Oberts et al. 2000). Consequently, stormwater ponds could be acting as ecological traps, in other words, attractive habitats that cannot support the full lifecycle of an organism due to poor environmental quality. Stormwater ponds may be ecological traps for frogs, as they are used for breeding, yet tadpole development can be negatively affected from poor water quality (Sievers et al. 2018). On the other hand, there is some evidence that contaminant levels in stormwater ponds may be below toxicological thresholds; a few studies have reported no significant differences in metal bioaccumulation rates in macroinvertebrates from stormwater ponds, especially ponds embedded in residential areas, compared to those from natural reference systems (Karouna-Reiner and Sparling 2001; Søberg et al. 2016). Thus, there is a need to better understand how the chemistry of stormwater runoff impacts the biological communities inhabiting these engineered systems.

The present study was designed to determine the effect of water quality on a group of aquatic macroinvertebrates in stormwater ponds, Odonata, which are recognized bioindicators of wetland ecosystems (Briers and Biggs 2003; Foote and Rice Hornung 2005; Kutcher and Bried 2014). I focused on the aquatic life stage of Odonata including dragonflies (Anisoptera) and damselflies (Zygoptera). Odonates spend the majority of their lifecycle as nymphs in freshwaters and, as part of the benthic macroinvertebrate community, are important predators and prey of aquatic habitats (Corbet 1999; Butler and deMaynadier 2008). As adults (terrestrial/aerial life stage), both dragonflies and damselflies actively select habitats for reproduction based on the presence of water and macrophytes (Wildermuth 1998; Purse and Thompson 2009; Kutcher and Bried 2014). Adult dragonflies have a higher dispersal ability than damselflies and typically move approximately one km around habitats (Dolný et al. 2014), with the exception of several migratory species. Adult damselflies have smaller home ranges, typically moving 50 to 300 m between habitat patches (Purse et al. 2003). Odonata have a wide range of tolerance to water pollution, with some taxa more sensitive to pollutants than others (Corbet 1999; Rychła et al. 2011; Fletcher et al. 2017; Mangahas et al. 2019). I hypothesized that stormwater ponds would harbour different Odonata nymph communities than natural systems that do not receive urban runoff. I predicted lower Odonata species richness, abundance and diversity in stormwater ponds compared to natural ponds as a result of poor water quality. To test this hypothesis, Odonata nymph communities and water quality in stormwater ponds were compared to those of natural ponds, with a subset of the stormwater ponds studied over four years. I also tested whether Odonata nymph assemblages varied in relation to the water quality index (WQI) for the protection of aquatic life developed by the Canadian Council of Ministers of the Environment

(CCME). The CCME WQI is used around the world as a monitoring tool (e.g. Brazil see Ferreira et al. 2011; and Iraq see Ali 2010) but it has rarely been tested against biological data.

3.3 Methods

3.3.1 Study sites

A total of 41 stormwater ponds were selected within the City of Ottawa, Ontario, Canada (Fig. 3.1). The selection criteria included a similar size of open water (approximately one hectare) and a permanent body of water (depth ranging from 1-2 m). Ponds were also located at a minimum of 1 km away from any large river or lake habitat to avoid the possibility of riverine or lacustrine odonate species overlapping with pond species (Dolný et al. 2014). However, ponds could not be distanced from small streams as ponds typically discharge into natural downstream systems. The ponds were mainly within residential areas and small-scale commercial areas (31 residential ponds, 9 commercial ponds and one highway pond (catchment basin of pond draining major road)), as the City does not have much industry or manufacturing. The percent of impervious surfaces (paved areas and roofs of residential or commercial buildings) of the ponds' catchment basins ranged from 8.3 to 74.3% (Table S3.1), such that a wide variation in pond water quality was anticipated. As reference systems, ten natural ponds were selected in more rural locations across the National Capital Region of Canada (NCRC) which encompasses Ottawa, Ontario and Gatineau, Québec. The natural ponds followed the same selection criteria but were naturally occurring water bodies and surrounded mainly by wooded areas (Fig. 3.1). The natural ponds had larger catchment basins (average area of 2.81 km^2) than the stormwater ponds (average area 0.35 km^2) and had significantly less impervious surface within their catchment basins (<0.04%) (Table S3.1). The natural ponds thus received little to no urban runoff. Of these 51 ponds, 38 stormwater ponds and five natural ponds were sampled in 2015 and an additional three stormwater ponds and five natural ponds were sampled in 2016 to increase the range in stormwater pond age and to increase the sample size of natural ponds (Table S3.1).

The stormwater pond catchment and impervious surface data were obtained from the City of Ottawa (2014). Data on six stormwater ponds were not available. The catchments of the natural ponds were calculated using ArcMap (version 10.7) and were based on digital elevation models (DEM's) (Ontario Ministry of Natural Resources and Forestry 2014; Government of Quebec 2019). Any noise (peaks and sinks) in the DEM data were removed using the Fill tool from the *Spatial Analyst* toolbox. Flow direction and flow accumulation (using the default method D8) were calculated based on the DEM's with the *Spatial Analyst* toolbox. The point of highest accumulation from the pond was determined based on the flow accumulation map. The catchments were calculated using the Watershed tool from the *Spatial Analyst* toolbox based on the flow direction map and the point of highest accumulation from the pond. A polygon file of all impervious surface (paved roads and roofs) within the catchment was created based on satellite imagery (Environmental Systems Research Institute 2015). The area of impervious surface was divided by the total catchment area to obtain a percent imperviousness of the natural pond catchment.

3.3.2 Odonata nymph sampling

Odonata nymphs were sampled during the month of May, as Odonata will overwinter as nymphs or as eggs laid in the previous year in this region. The perimeter of each pond was divided into ten equal sections, one location from each section was randomly selected and a "Z-swipe” sampling was conducted. The “Z-swipe” collected nymphs dwelling near the surface of the water and/or attached to any floating vegetation, at mid-level in the water column collecting any nymphs attached to rooted macrophytes and at benthic-levels which scrapes sediments for benthic-dwelling nymphs using a framed net (net design and sampling method in Hutchinson and Ménard 2016). Dragonfly and damselfly nymphs were separated and preserved in 70% ethanol for subsequent identification to genus using Hutchinson and Ménard (2016) and dragonflies to species using Walker (1958) and Walker and Corbet (1975). Damselflies could not be identified at three ponds because of evaporation of ethanol from those samples, which made correct identifications difficult. Thus, counts were possible, but individuals could not be reliably identified to genus at these three ponds.

3.3.3 Water quality

Water samples were collected within each pond and close to the stormwater pond outlets (all stormwater ponds sampled had a single outlet); these conditions were considered more representative of the pond environment (as opposed to the inflow that reflects runoff chemistry). In the natural ponds, water samples were also collected near the outlets but if there was no evident outlet, water samples were collected opposing the inlet or at a random location around the pond if the inlet was also not evident. Two surface water samples were collected at each pond, one in late spring/early summer (June to mid-July) and the other in late summer/early fall (September). Nalgene bottles (1 L) were rinsed three times with pond water prior to sample. Water samples were then placed in a cooler and brought back to the lab for processing. Each water sample was mixed and subsampled for nutrient analyses, metal analyses and for planktonic chlorophyll *a* (as a proxy for pond productivity). Metals and metalloids measured included a full

ICP suite of elements (i.e. Ag, Al, As, B, Ba, Be, Bi, Cd, Cu, Cr, Co, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Th, Ti, V, W, Zn and Zr). Nutrients measured included various fractions of nitrogen and phosphorus (RP, TP, TKN, NO_3^- and TN). Cl^- was also measured to track road salt impact (Marsalek 2003). Water samples were analyzed at the Robert O. Pickard Center, a certified laboratory of the City of Ottawa, following standard protocols for the analysis of surface waters (Standard Methods 2004; Ontario Ministry of the Environment 2007; Ontario Ministry of the Environment 2017)

Planktonic chlorophyll *a* (an estimate of algal biomass) was measured from a pond water subsample (0.5 L), which was filtered through a glass microfibre filter (Whatman 934-AH™, pore size ~1.5 μm). The filter was then frozen at -80°C and stored until chlorophyll *a* could be extracted. Each filter was then transferred from the freezer to a 15 ml polystyrene tube covered with foil (eliminate light exposure) and immersed in 15 ml of 95% ethanol. Chlorophyll *a* concentrations were obtained following Jespersen and Christoffersen (1987).

In addition to water sampling, *in situ* measurements of temperature, pH, conductivity and dissolved oxygen were obtained at each pond with a HydroLab MiniSonde at the pond outlet every 0.5 m through the water column, as pond depth allowed, on three separate occasions that were concurrent with nymph and water sampling (spring, summer, fall).

3.3.4 Temporal variation

Five stormwater ponds (Fig. 3.1) were chosen to study the temporal variation in Odonata nymph communities and water quality over a four-year period (2015-2018) in order to capture different climatic conditions. These five ponds represented a range of catchment imperviousness (34-74%) and hence were expected to encompass a range of water chemistries. All four years had similar mean temperatures (Fig. S3.1); in contrast, precipitation varied between the years (Fig. S3.2).

3.3.5 Water Quality Index

The water quality index (WQI) developed by the Canadian Council of Ministers of the Environment (CCME) for the protection of aquatic life summarizes the multivariate nature of water quality data into a single value that, in theory, should reflect habitat quality for aquatic organisms. The guidelines for a series of pollutants (e.g. nickel, chloride, nitrate, etc.) are based on chronic and/or acute toxicity of each specific water quality variable for a series of species (representative of all components of the ecosystem from algae to fish) and by determining the lowest observed effect level to protect 95% of the species tested. Some guidelines are also dependent on other variables such as pH and hardness (Canadian Council of Ministers of the Environment 2007).

The CCME WQI was calculated with the WQI calculator Version 2.0 (Canadian Council of Ministers of the Environment 2017) created by incorporating three components; the Scope (F_1), the Frequency (F_2) and the Amplitude (F_3) (Equation 1). The Scope (F_1) is defined as the percentage of the variables that do not meet the guidelines. The Frequency (F_2) is the percentage of incidences where variables fail to meet guidelines throughout the entire sampling period (i.e. including numerous samples taken at one site). The Amplitude (F_3) is the amount of which these variables do not meet their specific guidelines.

Equation 1 $$CCME\ WQI = 100 - \left(\frac{\sqrt{{F_1}^2 + {F_2}^2 + {F_3}^2}}{1.732}\right)$$

The index value ranges between zero and 100 expressing the following categories; 0-44 for poor quality, 45-64 for marginal quality, 65-79 for fair quality, 80-94 for good quality and 95-100 for excellent quality (Canadian Council of Ministers of the Environment 2017). In the present study, 19 variables were used for each of the two water sampling events to compute the pond index: pH, DO, temperature, NO_3^-, TP, Al, As, Cl^-, Cu, Cd, Fe, Mo, Ni, Pb, Se, Ag, Th, U and Zn. Since hardness was not sampled in this study, the guidelines that were dependant on hardness were assigned the values suggested by the CCME if hardness was not available, these included Ni (25 μg/L), Cu (2 μg/L), Pb (1 μg/L) and Cd (0.09 μg/L).

3.3.6 Statistical analyses

All statistical analyses were conducted in R (version 3.4.2) and RStudio software (version 1.1.456 and 1.2.5019). Data residuals were tested for normality using the Shapiro-Wilks test from the *stats* package (R Core Team 2017) and if required, data were transformed accordingly (square-root or log transformation). Differences in Odonata abundance, dragonfly species richness and the inverse Simpson Index (based on genera) between stormwater ponds and natural ponds were reported with boxplots created using the *graphics* package (R Core Team 2017). The inverse Simpson Index is a suitable diversity index for community assemblages that have common taxa (Morris et al. 2014). Depending on the nature of the data, either parametric (t-tests) or non-parametric (Mann-Whitney U tests) pairwise comparisons were conducted on the Odonata nymph data as well as on the water quality data (averages) to statistically compare the differences between stormwater ponds and natural ponds using the *stats* package. If a water quality variable had a large number of measurements below detection, tests were not conducted as the power of the test would not be adequate.

All water quality data were analyzed with a principal component analysis (PCA) using the *factoextra* package (Kassambara and Mundt 2017). A PCA was used to summarize the variation in water quality between stormwater ponds themselves and in relation to the natural ponds as well as to determine what water quality variables were highly associated with one another. A PCA was used to examine the ranked water quality data (with averages assigned to tied values) since some elements (8 variables) were 80-100% below detection limit as recommended by Helsel (2012). I also conducted a PCA on the scaled water quality data and included variables that were measured mostly above detection limit, thus removing the rare elements that were under detection limits 80-100% of the time (i.e. Ag, Cd, Be, Bi, Sn, Th, W and Zr). All other variables were found at concentrations above their respective detection limits in over 50% of samples. When an individual measurement was below its detection limit, it was assigned a value equal to half the detection limit (United States Environmental Protection Agency 2006). The PCA based on the ranked water quality data was compared to the PCA based on the data that had available distributions (with rare elements removed); the rare elements did not contribute greatly to the PCA as the vectors were very small (hardly visible). Water quality variables that were correlated in the PCA based on the ranked data were similar to the correlations found with the scaled data (with no rare elements), thus both figures were included (Fig. S3.3, Fig. 3.3).

For the analysis of temporal trends, the nymph community data collected over the four-year sampling period were transformed, with the *vegan* package (Oksanen et al. 2019), using a Hellinger transformation and water quality data were scaled and centered. Each dataset (pond and year) was then analyzed with a space-time interaction model (Legendre et al. 2010), which calculated the effects of time, space and space-time interaction (F statistics, *p*-values were calculated through 9,999 permutations) using the *adespatial* package (Dray et al. 2017). The number of water quality variables at the five stormwater ponds studied through time was reduced by removing highly correlated variables. The data from the five stormwater ponds selected for the temporal analysis were displayed through space and through time with a PCA. Odonata nymph community structure (based on rank-abundance curves) was examined with an analysis of covariance (ANCOVA) in the *stats* package to examine the interaction between community structure and time.

The water quality variables that most frequently failed to meet federal guidelines (CCME) were identified in the stormwater ponds and the natural ponds separately, then plotted using *RcmdrMisc* package (Fox 2017). Based on the distribution of the residuals of each of the response variables (normal versus non-normal data), associations were tested between nymph diversity measures and the imperviousness of pond catchments as well as the WQI with Pearson's correlation and linear regression using the *stats* package. Dragonfly species richness did not meet the assumptions for normality, thus relationships to imperviousness and the WQI were tested using quasi-Poisson generalized linear models to account for moderate overdispersion (higher variance than expected based on Poisson distribution) using the *stats* package. Dragonfly and damselfly abundance did not meet the assumption of normality either, thus relationships to imperviousness and the WQI were tested using a negative binominal generalized linear model to account for high overdispersion (much higher variance than expected based on a Poisson distribution), using the *MASS* package (Venables and Ripley 2002). Relationships between Odonata nymph abundance of each genus and the WQI were tested using generalized linear models (quasi-Poisson, negative binominal or zero-inflated models) using either the *stats*, *MASS* or *pscl* package (Zeileis et al. 2008). The relationships between dragonfly species richness, abundance and damselfly abundance to single water quality variables (e.g., Cl^-) were tested using generalized-linear models as well (quasi-Poisson, *stats* package, and negative binominal, *MASS* package). Strontium was chosen to model relationships of metals/metalloids concentrations to the Odonata data as Sr was highly correlated with many metals (Co, Cr, B, Ba, As, Ni) but not highly correlated with chloride.

Given that a few of the ponds were close geographically (Fig. 3.1), I tested spatial autocorrelation using a redundancy analysis (RDA) of the community matrix restrained by space (X, Y coordinates), with the *stats* package, among the Odonata community structure. There was no significant spatial effect for dragonfly nymph communities (F=0.78, p=0.70) or damselfly nymph communities (F=0.85, p=0.50). A transformation-based redundancy analysis (tb-RDA) was then used to determine the relationship between the water quality data and the dragonfly (genus, species) as well as the damselfly (genus) nymph community structure (Legendre and Anderson 1999; Legendre and Gallagher 2001). The water quality data were standardized and centered, as the units of measure differed among variables. The nymph count data were transformed using a Hellinger transformation, which minimizes the weights of rare species present in the data set (Legendre and Gallagher 2001). The water quality variables that significantly ($p<0.05$) explained variation in nymph community structure were determined using stepwise forward regression through permutation (=9,999) and were retained to produce significant RDA models with adjusted R^2 values. All of these analyses were conducted using the *vegan* package. The RDA models and the RDA axes were tested for significance ($p<0.05$) using the *stats* package. The RDA models were then plotted in two-dimensional space using the *graphics* package.

3.4 Results

3.4.1 Odonata nymphs in stormwater ponds versus natural ponds

A total of 774 dragonfly nymphs were collected (~33% of the total Odonata abundance), representing 22 different species. Dragonfly abundance ranged from 0 to 84 nymphs per stormwater pond with an average of ~8 nymphs while natural ponds had significantly higher dragonfly nymph abundance with an average of ~43 dragonfly nymphs (3-132 nymphs per pond) (W=61, p<0.001, Fig. 3.2a). Stormwater ponds had an average of 2-3 dragonfly species (0-7 species per pond) while natural ponds had significantly more dragonfly species with an average of ~6 species (1-9 species per pond) (W=71.5, p=0.0015, Fig. 3.2c). In terms of taxonomic composition, the dragonflies from the genera *Leucorrhinia* and *Sympetrum* were not as common in the stormwater ponds (~25-40% of the ponds) compared to the natural ponds (80-90% of the ponds) (Table 3.1). In contrast, *Plathemis, Erythemis and Anax* were found exclusively in the stormwater ponds, whereas *Cordulia* and *Dorocordulia* were found exclusively in the natural ponds (Table 3.1).

The majority of Odonata nymphs were damselflies (67%), with 1,552 collected. As with the dragonflies, there was a lower damselfly abundance in the stormwater ponds compared to the natural ponds. Stormwater ponds had an average of ~26 damselfly nymphs (0-114 nymphs per pond), a significantly lower number than at the natural ponds (average of 48 nymphs with a range of 6 to 169 nymphs per pond) (W=113.5, p= 0.031, Fig. 3.2b). The damselflies from the genus *Lestes* were found less frequently at stormwater ponds (~10% of the ponds) than at natural ponds (~25% of the ponds) (Table 3.1). The genera *Enallagma, Nehalennia* and *Ischnura* were found most frequently at the stormwater ponds (Table 3.1).

Stormwater ponds and natural ponds supported the same six families of Odonata: Lestidae, Coenagrionidae, Aeshnidae, Gomphidae, Corduliidae and Libellulidae, but they differed in community structure (Table 3.1). Overall, the Odonata inverse Simpson's diversity was significantly lower in stormwater ponds compared to natural ponds (W=70, p=0.038, Fig. 3.2d). Total nymph abundance in the stormwater ponds was, on average, less than half the abundance found in the natural ponds (t=3.94, p<0.001, Fig. S3.4). However, there was a large variation in dragonfly species richness (Fig. 3.2c) and overall Odonata diversity (Fig. 3.2d) among the stormwater ponds themselves with several stormwater ponds comparable to the natural ponds.

3.4.2 Water quality in stormwater ponds versus natural ponds

Stormwater ponds and natural ponds differed in water quality, with a small percentage of stormwater ponds having similar water quality to natural ponds (Table 3.2, Fig. 3.3). Stormwater ponds had significantly higher conductivity (t=-10.6, p<0.001, Table 3.2), which was strongly correlated with chloride concentrations (R^2=0.71, p<0.001, Fig. S3.5). Chloride and conductivity were positively related with the percent of impervious surface on pond catchment basins (R^2=0.29, p<0.001, Fig. S3.6a and R^2=0.27, p<0.001 respectively). Stormwater ponds had significantly higher pH (W=348.5, p<0.001), but there was no significant difference in dissolved oxygen concentrations (t=1.91, p=0.062) or water temperature (t=0.19, p=0.85) in the stormwater ponds compared to the natural ponds (Table 3.2).

The stormwater ponds compared to the natural ponds had significantly higher concentrations of the following metals/metalloids: As (t=3.36, p=0.002), B (W=336, p<0.001), Ba (t=6.17, p<0.001), Cu (t=7.48, p<0.001), Mo (W=369.5, p<0.001), Ni (t=8.52, p<0.001), Sb

(W=300, p=0.019), Se (W=290.5, p=0.027), Sr (t=8.27, p<0.001), Ti (t=3.78, p<0.001), U (W=335.5, p=0.002) and V (t=4.16, p<0.001) (Table 3.2). Several metals were highly correlated with one another (e.g. Zn with V, Cu with Cr) (Fig. 3.3). Some metals were related to the imperviousness of pond catchments (e.g. Zn, R^2=0.12, p=0.022, Fig. S3.6b) while others were not (e.g. Ni, R^2=-0.03, p=0.80). In contrast, the stormwater ponds had significantly lower Fe than natural ponds (t=3.69, p<0.001) (Table 3.2). Furthermore, there was no significant difference between concentrations of Al (t=0.19, p=0.85), Cr (W=284, p=0.06), Mn (t=-1.11, p=0.27), Pb (W=160, p=0.28) and Zn (t=-1.33, p=0.19) in the stormwater ponds compared to natural ponds (Table 3.2). Ag, Be, Bi, Cd, Co, Th, W and Zr were almost always at very low concentrations, essentially below detection in all the ponds (Table 3.2).

With respect to measures of trophic state and productivity, there was no significant difference between total phosphorus (TP, t=1.59, p=0.12), reactive phosphorus (RP, t=0.05, p=0.96), total nitrogen (TN, W=149, p=0.19) and chlorophyll *a* (t=-1.11, p=0.27) in the stormwater ponds compared to the natural ponds (Table 3.2). However, nitrate (NO_3^-) was significantly higher in the stormwater ponds (W=330, p=0.002), while TKN was significantly higher in the natural ponds (W=56, p<0.001) (Table 3.2). Chlorophyll *a* was positively related to TP (R^2=0.33, p<0.001) and TN (R^2=0.27, p<0.001) across all ponds (stormwater and natural).

Although some stormwater ponds had significantly higher concentrations of certain elements, only a few exceeded guidelines for the protection of aquatic life (Canadian Council of Ministers of the Environment 2007). On average, Cl^- and Cu exceeded water quality guidelines only in the stormwater ponds, while TP concentrations exceeded guidelines in both the stormwater and natural ponds (Table 3.2). Fe exceeded the guidelines only in the natural ponds and was generally below guidelines in the stormwater ponds (Table 3.2).

3.4.3 Temporal variation in Odonata communities and water quality in stormwater ponds

Weather conditions varied across the four years of study, particularly with respect to precipitation. Average April temperatures varied by a few degrees with 2015 and 2017 being warmer than 2016 and 2018. The 2015-2018 average monthly temperatures for May through September were fairly similar (Fig. S3.1). Precipitation varied more than temperature across the four years, with 2017 receiving almost twice as much annual precipitation as 2015 and 2016 (Fig. S3.2).

Based on the space-time interaction models, there was a significant effect of time and space on both Odonata nymphs and water quality in the subset of stormwater ponds. Space was more influential on the Odonata nymph communities (R^2=0.23, F=1.62, p=0.018) and on water quality (R^2=0.29, F=2.81, p<0.001, Fig. 3.4), meaning that there was a larger difference in nymphs and water between ponds than within the same pond over several years. Nonetheless, time also had a significant influence on Odonata nymph communities (R^2=0.22, F=2.52, p=0.021) and on water quality (R^2=0.18, F=1.13, p=0.003, Fig. S3.7), pointing to some differences in nymphs and water in the same pond between different years.

When nymph community structure was examined for each pond through the four-year sampling period, the effect of year on community structure was only significant in one of the ponds (SWF-1204) (p=0.002, Fig. S3.8b). All other stormwater ponds had consistent Odonata nymph community structure through time (e.g. Fig. S3.8a), whereby the dominant genera at each pond were similar between years although their specific ranking sometimes varied. One pond, SWF-1227, had a single-genus (*Ischnura*) that was only present in two out of four years.

The commercial pond SWF-1204 had very high chloride (average of 1,038 mg/L, above the 120 mg/L guideline) and conductivity (average of 3,286 μS/cm), consistently across years (Fig. 3.4). Residential pond SWF-1209 was not particularly contaminated, yet water quality displayed some temporal variation with 2015-2016 different from 2017-2018, which could be linked to the higher precipitation in the latter years (Fig. 3.4). Residential pond SWF-1227 had similar water quality from 2015 through 2018 with consistently high uranium concentrations (average 8.4 μg/L, but below to 15 μg/L guideline) and high dissolved oxygen (average 11.4 mg/L) (Fig. 3.4). Commercial pond SWF-1347, which was connected to a road with moderate traffic, had elevated conductivity and aluminum concentrations and displayed little variation in water quality over the four years (Fig. 3.4). Similarly, there was little temporal variation in the water quality of residential pond SWF-1616; this pond had particularly high total phosphorus (Fig. 3.4).

3.4.4 Effects of water quality on Odonata nymph communities

Dragonfly nymph abundance was negatively associated with chloride (p=0.006, Fig. 3.5) and strontium concentrations (which correlated with several other metals) (p=0.002, Fig. S3.9) in all ponds (stormwater and natural). However, when natural ponds were removed from the model, the relationship between dragonfly nymph abundance and chloride was no longer significant (p=0.285). There were no significant relationships between the imperviousness of the pond catchment and total nymph abundance (p=0.22), dragonfly nymph species richness (p=0.88), dragonfly nymph abundance (p=0.59) or damselfly nymph abundance (p=0.13).

For the most part, dragonfly communities in stormwater ponds were distinct from the communities in natural ponds (Fig. 3.6). However, there were ~7 stormwater ponds with similar dragonfly communities and water quality to that of natural ponds (Fig. 3.6). Dragonfly communities were significantly associated with six water quality variables: conductivity (p=0.006), TKN (p=0.01), TP (p=0.03), zinc (p=0.002), arsenic (p=0.006) and barium (p=0.002) which together explained 24.9% of the variation in genera composition (Fig. 3.6). The genera, *Leucorrhinia* and *Sympetrum* were characteristic of natural ponds as well as the stormwater ponds with low conductivity. In contrast, *Aeshna* and *Anax* were more characteristic of stormwater ponds with high metals/metalloids (Zn and As) and high TP (Fig. 3.6). The genera *Cordulia, Dorocordulia* and *Ladona* were not found in ponds with high conductivity (Fig. 3.6). At the species-level, dragonflies were related to seven water quality variables: pH (p=0.040), chlorophyll *a* (p=0.040), conductivity (p=0.045), TP (p=0.025), zinc (p=0.005), arsenic (p=0.005) and barium (p=0.005), explaining 19.5% of the variation in dragonfly nymph species composition (Fig. S3.10). Three dragonfly species from the family Aeshnidae were characteristic of ponds with higher contaminant loads. The shadow darner (*Aeshna umbrosa)* was strongly associated to ponds with high conductivity, the Canada darner (*Aeshna canadensis*) was found at ponds with high zinc concentrations and the green darner (*Anax junius*) was typical of ponds with high nutrient concentrations (i.e. TP) (Fig. S3.10).

In contrast to dragonflies, damselfly communities in stormwater ponds were similar to the communities found in natural ponds (Fig. 3.7). Overall, TN (p= 0.036), chlorophyll *a* (p=0.004) and titanium (p=0.002) explained 18.8% of the variation in damselfly genera composition among the ponds. There was a notable arch effect (Van Der Maarel 1980) even after Hellinger transformation of the damselfly community data. The genus *Ischnura* tended to be more characteristic of stormwater ponds, but this was not explained by any specific water quality variable (Fig. 3.7). The genera *Lestes* and *Nehalennia* were positively associated to ponds with high TN and chlorophyll *a* concentrations and the genus *Enallagma* was negatively associated to ponds with high Ti concentrations (Fig. 3.7).

3.4.5 The CCME Water Quality Index (WQI)

On average, the CCME WQI did not differ significantly between stormwater ponds and natural ponds (t=0.93, p=0.38, Table 3.2). The WQI for stormwater ponds ranged from "fair" to "good" quality and were on average representative of "good" quality. The natural ponds ranged from "marginal" to "good" water quality. On average, most natural ponds were of "fair" quality, therefore considered of lesser quality than the stormwater ponds.

The most frequent water quality variables that failed to meet the guidelines in the calculation of the WQI were different between stormwater ponds and natural ponds (Fig. S3.11). In stormwater ponds, the most common variable was copper which exceeded guidelines at approximately 77% of the ponds (Fig. S3.11a). However, it is important to note that I did not have hardness measures for the pond water in this study, thus the CCME suggested the use of the most conservative guideline of 2 μg/L, as opposed the 4 μg/L guideline in hard waters (Canadian Council of Ministers of the Environment 2007). The second most frequent variable was chloride, which exceeded the guideline in over 68% of the stormwater ponds (Fig. S3.11a). The next most frequent variables were dissolved oxygen and total phosphorus, which did not meet the guidelines in ~60% of the stormwater ponds (Fig. S3.11a). In contrast, in natural ponds, the most frequent variable was total phosphorus which did not meet guidelines in over 83% of the ponds, followed by iron (50% of ponds) and dissolved oxygen (50% of the ponds) (Fig. S3.11b).

The WQI was not significantly associated with any metric of Odonata nymph biodiversity whether total nymph abundance (p=0.30), dragonfly nymph abundance (p=0.44), dragonfly species richness (*p*=0.98) or damselfly nymph abundance (*p*=0.40). The WQI was also not significantly related to Odonata community structure including no significant relationships with all the genera present: *Aeshna* (*p*=0.27), *Anax* (*p*=0.48), *Arigomphus* (*p*=0.69), *Epitheca* (*p*=0.91), *Cordulia* (*p*=0.31), *Dorocordulia* (*p*=0.21), *Ladona* (*p*=0.72), *Plathemis* (*p*=0.86), *Libellula* (*p*=0.36), *Sympetrum* (*p*=0.59), *Leucorrhinia* (*p*=0.88), *Erythemis* (*p*=0.94), *Enallagma* (*p*=0.17), *Lestes* (*p*=0.39), *Ischnura* (*p*=0.31) or *Nehalennia* (*p*=0.70).

3.5 Discussion

I predicted that water quality in the stormwater ponds would negatively affect Odonata nymph communities. Odonata abundance and diversity was indeed lower in stormwater ponds compared to natural ponds; however, water quality explained less than 25% of the overall variation in Odonata community structure, despite the wide range in water chemistry encountered.

3.5.1 Water quality in stormwater ponds

Water quality varied significantly across the stormwater ponds with several variables spanning about two orders of magnitude in concentration including several metals (e.g. Al, Ti, B), chloride, planktonic chlorophyll *a* and nutrients (e.g. NO_3^-, TP) (Table 3.2). This variation was partially the result of the large range in percent imperviousness of the stormwater pond catchments (Table S3.1, Fig. S3.6), also likely due to the inclusion of ponds with commercial activities in addition to residential homes in their catchments. Overall, there was more variation spatially across the ponds than within ponds over time: water quality was relatively constant in the stormwater ponds studied over four years, with some slight differences between years of high and low precipitation (Fig. 3.4). In a study of 18 residential ponds in North America, Casey et al. (2006) found that metal concentrations remained fairly constant over a 10-year period.

Despite the wide range in concentrations, most water quality variables were below toxicological guidelines for the protection of aquatic life (Table 3.2). Dissolved oxygen varied widely in the stormwater ponds, with a few ponds having oxygen concentrations below guidelines, but many having concentrations above guidelines (Table 3.2). Copper, chloride and total phosphorus were the variables that exceeded guidelines in the majority of stormwater ponds (Table 3.2). Copper, which exceeded guidelines in nearly 80% of the ponds, is typically elevated in urban areas and can originate from siding and/or roofs as well as vehicle brakes (Davis et al., 2001). Other metals/metalloids, such as nickel, cadmium and arsenic, which are often found in urban runoff (Bishop et al. 2000a; Vincent and Kirkwood 2014; Frost et al. 2015), did not exceed guidelines in any of the stormwater ponds (Fig. S3.11a).

Chloride was a major pollutant in the majority of the stormwater ponds (Fig. S3.11a) and was persistent in stormwater ponds through time (Fig. 3.4). In contrast, all the natural ponds were below the chloride guideline (Fig. S3.11b). High chloride concentrations are undoubtedly the result of winter road salt applications as the province of Ontario applies hundreds of thousands of tonnes of road salts annually (Marsalek 2003). Chloride and conductivity were highly correlated: with road salt applications, sodium and chloride become significant ions contributing to conductivity. Elevated conductivity is a well-known signal of urbanization in streams (Paul and Meyer 2001) as well as ponds (Wren et al. 1997). Chloride can have direct sublethal and lethal effects on biota; the concentrations in the stormwater ponds ranged from 10.1 mg/L, which is below the toxicological risks to wildlife (Canadian Council of Ministers of the Environment 2011) to as high as 1,048.5 mg/L, which can affect survival, growth and reproduction in many organisms from invertebrates (e.g. Elphick et al. 2011; Cañedo-Argüelles et al. 2013) to fish (e.g. Hintz and Relyea 2017). Chloride can also affect the mobility of metals (Bauske and Goetz 2000; Oberts et al. 2000; Mayer et al. 2008).

Surprisingly, and in contrast to my predictions, the water quality index was, on average, better in stormwater ponds than natural ponds (Table 3.2), despite the tendency for higher metal and chloride concentrations in the former. The low oxygen levels recorded in the natural ponds along with high phosphorus concentrations contributed to the lower average WQI (Fig. S3.11b). Natural wetland environments such as ponds are typically stagnant, highly productive systems that exhibit large diurnal and seasonal swings in oxygen (Keddy 2010). The number of samples collected in this study as well as the number recommended for the CCME WQI was likely too low to adequately assess the overall oxygen regime of these ponds. While water quality indices are frequently used to rank water bodies (e.g. Ali 2010; Ferreira et al. 2011), they have rarely been directly compared to biological indicators of habitat quality. Kilgour et al. (2013) examined the relationship between the CCME WQI and benthic macroinvertebrate diversity metrics and found a positive relationship with sensitive stream taxa, the percent of Ephemeroptera, Plecoptera, Trichoptera (%EPT), but their study was conducted in lotic (flowing) waters. In the present study, I found no significant relationships between the CCME WQI and any measure of Odonata biodiversity and surprisingly higher index values in the stormwater ponds compared to the natural ponds. I conclude that the CCME WQI in its current form is not useful in characterizing the habitat quality of ponds and wetland systems, which support organisms that are adapted to the conditions associated with stagnant waters.

Overall, there were few instances where elements failed to meet the guidelines for the protection of aquatic life in stormwater ponds; this is likely because most of the ponds were located in residential developments. Stormwater ponds in more industrial areas would be expected to have poorer water quality, particularly with respect to metals (Egemose et al. 2015). Furthermore, pond water was only sampled twice throughout the field season and at least a few days after any rainfall. Thus, events that would have brought potentially high pollutant loads into the pond would not have been captured, resulting in an underestimation of contaminant exposure. Another limitation is that I did not sample for organic pollutants, such as PAH's and other compounds associated with fossil fuel usage. I also sampled total metal concentration (particulate and dissolved forms together) and analysis of the dissolved fractions of metals may be more indicative of toxicological effects on aquatic life (Calmano et al. 1993). Even though metal concentrations were often low in the stormwater ponds, this would not exclude the potential for bioaccumulation. A small amount of contaminant bioaccumulation in benthic macroinvertebrates could be amplified through food webs to higher trophic levels and have toxicological effects (Sparling et al. 2004).

3.5.2 The effect of water quality on Odonata nymphs

On average, the stormwater ponds supported lower dragonfly species richness and abundance, lower damselfly abundance and lower total Odonata diversity when compared to the natural ponds (Fig. 3.2). However, the Odonata genera present at stormwater ponds were mostly the same ones present at natural ponds and contained three additional species that were not recorded at the natural ponds: *Anax junius* (family: Aeshnidae), *Plathemis lydia* and *Erythemis simplicicollis* (family: Libellulidae). These three species in particular are considered generalist species and tolerant of high conductivity and pH (Hilsenhoff 1987; Osborn 2005). Studies of macroinvertebrate community structure have noted that a higher proportion of generalist species is typical of urban ponds (Le Viol et al. 2009; Goertzen and Suhling 2013).

I predicted that differences in Odonata nymph diversity at stormwater ponds and natural ponds would be strongly associated with the water quality, however water quality explained less than 25% of the variation in dragonfly community structure (Fig. 3.6) and even less of the damselfly community structure (19%) (Fig. 3.7). Three to seven water quality variables out of 38 potential variables were responsible for this water quality effect. Conductivity (which was highly correlated with chloride) explained a high proportion of dragonfly community structure and also had a negative relationship on dragonfly abundance. The dragonfly genera *Aeshna* (especially the species *Aeshna umbrosa*) and *Anax* were more common in highly saline ponds while the genera *Sympetrum, Leucorrhinia*, *Cordulia*, *Dorocordulia* and *Ladona* were rarely encountered (Fig. 3.6, Fig. S3.10). Salinity tolerances vary across taxa (Castillo et al., 2018) and Odonata species distribution differs between habitats varying in salinity (Cannings and Cannings, 1987). Based on 18 North American lakes, Cannings and Cannings (1987) found that two *Sympetrum* species (*S. obstrum*, *S. costiferum)* were also excluded from inland waters with high conductivity. Under laboratory conditions, high salinity can affect nymph instar development rate and emergence rate (Kefford et al. 2006) as well as immune responses in dragonfly nymphs (Mangahas et al., 2019) but these effects were seen at a much higher salinity than those encountered in the present study.

In terms of specific water chemistry variables that may be affecting Odonata nymphs, arsenic, barium and zinc were statistically associated with dragonfly communities while titanium was significantly associated with damselfly communities (Fig. 3.6, 3.7). These variables were at higher concentrations in the stormwater ponds (but did not exceed guidelines) and may simply reflect urban runoff in general as several metals were correlated in the dataset (Fig. 3.3).

Dragonfly and damselfly community structure were also significantly associated with nutrient concentrations (TP, TN and TKN). There was no difference in TP and TN concentrations between stormwater ponds and natural ponds, although higher TKN tended to occur at the natural ponds. These results are consistent with an overall effect of system productivity on community structure. In particular, the green darner (*Anax junius*), a migratory species, was typical of ponds with high TP concentrations (Fig. S3.10) and *Lestes* damselflies were found in ponds with higher TN and chlorophyll *a* concentrations (Fig. 3.7).

Benthic macroinvertebrates, that include Odonata nymphs, are commonly used as bioindicators of water quality (Rosenberg and Resh 1993). However, this study suggests that Odonata nymphs, and in particular damselfly nymphs, are less responsive to water quality than to other factors in their environment. In a recent study of Australian streams, dragonfly nymphs were also not reliable indicators of water quality changes resulting from urbanization (Tippler et al. 2018). Odonata nymphs may be more affected by other habitat characteristics such as the littoral plant community structure and predator-prey interactions. Stormwater ponds typically have very different plant communities than natural systems as the littoral is often “hardscaped” (with rock or gabion walls), with overall less vegetation and a higher proportion of weedy and non-native species (Oertli and Parris 2019; Perron and Pick 2020). Overall, ponds with higher species richness of wetland plants can attract higher abundances of adult dragonflies and damselflies (Perron and Pick 2020). The presence and diversity of plant communities can affect habitat selection and egg hatching success of particular Odonata species (Ward and Mill 2005; Purse and Thompson 2009). As nymphs, some species of Odonata rely on plants to provide resources and refuges from predation (Baker and Dixon 1986; Thompson 1987; Wellborn and Robinson 1987; Remsburg and Turner 2009). Further studies are needed that directly test the role of plants and the type of plants that may influence abundance and diversity of Odonata nymphs. Also, the presence of nymphs is not an indication of successful completion of the Odonata lifecycle. Further studies examining Odonata emergence and exuviae collections (last instar exoskeleton) are needed (as in Raebel et al. 2010) to rule out the potential for stormwater ponds to be acting as ecological traps for Odonata.

3.6 Conclusions

Odonata nymphs, especially dragonfly nymphs, were less abundant in stormwater ponds than natural ponds. Water quality variables explained about a quarter of the variation in nymph community structure and few variables exceeded guidelines for the protection of aquatic life and were of potential concern. However, a major exception was chloride, with concentrations frequently exceeding guidelines for the protection of aquatic life and can be associated with low dragonfly nymph abundance. These results provide further evidence that road salts are one of the most pervasive pollutants in temperate and northern inland waters (Marsalek 2003). Alternatives to rock salt (NaCl) for winter road maintenance (e.g. organic de-icers, Fu et al. 2012) and reducing the amount of impervious surface in stormwater pond catchments (e.g. narrower roads, green road shoulders, etc.) may improve water quality. If properly designed and managed, stormwater ponds and their catchments can support diverse Odonata communities, analogous to those of natural ponds. As urbanization accelerates, stormwater ponds could therefore provide some of the ecological services associated with biodiversity in addition to flood control.

See Appendix B for Supplementary Material

Table 3.1

The frequency of occurrence of specific Odonata nymph genera at the stormwater ponds (SWP) and the natural ponds (NAT). Sample size for dragonfly genera consists of 41 stormwater ponds and 10 natural ponds and sample size for damselfly genera (marked with *) consists of 40 stormwater ponds and 8 natural ponds.

Genus	**SWP**	**NAT**
*Enallagma**	75%	88%
*Nehalennia**	48%	25%
Libellula	41%	20%
*Ischnura**	40%	38%
Leucorrhinia	39%	80%
Aeshna	29%	70%
Epitheca	27%	20%
Sympetrum	24%	90%
Plathemis	17%	0%
Erythemis	12%	0%
Anax	10%	0%
Arigomphus	10%	20%
*Lestes**	10%	25%
Ladona	2%	60%
Cordulia	0%	70%
Dorocordulia	0%	40%

Table 3.2

Average physical and chemical variables in stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10) from two sampling periods (spring and summer) with range of variables in brackets. Detection limits (DL) were indicated for all elements and the CCME guidelines (long-term exposure) for the protection of aquatic life (Canadian Council of Ministers of the Environment 2007) were provided when available (NGA indicated when no guideline available). If the average concentration of a variable did not meet the CCME guidelines for the protection of aquatic life, the variable was bolded. Pairwise comparisons (unpaired t-tests, Mann-Whitney U tests) tested differences between variables in SWP and NAT with significance levels (p *=<0.05, **= <0.01, *** =<0.001, ns=>0.05), when sufficient data were available (- most concentrations below detection limit so no statistical test could be conducted).

Pond Water Variables	**SWP Mean (Range)**	**NAT Mean (Range)**	**Pairwise Comparisons**	**DL**	**Guideline**
Temperature (^{o}C)	20.45 (15.38-24.23)	20.30 (13.81-23.73)	ns	0.01	Variable
DO (mg/L)	9.97 (4.21-15.61)	**8.25** (2.56-11.11)	ns	0.01	9.5
pH	7.74 (7.11-9.24)	6.83 (5.77-7.74)	***	0.01	6.5-9
Conductivity (μS/cm)	1529.6 (465.7-5761)	184.3 (43.5-606.9)	***	1	NGA
Chlorophyll *a* (μg/L)	9.6 (0.5-63)	17.9 (0.7-62.4)	ns	0.05	NGA
Al (μg/L)	65.90 (6.35-441.85)	55.67 (3.40-163.30)	ns	0.5	5 (pH< 5.5), 100 (pH ≥ 6.5)
Ag (μg/L)	<DL (<DL)	<DL (<DL)	--	0.1	0.25
As (μg/L)	0.40 (<DL-1.45)	0.22 (<DL-0.55)	**	0.2	5
B (μg/L)	44.28 (9.25-146.40)	12.51 (5.40-33.05)	***	0.5	1,500
Ba (μg/L)	70.60 (25.65-151.80)	30.08 (11.95-51.70)	***	0.1	NGA
Be (μg/L)	<DL (<DL)	<DL (<DL)	--	0.1	NGA
Bi (μg/L)	<DL (<DL)	<DL (<DL)	--	0.1	NGA
Cd (μg/L)	<DL (<DL)	<DL (<DL)	--	0.1	0.09 (related to hardness)
Cl^- (mg/L)	**265.8** (10.1-1048.5)	11.97 (0.1-43.95)	***	0.1	120
Co (μg/L)	<DL (<DL-0.55)	0.12 (<DL-0.48)	--	0.1	NGA
Cr (μg/L)	0.56 (0.13-1.60)	0.33 (<DL-0.6)	ns	0.1	NGA
Cu (μg/L)	**3.58** (0.68-8.6)	1.05 (<DL-2.20)	***	0.5	2 (related to hardness)
Fe (μg/L)	131.57 (22.15-558.60)	**506.81** (89.95-2635.50)	***	0.5	300
Mn (μg/L)	40.29 (8.75-192.85)	62.76 (13.00-219.20)	ns	0.1	NGA
Mo (μg/L)	1.86 (<DL-8.45)	<DL (<DL-1.25)	***	0.5	73
Ni (μg/L)	2.44 (0.63-5.00)	0.59 (<DL-1.50)	***	0.1	25 (related to hardness)
Pb (μg/L)	0.11 (<DL-0.55)	0.26 (<DL-1.10)	ns	0.1	1 (related to hardness)
Sb (μg/L)	0.22 (<DL-0.50)	<DL (<DL-0.20)	*	0.2	NGA
Se (μg/L)	0.27 (<DL-2.20)	<DL (<DL-0.35)	*	0.2	1
Sr (μg/L)	1736.7 (102.00-8535.00)	83.84 (23.70-249.00)	***	0.1	NGA
Th (μg/L)	<DL (<DL-0.23)	<DL (<DL)	--	0.1	0.8
Ti (μg/L)	4.89 (0.40-33.95)	1.59 (<DL-7.95)	***	0.2	NGA
U (μg/L)	1.84 (0.13-9.95)	0.54 (<DL-2.50)	**	0.1	15
V (μg/L)	0.86 (0.15-2.80)	0.38 (0.10-1.05)	***	0.1	NGA
W (μg/L)	<DL (<DL-0.7)	<DL (<DL)	--	0.2	NGA
Zn (μg/L)	2.98 (<DL-14.20)	2.34 (0.58-8.10)	ns	0.5	7.0 (depends on hardness, pH and DOC)
Zr (μg/L)	<DL (<DL-0.13)	<DL (<DL-0.28)	--	0.1	NGA
TN (mg/L)	1.01 (0.37-3.87)	1.38 (0.71-4.49)	ns	0.1	NGA
NO_3^- (mg/L)	0.38 (<DL-3.28)	<DL (<DL)	**	0.1	13
TKN (mg/L)	0.65 (0.37-1.68)	1.37 (0.70-4.49)	***	0.02	NGA
RP (mg/L)	0.0091 (<DL-0.0540)	0.0078 (0.0030-0.0180)	ns	0.002	NGA
TP (mg/L)	**0.0369** (0.009-0.1870)	**0.0496** (0.0185-0.1125)	ns	0.005	0.01-0.02 (seasonal)
WQI	81.8 (65.8-91.9)	77.1 (51-92.8)	ns	0	NGA

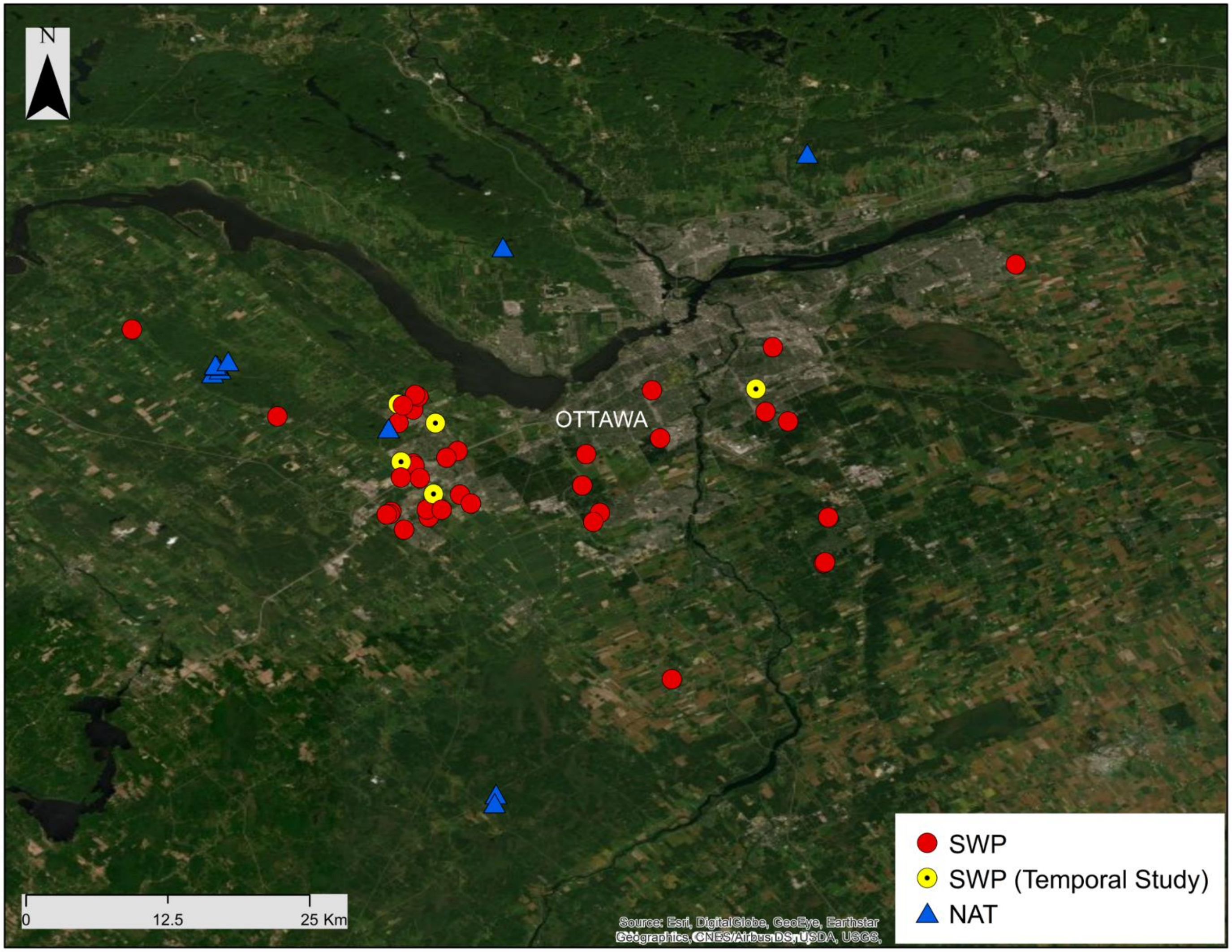

Figure 3.1 The National Capital Region of Canada (NCRC) showing location of study sites. Stormwater ponds are represented by red and yellow circles (n=41) and natural ponds are represented by blue triangles (n=10). The stormwater ponds represented by red circles were studied for one year whereas the stormwater ponds represented by yellow circles were studied over four years for a temporal analysis. Data were obtained through the City of Ottawa (2014) and Environmental Systems Research Institute satellite images (2015).

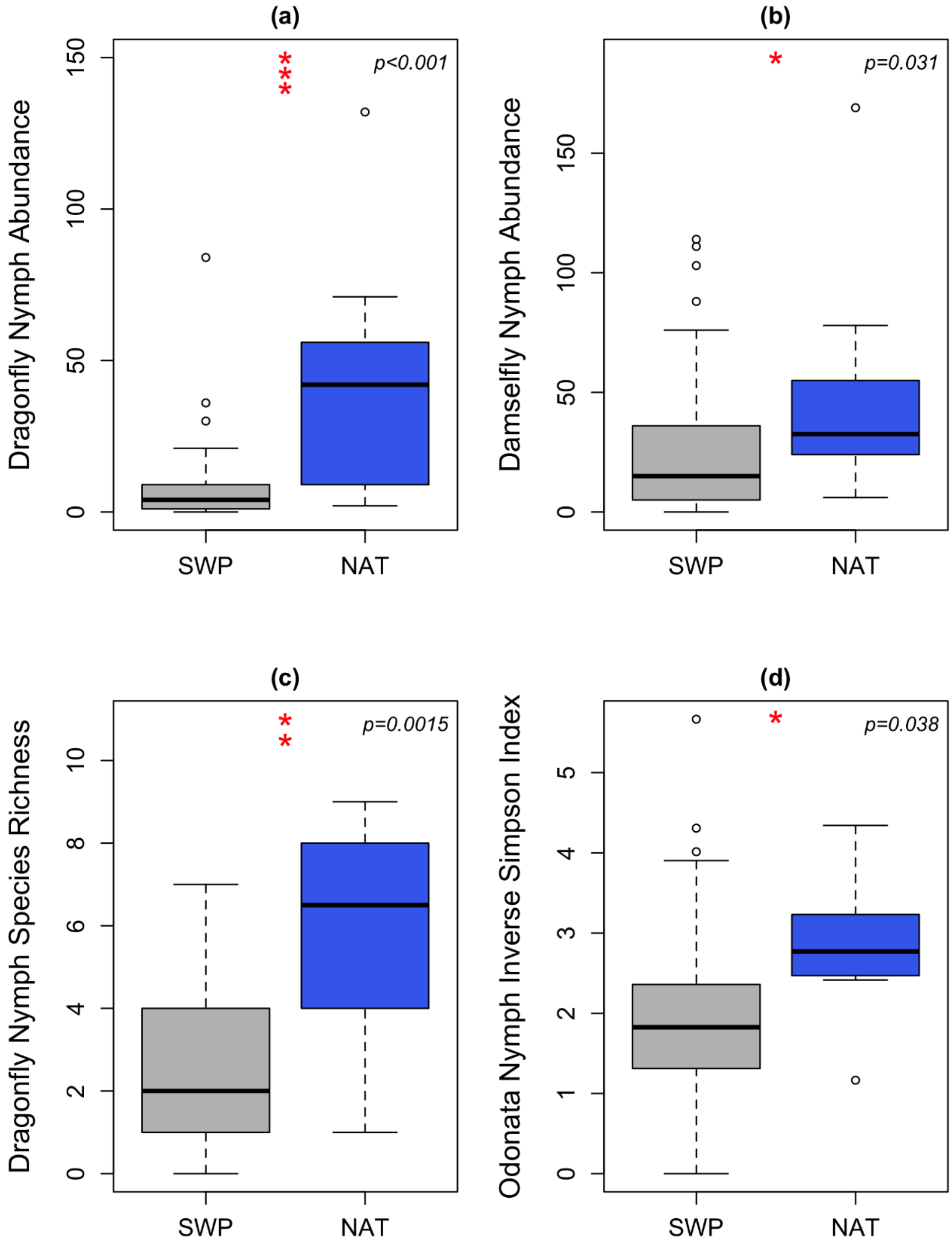

Figure 3.2 Comparisons between (a) dragonfly (Anisoptera) nymph abundance, (b) damselfly (Zygoptera) nymph abundance, (c) dragonfly nymph species richness and (d) total Odonata nymph inverse Simpson's diversity diversity* at stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10), * indicates sample size of SWP n=40 and NAT n=8.

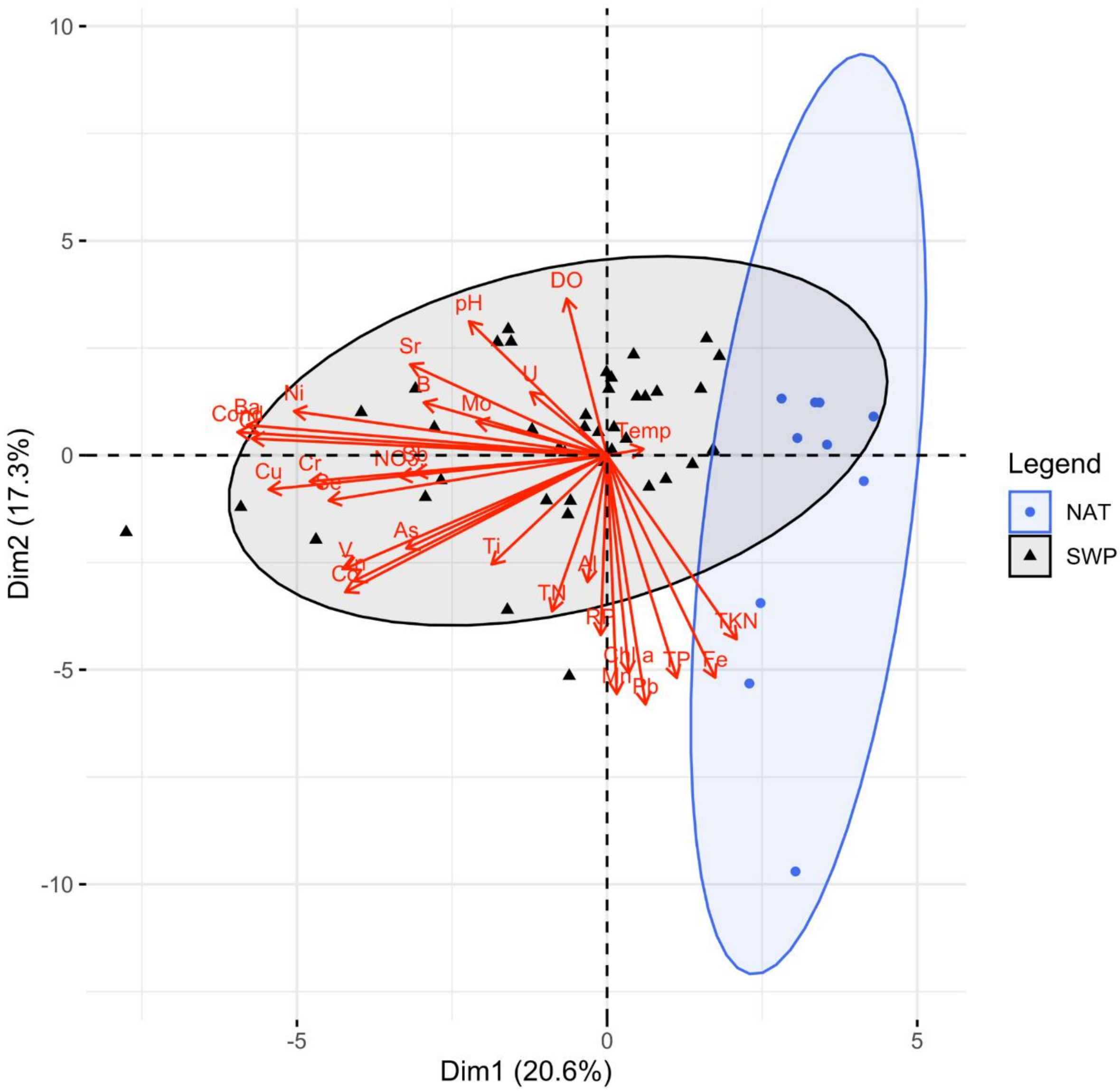

Figure 3.3 Principal Component Analysis (PCA) of 30 water quality variables sampled in stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10) with 95% confidence ellipses based on pond type (SWP, NAT) means. Water quality variables that were included in the analysis were those with >50% of measurements above detection limit (variables removed were Ag, Cd, Be, Bi, Sn, Th, W and Zr, as they were 80-100% below detection limit and did not add much information to the plot, see Fig. S3 for non- parametric version of PCA with these variables included). Values that were below detection limit were replaced with half the value of the corresponding detection. The variables were scaled and centered as units differed. The following variables were highly correlated (superimposed vectors or vectors in close proximity): pH and U; Mo, B and Sr; Ni, Ba, conductivity and Cl^-; Cu, Cr, Se, Sb and $NO3^-$; As, V, Zn and Co; TN, Al, RP, Mn, Pb, chlorophyll *a*, TP, Fe and TKN.

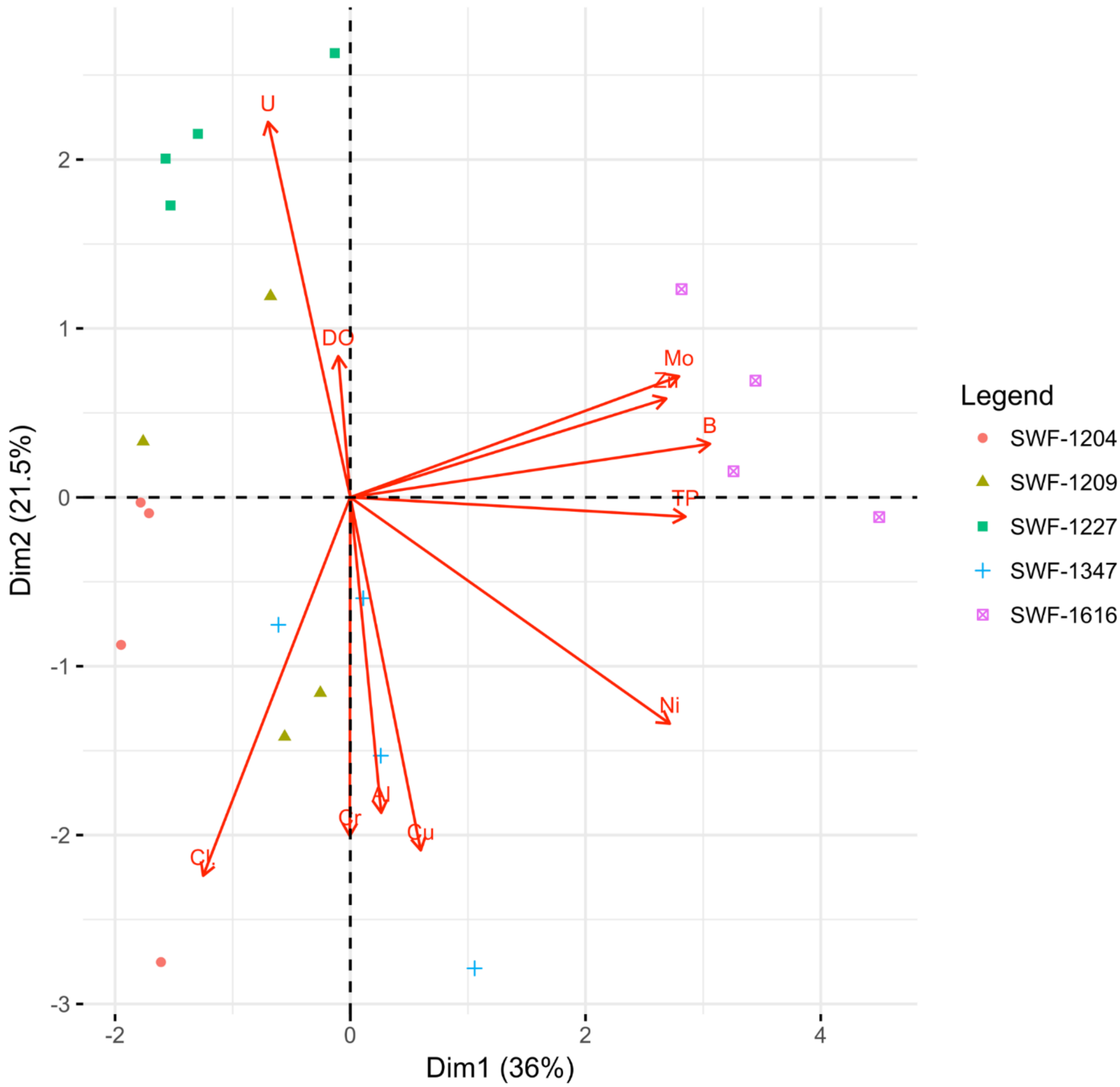

Figure 3.4 Principal Component Analysis (PCA) of 11 water quality variables, displayed by pond, sampled in stormwater ponds (N_{pond}=5) over a four-year period (N_{time}=4). The number of water quality variables was reduced by removing highly correlated variables. Measurements that were below detection limits were replaced with half the value of the corresponding detection limit. Water quality variables were scaled and centered as units differed.

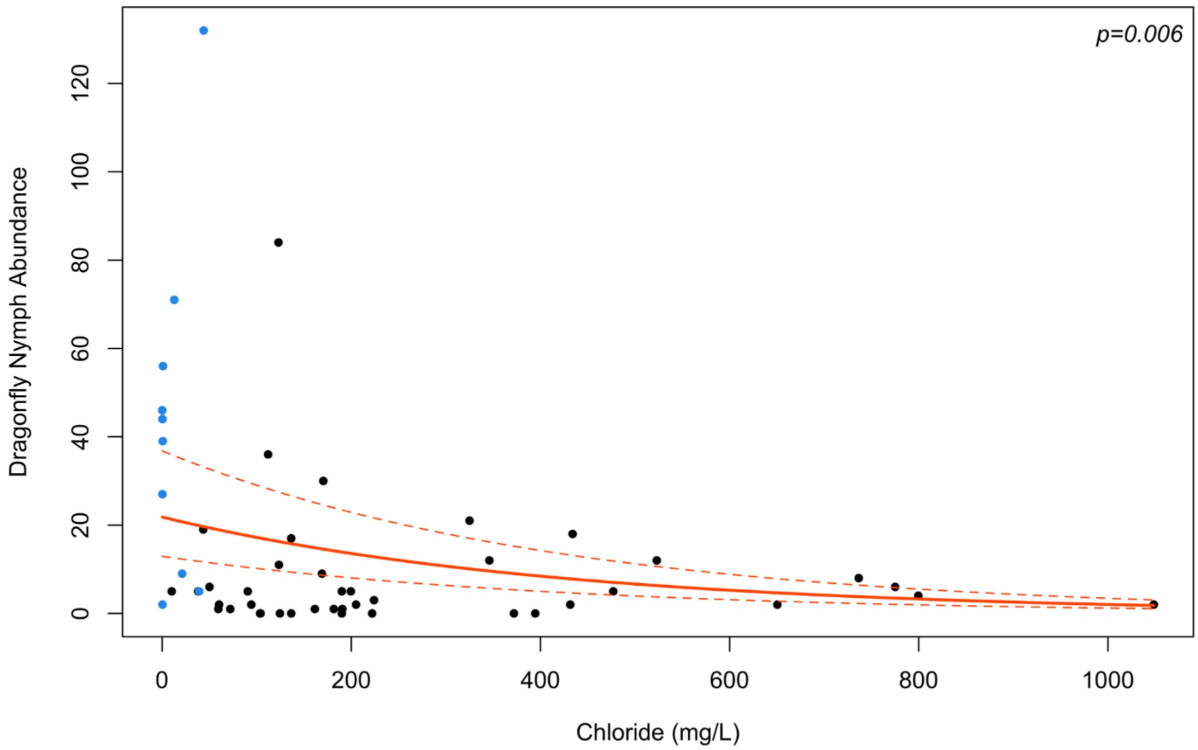

Figure 3.5 Negative binominal generalized linear model of the relationship between chloride concentrations (mg/L) and dragonfly nymph abundance in stormwater ponds (black, n=41) and natural ponds (blue, n=10).

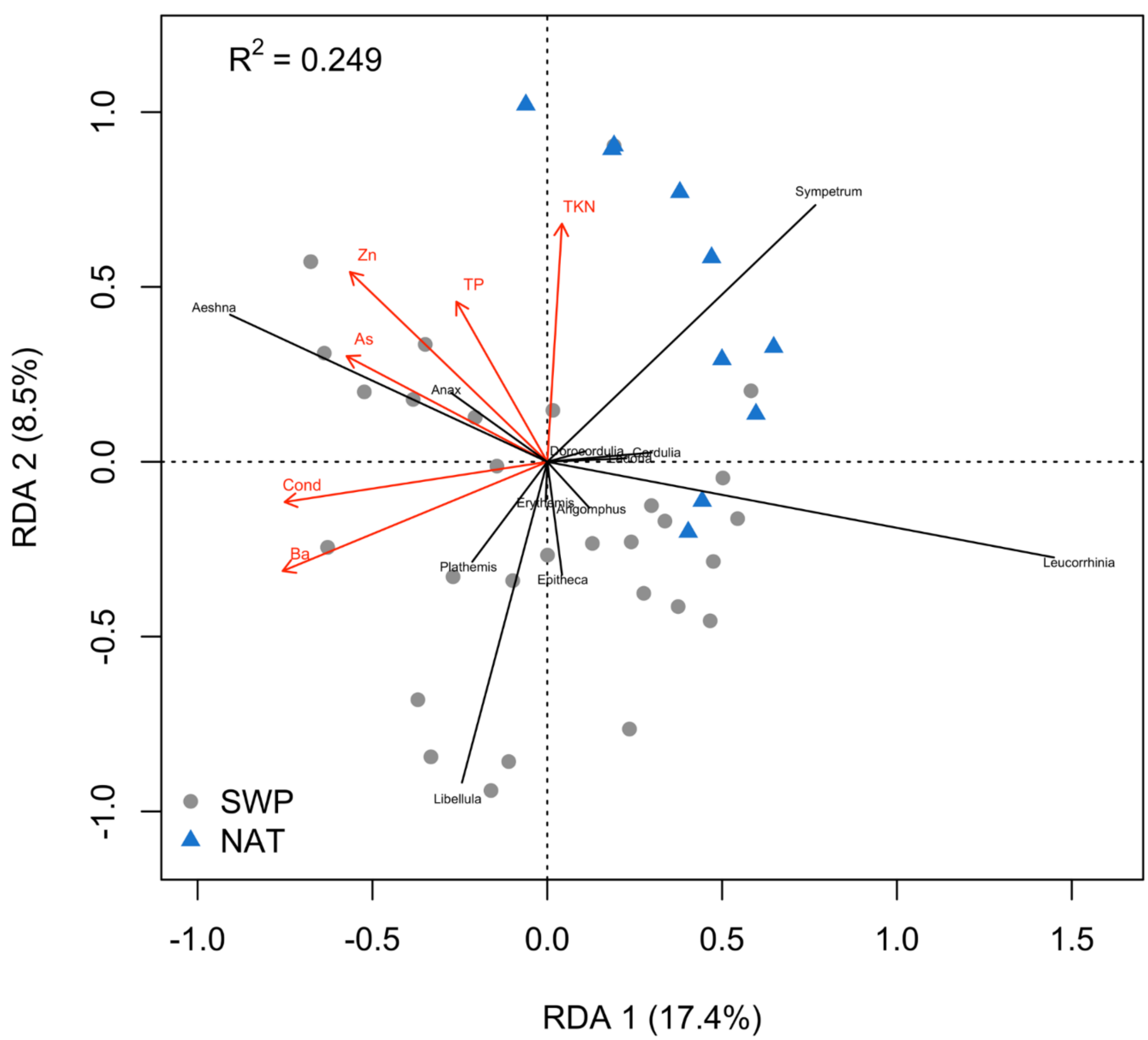

Figure 3.6 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between dragonfly (Anisoptera) genera composition (represented by black vectors without arrows) and significant (*p*<0.05) water quality variables determined through forward stepwise regression (represented by red vectors with arrows) at stormwater ponds (SWP, grey circles, n=41) and natural ponds (NAT, blue triangles, n=10). Data plotted in scaling type 2, appropriate for interpreting distance among communities.

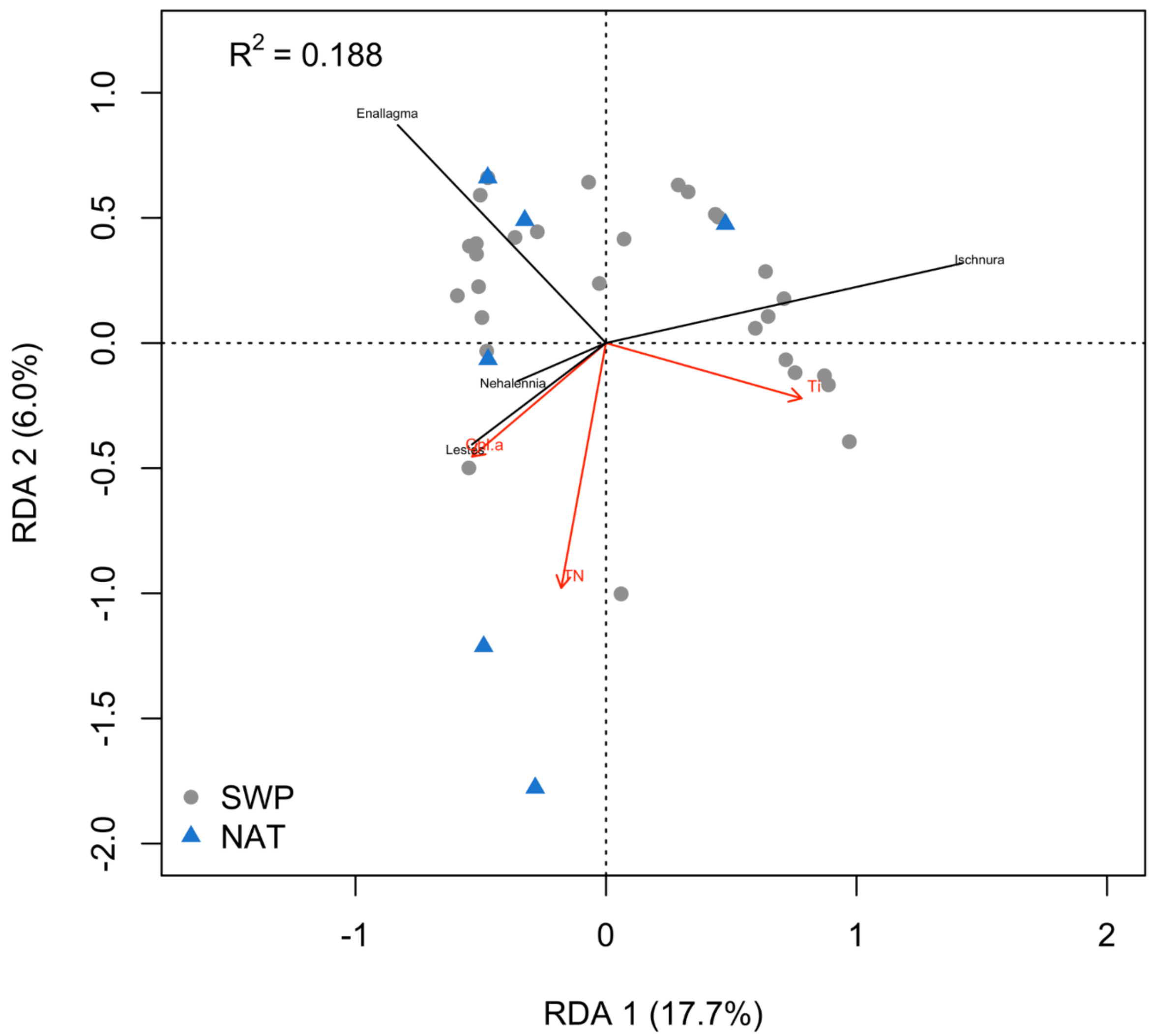

Figure 3.7 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between damselfly (Zygoptera) genera composition (represented by black vectors without arrows) and significant (*p*<0.05) water quality variables determined through forward stepwise regression (represented by red vectors with arrows) at stormwater ponds (SWP, grey circles, n=40) and natural ponds (NAT, blue triangles, n=8). Data plotted in scaling type 2, appropriate for interpreting distance among communities.

Chapter 4: Odonata reproduction and emergence: a comparison of urban stormwater and natural ponds

4.1 Abstract

Adult damselflies and dragonflies (order: Odonata) can be found at stormwater ponds in cities. However, since stormwater ponds are constructed to receive urban runoff, Odonata reproduction may be hindered due to poor water quality. The goal of this study was to determine whether stormwater ponds can support the successful reproduction of Odonata, despite potentially less suitable habitat compared to natural systems. Measures of water quality (temperature, pH, dissolved oxygen and conductivity) were obtained from stormwater ponds (n=5) and natural ponds (n=5) across a temperate metropolitan area (Ottawa, Ontario, Canada), along with estimates of adult Odonata abundance and species richness. Odonata exuviae (last instar exoskeleton) were collected and identified to provide a measure of reproductive success at each pond. On average, stormwater ponds had higher pH, dissolved oxygen and conductivity, but similar water temperatures compared to natural ponds. Odonata adults and exuviae were generally less abundant at the stormwater ponds compared to the natural ponds, but dragonfly species richness was similar. Stormwater and natural ponds shared ~70% of the same dragonfly species that were able to complete their lifecycle. Although the number of dragonfly species that successfully reproduced varied between the stormwater ponds themselves, there was no evidence that these ponds were acting as ecological traps for either specialist or generalist species. Rather, the stormwater ponds simply attracted fewer adults while producing similar proportions of offspring as found at the natural ponds. Overall, urban stormwater ponds can support the entire lifecycle of Odonata and can be valuable breeding habitats in cities.

Keywords ecological trap; dragonflies; damselflies; exuviae; lifecycle; secondary habitat

4.2 Introduction

Natural areas around the world are experiencing rapid change from historical ecological conditions to conditions with novel interactions between species and their environment (Radeloff et al. 2015). Cities, in particular, develop novel ecosystems due to extensive changes in land cover types and the increased presence of non-native species (Hobbs et al. 2006; Hobbs et al. 2009; Lugo et al. 2012). Stormwater ponds are an example of novel systems, engineered with ecological conditions unlike natural ecosystems (Bishop et al. 2000a, b; Marsalek et al. 2005). Stormwater ponds are designed to provide protection against more frequent and intense flooding associated with increased imperviousness in urban areas (Schueler 1992). They receive runoff typically high in contaminants that results in significantly poorer water quality than found in natural ponds (Frost et al. 2015). In addition, nearly half (~43%) of the plants present at stormwater ponds are non-native species (Perron and Pick 2020). While stormwater ponds are not designed to maintain biological communities, wildlife typically colonize these systems (Bishop et al. 2000a). Interest in the biodiversity associated with stormwater ponds has increased; studies over the past 1-2 decades have focused on various taxa: algae (e.g. Vincent and Kirkwood 2014), macroinvertebrates (e.g. Casey et al. 2006), amphibians (e.g. Gallagher et al. 2014) and birds (e.g. Sparling et al. 2004). Some studies suggest that stormwater ponds can provide habitat for species in cities (e.g. Stephansen et al. 2014; Hassall and Anderson 2015), while others emphasize the need to deter species away from these systems due to potential toxicological risks (Wren et al. 1997; Bishop et al. 2000a, b).

Wildlife populations are directly associated with the quality of habitats occupied. On a landscape scale, habitats are present at various levels of quality (Robertson 1971; Dias 1996). A high-quality habitat, also known as a source habitat, provides the availability of resources and optimal conditions required for the successful production of progeny of an individual and is readily selected by individuals (Pulliam 1988; Pulliam and Danielson 1991; Johnson 2005). In a low-quality habitat, or a sink habitat, the conditions present will likely impair the successful reproduction of an individual and is only selected when capacity is reached at other available source habitats (Pulliam 1988; Pulliam and Danielson 1991; Johnson 2005). In this light, urban systems may be acting as ecological traps, that is they represent a sink habitat that is as attractive as a source habitat and chosen over other available source habitats (Battin 2004). Ecological traps can have major consequences on population persistence and can lead to regional extinctions of species (Hutto 1985; Robertson and Hutto 2006). There is a concern that stormwater ponds could be acting as ecological traps for wildlife, given their potential for poor water quality (e.g. Sievers et al. 2018).

Odonata (damselflies and dragonflies) are frequently found at stormwater ponds (Hassall and Anderson 2015; Perron and Pick 2020). All species have a biphasic lifecycle: their adult phase is spent in the terrestrial/aerial environment adjacent to water bodies and their nymph stage directly in the aquatic environment (Corbet 1999). As adults, they actively select their habitat based on a set of visual cues (Wildermuth and Spinner 1991; Wildermuth 1998), more specifically the presence of water and macrophytes (Dunkle 1976; Ward and Mill 2005; Guillermo-Ferreira and Del-Claro 2011). Odonata can withstand a wide range of environmental conditions and are considered bioindicators of wetland systems (Foote and Rice Hornung 2005; Kutcher and Bried 2014). As an odonate successfully completes its lifecycle, it emerges from water and molts into an adult, leaving behind the last instar exoskeleton of the nymph known as the exuviae (Corbet 1999). Exuviae can be collected and identified to determine the species that successfully reproduce in a habitat and can be used to assess habitat suitability (Raebel et al. 2010). For example, Raebel et al. (2010) found that farmland ponds in the United Kingdom are potential ecological traps for Odonata, as exuviae from certain taxa were not collected in habitats where adults were recorded breeding.

The goal of this study was to determine whether urban stormwater ponds can support the successful reproduction of Odonata, despite potentially less suitable habitat compared to natural ponds. As a result, this study hypothesized that stormwater ponds are less suitable habitats for dragonfly emergence than natural ponds given the stressors in urban systems. I predicted that there would be fewer numbers and species of dragonfly nymphs emerging relative to the numbers and species observed as adults at a given stormwater pond compared to the natural ponds.

4.3 Methods

4.3.1 Study sites

Based on a wider survey (Perron and Pick 2020), five stormwater ponds (SWF-1204, SWF-1209, SWF-1227, SWF-1347 and SWF-1616) were selected across the National Capital region of Canada (population ~ 1 million) (Table 4.1, Fig. 4.1). Ponds were selected to encompass a range of imperviousness of the pond catchment (33.7%-74.3%) and hence water quality (Brabec et al. 2002). Four of the stormwater ponds received runoff from residential areas, whereas one pond, SWF-1204, received runoff from commercial developments (with significant vehicle parking lots). Pond SWF-1227 was the only pond that was completely hardscaped, with rock walls and little littoral zone (Fig. S4.1a). The stormwater ponds also ranged in age post construction (ranging from 6 to 19 years). Another five natural ponds were selected from rural parts within the city boundary as reference systems (Table 4.1, Fig. 4.1). These natural ponds had minimal impervious surfaces in their catchment basins and were surrounded mainly by wooded areas, rock barren (exposed rock outcrop) and other wetlands (Fig. 4.1). All stormwater ponds and natural ponds were small and similar in size (<1 hectare) to standardize for species-area relationships (Table 4.1) and held a permanent body of water (~2 m in depth).

4.3.2 Pond water quality

Four water quality variables (water temperature, pH, dissolved oxygen and conductivity) were measured *in situ* using a HydroLab MiniSonde approximately once a week from April 24th to September 12th, 2017 at each pond (concurrent with Odonata exuviae sampling). These variables are important for the development of the nymph stage of Odonata and are known to also affect species composition (Wichard and Komnick 1974; Rychła et al. 2011; Suhling et al. 2015). For each sampling, two measurements were taken adjacent to the pond outlets and these were averaged to represent the conditions of that time. Conductivity was positively related to chloride concentrations, even with the small sample size of five ponds (Fig. S4.2). High pond conductivity was likely a result of road salt (NaCl) usage in the city (Vincent and Kirkwood 2014), which would increase with the percentage of imperviousness of the catchment basins (Fig. S4.3).

4.3.3 Odonata sampling

4.3.3.1 Adults

Adult Odonata were sampled twice at each pond (early summer corresponding to 6-18 July and late summer corresponding to 8-19 August of 2017) to maximize the potential of encountering all early and late flying species (local flying information obtained from Bracken and Lewis 2008). All individuals were enumerated and identified to species in a 60-minute visual survey (methods following Perron and Pick 2020). Individual pairs that exhibited copulation behavior (i.e. in tandem) were recorded as breeding pairs.

4.3.3.2 Exuviae

Exuviae were sampled once a week at each pond from May 30th to September 12th, 2017 (excluding the first week of September), totaling 14 collections. Sampling did not take place when it was raining to avoid the loss and destruction of exuviae. Two methods were used to sample exuviae: (1) an artificial emergence screen method, and (2) a quadrat method, both non-destructive to tenerals (freshly emerged individuals). For each method, exuviae were sampled by the same observer to ensure sampling efforts were consistent through time. Damselfly and dragonfly exuviae were collected and placed in separate glass jars. The two different methods were compared to determine the most efficient way to collect exuviae from pond systems but for analyses, the exuviae collected using both methods were tallied to estimate abundances at each pond.

All exuviae were returned to the lab, sprayed with 70% ethanol and laid out to dry. Damselfly exuviae are small, fragile and difficult to identify to species thus, exuviae were estimated as total pond abundance only. Dragonfly exuviae, which are much larger, were identified to genus using Hutchinson and Ménard (2016) and to species using Walker (1958) and Walker and Corbet (1975). Approximately 14% of dragonfly exuviae were too damaged to accurately and confidently identify to species.

4.3.3.2.1 Artificial emergence screen method

Artificial emergence screens were constructed by assembling a wooden frame that measured 1 m in width and 0.8 m in height, an additional 0.2 m in height was added to the frame as legs/props to secure frame into the pond sediments, adapted from a design by Cook and Horn (1968). Fiberglass screen was stapled to the 1 x 0.8 m wooden frame to create an artificial emergence screen as a vertical substrate for Odonata to crawl up and emerge from. Ideally, Odonata legs would attach to screen preserving the exuviae on the screen for collection. Four artificial emergence screens were installed in the littoral zone (equally spaced apart along pond perimeter) of each pond perpendicular to the water's edge, partially submerged in the water (Fig. S4.4) and remained in place through the 15-week sampling period. Each week concurrent with the sampling of exuviae in quadrats, the artificial emergence screens were examined and any exuviae attached to the screens were collected.

4.3.3.2.2 Quadrat method

The littoral zone of each pond was divided into 2 x 1 m sections and each section was assigned a number. For each sampling event, using a random number generator, four 2 x 1 m sections were selected along the littoral zone of each pond. A 2 x 1 m quadrat was placed at each randomly generated section and the quadrat was exhaustively searched for damselfly and dragonfly exuviae by a single observer. Any exuviae found in the quadrat, including exuviae that were floating on the water were collected. Most exuviae were attached to plants and care was taken to remove exuviae without damaging features.

4.3.4 Data Analyses

Pond water quality variables (temperature, pH, dissolved oxygen and conductivity) were compared in two different ways: (i) between each individual pond, and (ii) between pond types (stormwater versus natural ponds). To compare each individual pond, each variable measured throughout the field season was averaged for each pond. To compare the water quality of pond types, averages and standard deviations of each variable were calculated for stormwater ponds (n=5) and natural ponds (n=5). This analysis was used to determine how water quality varied through the sampling season.

The residuals of the following data for both stormwater and natural ponds were tested for normality using the Shapiro-Wilks test from the *stats* package (R Core Team 2017) pond area, pond perimeter, water quality variables, Odonata abundances, number of Odonata breeding pairs, dragonfly species richness, the number and species richness of exuviae captured in both collecting methods. Pairwise comparisons (t-tests, Welch's test or Mann-Whitney U test from the *stats* package, depending on the nature of the data) were then used to test for differences in variables between the stormwater ponds and the natural ponds. Boxplots were created, with the *ggplot2* package (Wickham 2016), to visualize distributional patterns of the two exuviae collecting methods, the number of breeding pairs, damselfly and dragonfly abundances and dragonfly species richness between the stormwater ponds and the natural ponds.

Linear regression was used to analyze the relationships between the exuviae collecting methods to determine if ponds that had many exuviae collected in the quadrats also had many exuviae collected on the emergence screens using the *stats* package. Adult dragonfly species richness was plotted, using the *ggplot2* package, against the number of exuviae species at the stormwater ponds and the natural ponds, with their 95% confidence intervals. As adults were only sampled twice and exuviae were sampled on 14 occasions, the additional species that were present just as exuviae were eliminated for this test to standardize for differences between adult and exuviae sampling effort. Thus, the relationship between individual species of adults and their exuviae was based only on those species present as adults and whether or not the species was also present as exuviae. In theory, if stormwater ponds were acting as potential ecological traps, fewer dragonfly species as exuviae would be encountered relative to the number of species present as adults (Fig. 4.2).

A negative binomial mixed model, using the *MASS* package, was fitted to determine if the adult dragonfly abundance was a significant predictor of exuviae abundance and if this relationship differed between stormwater ponds and natural ponds. The model was limited to species of dragonflies that were present at both stormwater ponds and natural ponds as adults (n=7) which included the following: *Anax junius, Libellula luctuosa, Libellula pulchella, Leucorrhinia intacta, Sympetrum obstrusum, Sympetrum vicinum* and *Sympetrum semicinctum*. In the model, exuviae abundance was the response variable, adult abundance and pond type (SWP or NAT) were fixed effects and species and pond ID were random effects. All data analyses were performed in R (version 3.4.2) and Rstudio (version 1.1.456 and 1.2.5019).

4.4 Results

4.4.1 Pond characteristics

Water temperatures in the stormwater ponds were similar to those measured in the natural ponds (Table 4.1, t=0.10, p=0.920), with comparable fluctuations through time (Fig. 4.3a). The stormwater ponds had, on average, higher pH levels than the natural ponds (Table 4.1, W=25, p=0.011), but both pond types had a circumneutral pH with moderate fluctuations over time (Fig.

4.3b). Dissolved oxygen was also higher, on average, in the stormwater ponds (Table 4.1, Fig. 4.3c, t=4.78, p=0.0014). Conductivity was an order of magnitude higher in the stormwater ponds (average of 1,475.2 μS/cm) compared to the natural ponds (average of 157.1 μS/cm) Table 4.1, t=3.31, p=0.027), with much greater fluctuations over time (Fig. 4.3d). Stormwater pond SWF-1204 had the highest conductivity with an average of 2,437 μS/cm and a range of 1,100-3,789 μS/cm (Table 4.1) and was the only pond to receive commercial runoff.

4.4.2 Comparison of exuviae sampling methods

Overall, there was a significant positive relationship between the number of exuviae collected in the quadrat method compared to the artificial emergence screen method (Fig. S4.5, R^2=0.42, p=0.025). This positive relationship between the exuviae collected by both methods was largely driven by the damselfly exuviae collected (R^2=0.51, p=0.013); the dragonfly exuviae collected followed a positive trend between the two methods but the relationship was not highly significant (R^2=0.14, p=0.16). There were comparable numbers of damselfly exuviae collected with the artificial emergence screen method and the quadrat method (Fig. 4.4a, t=-1.62, p=0.123). However, the quadrat method was significantly more effective in capturing dragonfly exuviae as low numbers were collected with the artificial screen method in comparison (Fig. 4.4b, t=-2.7, p=0.023). The number of dragonfly species collected as exuviae was higher with the quadrat method (averaging nine species collected per pond) than the artificial emergence screen method which only captured on average three species per pond (Fig. 4.4c, t=3.0, p=0.011). In general, no new species were collected with the emergence screens that were not present in the quadrats, with the exception of one pond (three new species collected with the screens).

4.4.3 Odonata at stormwater ponds

A total of 3,896 adult Odonata were recorded in this study comprised of 2,212 adult damselflies and 1,684 adult dragonflies. Fewer exuviae were collected for a total of 2,343 of which 1,192 were damselflies and 1,151 were dragonflies. On average, there were fewer Odonata from both life stages at the stormwater ponds compared to the natural ponds (Fig. 4.5), however the difference was not significant because of high and overlapping variation in abundances of both pond types as well as the relatively small sample size. Some stormwater ponds therefore contained comparable Odonata abundances to some of the natural ponds. Overall, there were fewer adult damselflies at the stormwater ponds than the natural ponds, with averages of 172 and 271 respectively (Fig. 4.5a, t=-1.73, p=0.122). Also, fewer damselfly exuviae were collected at the stormwater ponds compared to the natural ponds, with averages of 51 and 187 respectively (Fig. 4.5b, t=-1.30, p=0.262). Dragonflies were also less abundant at the stormwater ponds in comparison to the natural ponds as adults, with averages of 54 and 283 respectively (Fig. 4.5c, t=-2.27, p=0.083) and as exuviae, with averages of 61 and 169 respectively (Fig. 4.5d, t=-1.64, p=0.140). The natural pond NAT-1 and the stormwater SWF-1227 had consistently fewer dragonflies than other ponds of their respective type (Fig. 4.5c-d). The natural pond NAT-11 held the highest abundances of damselflies at both life stages and dragonfly exuviae compared to all other ponds (Fig. 4.5a-b, d).

A total of 18 dragonfly species were identified as adults and a total of 27 dragonfly species were identified as exuviae. There was no difference in the species richness of adult dragonflies at the stormwater ponds compared to the natural ponds (Table 4.2, Fig. S4.6a, t=0.69, p=0.522). Adult dragonfly species richness ranged from three to nine species at the stormwater ponds and from five to seven species at the natural ponds (Table 4.2, Fig. S4.6a). There was also no difference in the species richness of dragonflies as exuviae at the stormwater ponds compared to the natural ponds (Table 4.2, Fig. S4.6b, t=-0.17, *p*=0.872). Dragonfly species richness as exuviae ranged from two to 15 species at the stormwater ponds and from three to 17 species at the natural ponds (Table 4.2, Fig. S4.6b). There was on average more dragonfly species collected as exuviae than as adults (Table 4.2), but this difference was not highly significant (t=-1.72, *p*=0.114). Odonata breeding rates were generally lower at the stormwater ponds compared to the natural ponds (Fig. 4.6, t=-2.24, *p*=0.056).

The stormwater ponds supported comparable richness of successful dragonfly species (i.e. reproducing species) as the natural ponds (Fig. 4.7). Nearly all ponds contained a species richness of dragonfly exuviae that was proportional to the adult species present at a pond, as shown by the inclusion of sites in the 95% confidence intervals for the stormwater ponds and the natural ponds (Fig. 4.7). The only pond that fell outside of the confidence intervals was in fact a natural pond, NAT-1 (Fig. 4.7); this pond also supported the lowest abundances of dragonfly adults and exuviae out of all the natural ponds (Fig. 4.5). Generally, ponds that attracted few adult dragonfly species supported the successful emergence of correspondingly few species (Fig. 4.7). The stormwater ponds followed a similar relationship (similar slope) of adult to exuviae species richness as the natural ponds, while the intercept of the stormwater ponds was slightly lower than the natural ponds (Fig. 4.7). There was also a wider variation in the adult to exuviae ratio in the stormwater ponds, with some ponds supporting the successful emergence of few dragonfly species while others supported a significant number of species. In fact, two of the stormwater ponds, SWF-1209 and SWF-1204, supported the successful emergence of more dragonfly species than most of the natural ponds (Table 4.2, Fig. 4.7); these same ones were the stormwater ponds with the highest overall abundances of dragonflies as well (Fig. 4.5). The ponds with the most species of dragonfly exuviae (Fig. 4.7) were generally also the ponds with the highest exuviae abundance (Fig. 4.5). Pond SWF-1227 had the least dragonfly species richness (Table 4.2, Fig 4.7). Adult abundance was a significant predictor of exuviae abundance (estimate: 0.013±0.006, z=2.1, p=0.04), while pond type (SWP vs. NAT) was not (estimate: 0.18±0.69, z= 0.263, p=0.79) based on the mixed effect model.

4.5 Discussion

4.5.1 Sampling considerations

Overall, exuviae collections identified more species of dragonflies per pond compared to the adult surveys (Table 4.2). There were a number of dragonfly species that were collected as exuviae at ponds where the adults were not recorded. This could be a result of sampling effort, as ponds were only visited twice for adult surveys and/or could be a result of cryptic adult species more easily detected as exuviae. The superiority of Odonata exuviae collections for species detection has been suggested in previous studies. Raebel et al. (2010) stressed the importance of exuviae collections since adult surveys can miss certain species (i.e. territorial fliers). The presence of adults also does not guarantee the reproduction of the species, thus sampling exuviae is critical when defining habitat suitability.

This study also tested two different exuviae collecting methods. Although, both methods collected comparable numbers of damselfly exuviae, the quadrat method was superior to the artificial emergence screen method for dragonfly exuviae. The quadrat method captured significantly higher abundances and species richness of dragonflies (Fig. 4.4). In addition, the quadrat method was also more economically feasible as the emergence screens were expensive to construct.

4.5.2 Odonata life stages at stormwater ponds

The hypothesis tested here was that stormwater ponds would be less suitable habitats for dragonfly emergence than natural ponds. The stormwater ponds selected were of similar size as the natural ponds, however, their surrounding land cover types and, in particular, the amount of impervious surface differed. Stormwater ponds were surrounded by developed lands (buildings, roads) and crop/pasture, whereas natural ponds were surrounded by wooded areas and other wetlands (Fig. 4.1). As expected, the water quality consequently differed from the natural ponds, with higher pH, dissolved oxygen and conductivity in the stormwater ponds but similar water temperatures between the two pond types (Table 4.1, Fig. 4.3). The higher conductivity can be explained by the use of winter road salts in the city, which would vary as a direct function of the amount of asphalted surface and traffic use (Fig. S4.3; Vincent and Kirkwood 2014). The high conductivity persists in these ponds through the summer months despite rain events that might be expected to return the ponds to more background levels (Fig. 4.3). The higher oxygen and higher pH in stormwater ponds are likely the result of higher day-time rates of photosynthesis from more algal and plant biomass associated with higher nutrient loading (Wium-Andersen et al. 2013).

As the land cover and water quality differed between the stormwater ponds and natural ponds, there were also differences in their Odonata communities. Stormwater ponds attracted generally fewer adult damselflies and dragonflies than the natural ponds (Fig. 4.5a, c); less breeding pairs were also recorded at the stormwater ponds (Fig. 4.6). There were similarly lower abundances of damselfly and dragonfly exuviae at the stormwater ponds (Fig. 4.5b, d). However, the species richness of dragonfly adults and exuviae were comparable between the stormwater ponds and the natural ponds (Table 4.2, Fig. S4.6). Previous literature has found similar species richness of macroinvertebrates at stormwater ponds compared to natural ponds, but differences in community structure with more generalists at stormwater ponds (Woodcock et al. 2010). In the present study, similar species were encountered in both pond types, with stormwater ponds sharing ~70% of the species pool of exuviae with the natural ponds (Table 4.2). Like the natural ponds, stormwater ponds supported the emergence of specialist dragonfly species that are locally uncommon (local information obtained from Bracken and Lewis 2008), such as the lake darner (*Aeshna eremita*), the frosted whiteface (*Leucorrhinia frigida*) and the horned clubtail (*Arigomphus cornutus*) (Table 4.2). In Ontario, the horned clubtail is considered a vulnerable species (an S3 rank from the Ministry of Natural Resources) (Brinker and Jones 2012), thus stormwater ponds could be important breeding habitats to support populations. Additionally, stormwater ponds supported the emergence of three dragonfly species that were not recorded in the natural ponds: the eastern pondhawk (*Erythemis simplicicollis*), the twelve-spotted skimmer (*Libellula pulchella*) and a migratory species, the green darner (*Anax junius*) (Bracken and Lewis 2008). Four out of the five stormwater ponds supported the emergence of the green darner, whereas the emergence of this species was not observed at any of the natural ponds (Table 4.2). Results from this study point to the importance of stormwater pond habitats for the regional diversity of dragonflies.

4.5.3 Stormwater ponds are not necessarily ecological traps

The prediction was that, relative to adult occurrences, stormwater ponds would have less Odonata emergence compared to that of natural ponds. As novel ecosystems, stormwater ponds could potentially be acting as ecological traps, as they are known to have poorer water quality than natural ponds (Frost et al. 2015) but still offer features that may be cues for habitat selection (Perron and Pick 2020). Dragonflies generally disperse from natal habitats to select breeding habitats (Corbet 1999). Dragonflies can have maladaptive habitat selection processes, i.e. dragonflies have been observed laying eggs on reflective gravestone (Horváth et al. 2007) and can be attracted to the reflective characteristics of crude oil (Horváth et al. 1998). Overall, the stormwater ponds were generally less attractive than the natural ponds for the adult stages of Odonata (Fig. 4.5, Fig 4.7). However, there was a range in the suitability of individual stormwater ponds themselves; the number of dragonfly species to successfully emerge was proportionate to the number of species of adult dragonflies the pond attracted (Fig. 4.7). In terms of abundance, the number of adults was a significant predictor of the number of exuviae of the seven common species considered. The relationship between adult dragonfly abundance and exuviae abundance for the subset of species did not differ between stormwater ponds and natural ponds further suggesting that stormwater ponds are important breeding habitats for dragonflies. The gradient present in the dragonfly species richness at the stormwater ponds suggest a range in habitat quality or suitability between the ponds, with some ponds being of low quality (such as SWF-1227) and others supporting the emergence of similar dragonfly species richness as natural ponds (such as SWF-1209). The most species rich ponds also had the highest abundances. The pond SWF-1227 had the least dragonfly exuviae (lowest abundances and species richness) out of all the ponds in this study. This pond also attracted the least adult dragonflies, thus was not highly selected for reproduction. The pond SWF-1227 was not particularly different in terms of water quality than the other ponds (Table 4.1), but this was the only pond sampled that was completely hardscaped with rock gabion walls and little littoral zone (Fig. S4.1a). Since adult dragonflies use the presence of macrophytes as a visual cue for habitat selection, pond SWF-

1227 therefore is potentially less attractive for breeding adults than other stormwater ponds that have vegetated banks such as SWF-1209 (Fig. S4.1b).

A low-quality habitat (a sink habitat) is not the same as an attractive trap (i.e. ecological trap). Sink habitats attract few individuals and support the successful progeny of few individuals, whereas an ecological trap attracts many but supports few (Battin 2004). Ecological traps are often created in environments that undergo rapid environmental change, which creates a discontinuity in the attractiveness of a habitat and its realized environmental quality (Battin 2004). Although, it is difficult to distinguish ecological traps in the landscape, assuming individuals from the same species respond to similar cues, the results from this research suggest that the stormwater ponds studied are not acting as ecological traps. This study shows the range of habitat quality found among stormwater ponds themselves, representing the presence of potential source and sink habitats. Both source and sink habitats can be important for species in human altered landscapes as they can support metapopulations (Harabiš and Dolný 2012). Dragonflies can form metapopulations in fragmented habitats as shown by Harabiš and Dolný (2012) in mining subsidence of Czech Republic, where adult dispersal can connect habitat patches (i.e. ponds) and sustain viable populations despite the presence of poor-quality habitats. To determine if pond networks are supporting dragonfly metapopulations, patch size and patch connectivity needs to be determined and related to patch colonization rates and extinction rates (also known as the incidence function model, Hanski 1994).

4.6 Conclusions

This study demonstrated that stormwater ponds can be viable habitats for Odonata populations in cities. Results based on the stormwater ponds sampled suggest comparable reproduction of dragonflies as natural ponds, although overall, they may be less attractive to adults than natural ponds. Stormwater ponds supported the life cycle completion of ~70% of the same dragonfly species as natural ponds did; with three species emerging from the stormwater ponds that were not present at the natural ponds, including a migratory species. This study also points to the importance of collecting exuviae for conservation studies as they provide evidence of species successful in aquatic habitats and furthermore can provide information on species that are more cryptic as adults. Stormwater ponds have the potential to be as important for dragonfly reproduction as natural systems and their attractiveness and suitability as breeding habitats may be linked to pond design (i.e. hardscape).

See Appendix C for Supplementary Material

Table 4.1

Stormwater pond (SWF) and natural pond (NAT) characteristics including pond location, size and perimeter. Physical variables of water quality were measured *in situ* at each pond from April to September 2017 (~once a week). Water quality variables were averaged for each pond and ranges of variable are provided in brackets. *p*-values from pairwise comparisons (unpaired t-test or Mann-Whitney U test) were used to test differences between the stormwater ponds and the natural ponds. Significance values are as followed: ns (no significant difference), * (p<0.05) and ** (p<0.01).

Pond ID	**X, Y coordinates**	**Area (m^2)**	**Perimeter (m)**	**Temperature (°C)** Mean (Range)	**pH** Mean (Range)	**DO (mg/L)** Mean (Range)	**Conductivity (µS/cm)** Mean (Range)
SWF-1204	4534220373 -75.90694549	2,935.5	462.0	21.4 (13.0-27.2)	7.7 (7.4-8.2)	8.2 (3.7-13.0)	2437.5 (1100.0-3789.0)
SWF-1209	45.31152481 -75.93421663	2,577.7	345.4	19.9 (11.0-26.0)	7.7 (7.1-8.7)	6.7 (4.2-12.8)	728.6 (232.0-1636.0)
SWF-1227	45.35740207 -75.9365356	8,153.6	440.5	20.3 (11.1-26.6)	8.1 (7.8-8.5)	10.1 (8.1-12.9)	619.8 (380.4-977.9)
SWF-1347	45.2860605 -75.90843208	1,553.4	184.1	21.6 (12.1-29.4)	7.7 (7.3-8.3)	9.5 (1.6-17.5)	2377.6 (1665.5-3231.0)
SWF-1616	45.36931473 -75.65283607	2,995.9	311.9	17.6 (9.1-22.5)	7.6 (7.5-8.2)	8.5 (3.0-16.1)	1212.5 (613.9-1625.0)
NAT-1	45.33810824 -75.94407793	1,907.6	187.0	19.4 (9.2-24.6)	6.5 (6.4-6.9)	3.5 (1.6-6.1)	70.1 (42.0-78.3)
NAT-2	45.38493452 -76.07759461	4,750.5	499.6	21.0 (12.9-25.4)	6.4 (6.1-6.9)	4.5 (1.9-7.9)	26.4 (17.2-33.1)
NAT-6	45.38193056 -76.08365175	2,963.1	275.0	20.5 (11.7-26.7)	7.1 (6.7-7.6)	6.2 (1.0-10.0)	87.1 (66.5-115.5)
NAT-7	45.39146021 -76.071336	7,999.2	436.9	19.8 (11.8-27.5)	6.6 (6.3-7.0)	3.8 (1.9-6.8)	248.6 (155.3-298.4)
NAT-11	45.38833154 -76.0705429	3,641.0	319.2	19.7 (10.9-26.1)	7.2 (7.0-7.5)	5.9 (3.4-8.9)	353.5 (144.4-871.5)
***p*-value (SWF vs. NAT)**		***0.593 (ns)***	***0.946 (ns)***	***0.920 (ns)***	***0.011(*)***	***0.0014 (**)***	***0.027 (*)***

Table 4.2

Dragonfly species present at stormwater ponds (SWF in grey, n=5) and natural ponds (NAT in blue, n=5) as adults (A) and/or collected as exuviae (E) at each pond.

Species	**SWF-1204**	**SWF-1209**	**SWF-1227**	**SWF-1347**	**SWF-1616**	**NAT-1**	**NAT-2**	**NAT-6**	**NAT-7**	**NAT-11**
Anax junius	A E	A E	E		A E	A				A
Aeshna canadensis	E	E						A E		E
Aeshna eremita	E	E						E		E
Aeshna constricta						A		E	E	
Aeshna tuberculifera								E		
Aeshna interrupta								E		
Aeshna umbrosa	E	E						E		
Arigomphus cornutus	E	E					E			E
Dorocordulia libera	E						E	E		E
Cordulia shurtleffii							A E	E		E
Epitheca canis	E	E					E			E
Epitheca spinigera	E						E			E
Epitheca cynosura	E	E	E							E
Libellula quadrimaculata		E		E			E	A		E
Libellula pulchella	A E	A E		A E	A		A	A		A
Libellula luctuosa	A	A		A						
Plathemis lydia			A	E	E			E		
Ladona julia				E				E		E
Pachydiplax longipennis	A E	A E		A	A E					E
Leucorrhinia intacta	A E	A E		A E	E	A		E		A E
Leucorrhinia frigida	E				E		A E	E	A	A E
Leucorrhinia proxima					E	A		A E	A E	A E
Sympetrum vicinum	A E	A E		A E	A E		A E	A E	A E	A E
Sympetrum obstrusum	A	A E		A	A E	A E	A	A E	A E	A E
Sympetrum semicinctum	E	A E			A				A	E
Sympetrum internum						A E			A E	
Sympetrum costiferum						E	E			
Celithemis elisa	A		A							
Erythemis simplicicollis	A	A	A	A E						

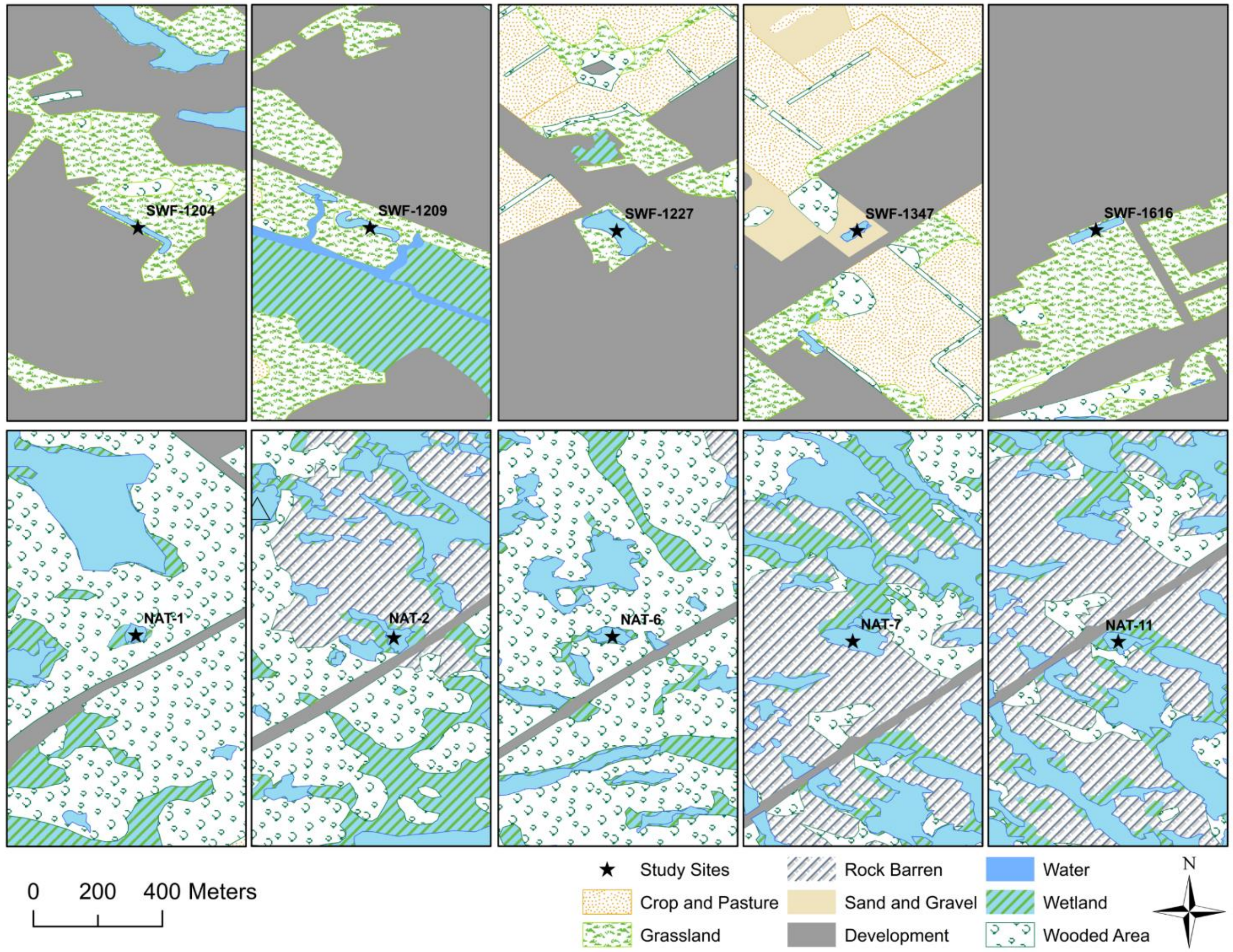

Figure 4.1 Land use map of study sites: stormwater ponds in the top row (SWF, n=5) and natural ponds in the bottom row (NAT, n=5) with their surrounding land cover types. Pond polygons and land cover data were obtained from the City of Ottawa (2011) and manually updated to reflect more current condition using Environmental Systems Research Institute (2015) satellite imagery.

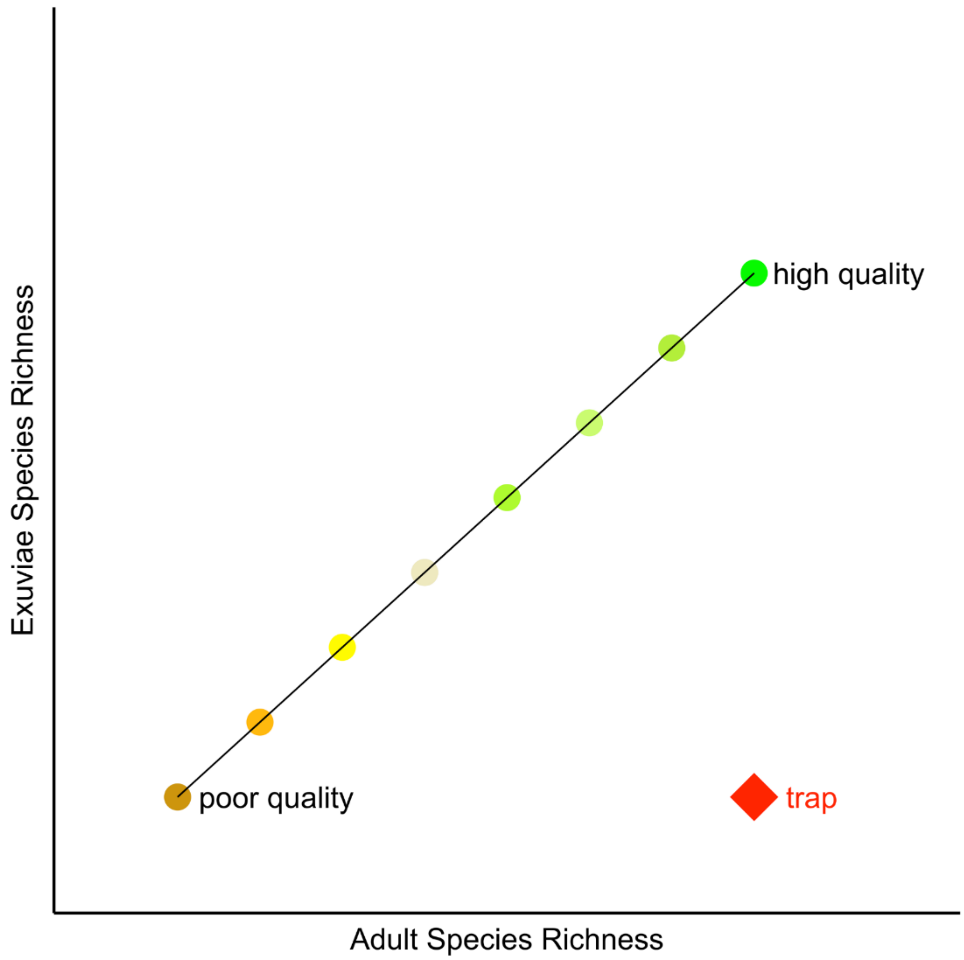

Figure 4.2 Hypothetical variation in quality (or suitability) of ponds as habitat for dragonfly reproduction. A pond (data points) can attract many species of adult dragonflies and support the emergence (i.e. life cycle completion estimated by presence of exuviae) of many species (highly suitable habitat) or a pond can attract few species of adult dragonflies and support the emergence of few species (unsuitable habitat). A trap habitat (i.e. ecological trap) will attract many species of adult dragonflies but support the emergence of few to no species (attractive habitats but unable to provide suitable quality to support life cycle completion).

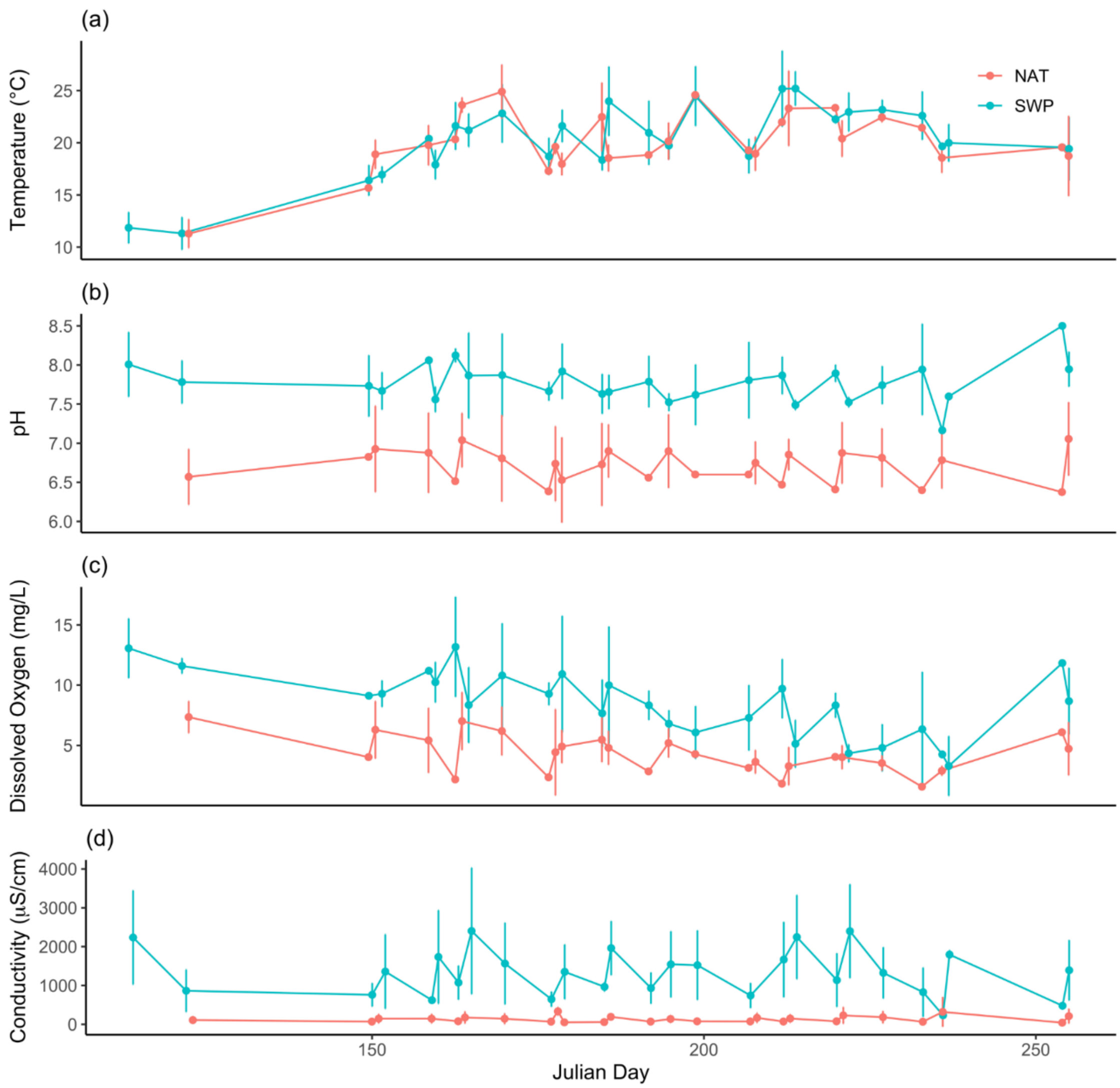

Figure 4.3 Averages and standard deviations of water quality variables measured *in situ* from Julian day 114 (April 24th) to Julian day 255 (September 12th) of 2017 at the natural ponds (NAT in red, n=5) and the stormwater ponds (SWP in blue, n=5) showing temporal trends in (a) water temperature (^{o}C), (b) pH, (c) dissolved oxygen (mg/L), and (d) conductivity (µS/cm).

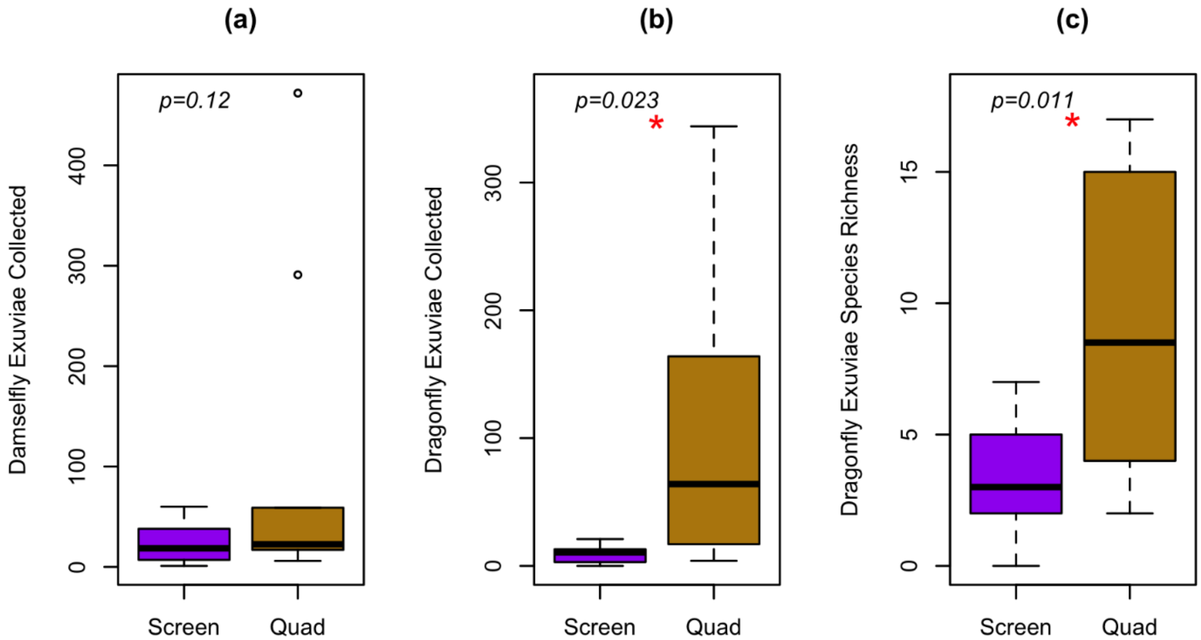

Figure 4.4 The distribution of the number of Odonata exuviae collected from study ponds (n=10) comparing the artificial emergence screen method to the quadrat method of (a) the number of damselfly exuviae collected, (b) the number of dragonfly exuviae collected, and (c) the number of dragonfly exuviae species collected.

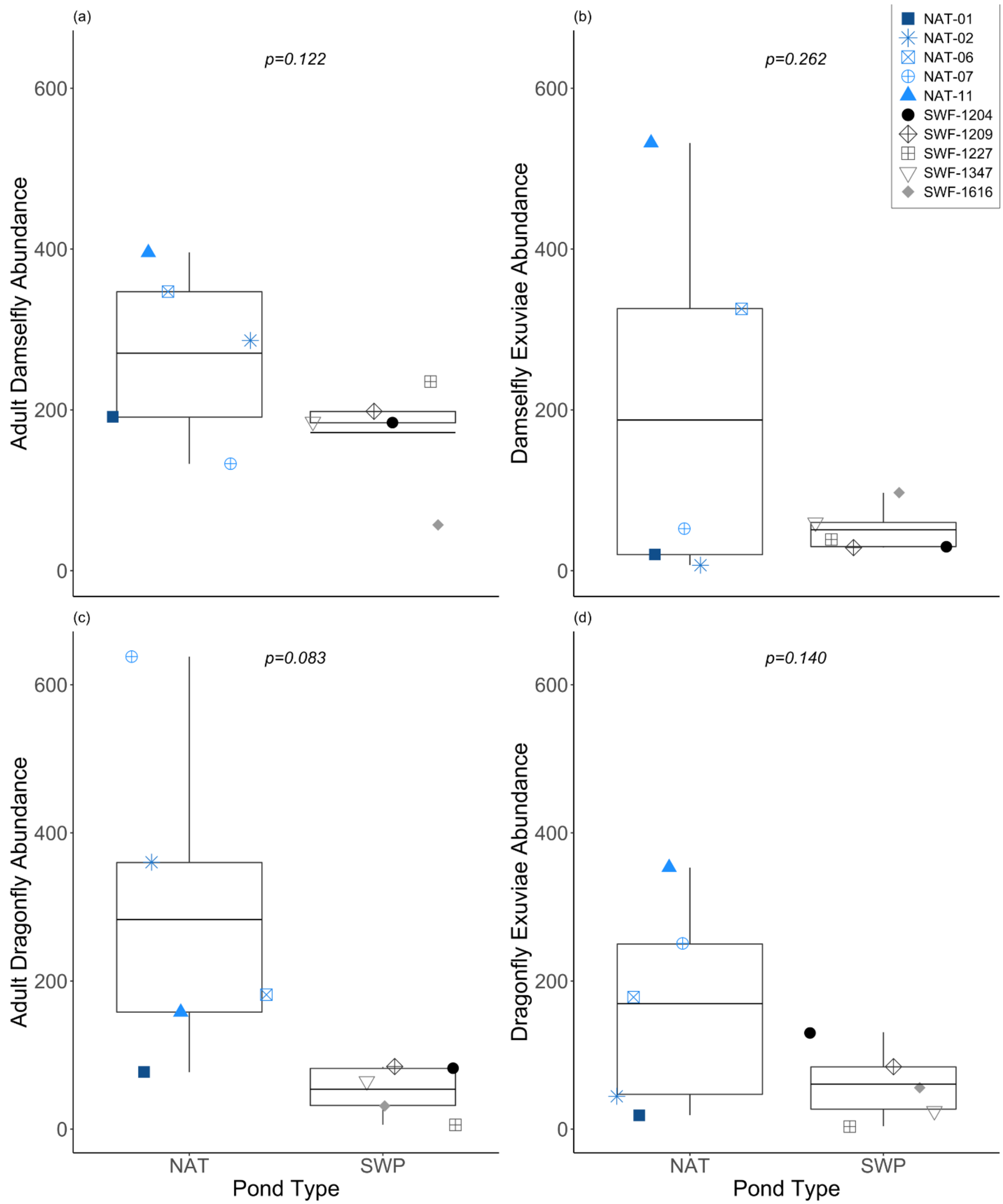

Figure 4.5 Average Odonata abundances at natural ponds (NAT, n=5) and at stormwater ponds (SWP, n=5) for (a) adult damselflies, (b) damselfly exuviae, (c) adult dragonflies, and (d) dragonfly exuviae. Difference in abundances between stormwater ponds and natural ponds with statistics from unpaired t-test. Each pond is represented by a unique marker to show differences between individual ponds.

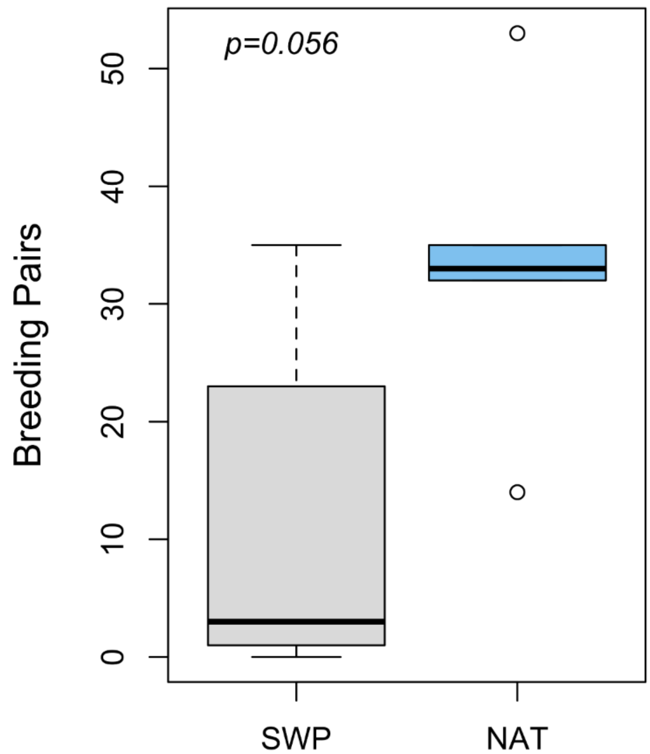

Figure 4.6 Average number of Odonata (both damselfly and dragonfly) breeding pairs observed at the stormwater ponds (SWP, n=5) and the natural ponds (NAT, n=5) with statistics from unpaired t-test.

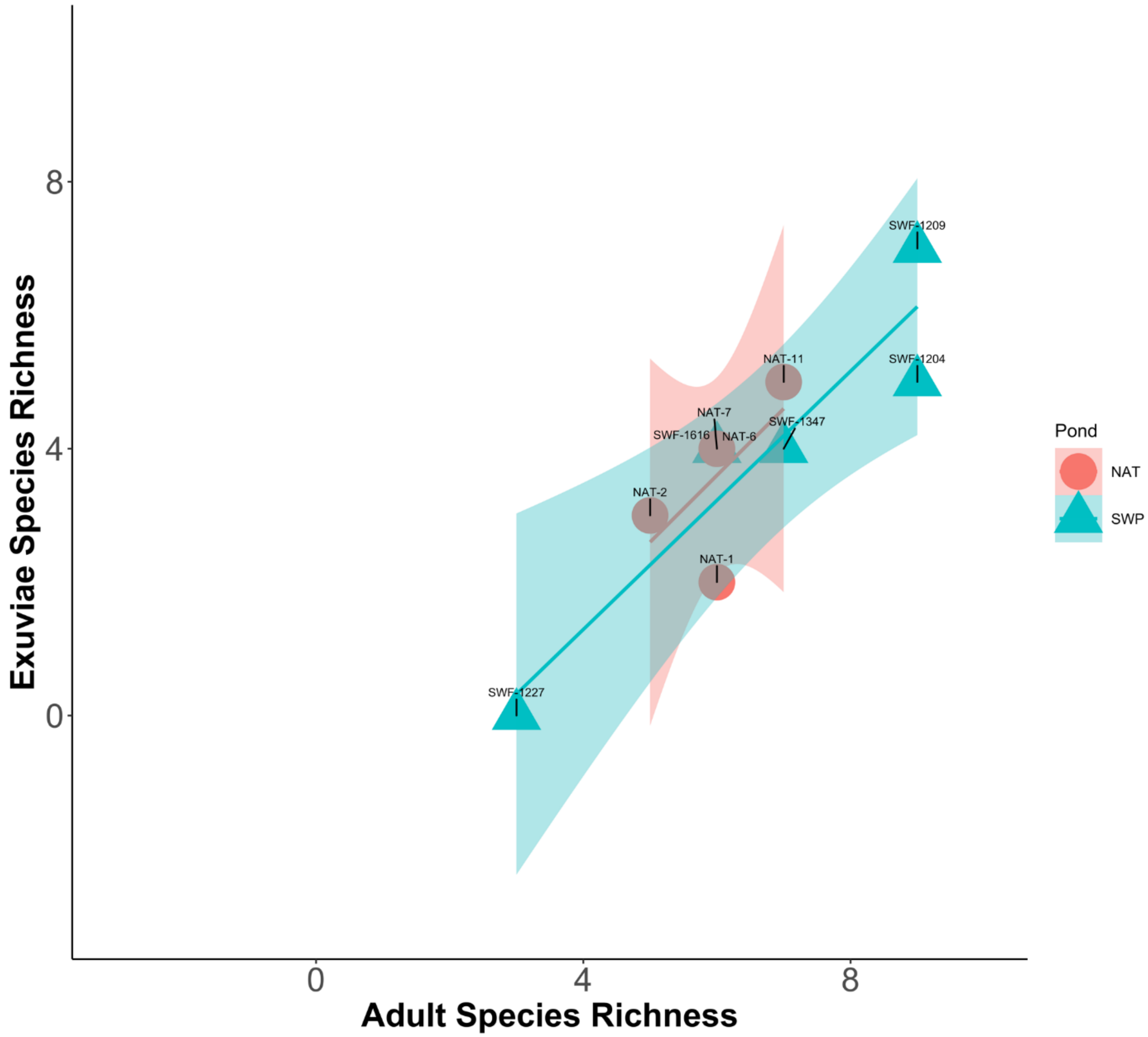

Figure 4.7 The relationship between adult dragonfly species richness and the species richness based on dragonfly exuviae (data were standardized to remove differences in sampling efforts between adults and exuviae) at the natural ponds (n=5, NAT in red circles) and at the stormwater ponds (n=5, SWP in blue triangles) and with their 95% confidence intervals.

Chapter 5: Plants, water and landscape as potential drivers of Odonata assemblages in urban stormwater ponds

5.1 Abstract

Stormwater ponds are built in cities to reduce the risk and severity of flooding; however, these ponds may also provide habitat for wildlife in urban areas. This study sought to determine the relative importance of local-scale factors (pond vegetation and water quality) to larger scale factors (surrounding land cover) in driving community structure of a group of biological indicators of aquatic systems. Odonata (dragonflies and damselflies) at both the adult and nymph life stages were sampled at 41 stormwater ponds and ten natural reference ponds in the National Capital Region of Canada (Ottawa/Gatineau) along with plant communities, pond water quality and surrounding land cover types. Plants consistently explained the largest amount of variation in both dragonfly and damselfly community structure at all life stages (22-40%). Water quality was the second most important driver of Odonata communities with dragonflies showing greater sensitivity to urban contaminants than damselflies. Overall, landscape features associated with the ponds explained little of the variation in Odonata communities, but the presence of adjacent ponds and wetlands had a measurable effect. Local scale habitat features were of relatively higher importance for Odonata community structure when compared to larger scale features. Stormwater ponds can potentially provide habitat for species when designed and managed to promote native wetland plant communities and water quality is maintained.

Keywords partitioning of variation; dragonflies; damselflies; urban ecosystems; land cover; secondary habitat

5.2 Introduction

The number of species on earth has declined since the beginning of the Anthropocene (Dirzo et al. 2014). Habitat destruction and alteration has contributed to the vast majority of biodiversity loss worldwide (McKinney 2006; Grimm et al. 2008). The losses and changes in vertebrate biodiversity are well known. In contrast, there has been less research on invertebrate biodiversity with only about one in ten conservation publications focused on invertebrates (Collen et al. 2012). This is problematic as invertebrates contribute ~80% of the global biodiversity (Scheffers et al. 2012) and their importance to ecosystem functions generally exceeds that of vertebrates (Wilson 1987). Among invertebrates, insects alone contribute 57 billion dollars annually in ecosystem services to the USA (Losey and Vaughan 2006). Additional research is needed to better understand the requirements of invertebrates both for biodiversity conservation as well as the maintenance of ecosystem services.

Freshwater invertebrates, in particular, are facing the highest threats of extinction (Collen et al. 2012). Odonata, including dragonflies and damselflies, are important invertebrates in freshwater systems acting as top predatory insects and prey for birds, amphibians and fish (Morse 1971; Rehfeldt 1990; Šigutová et al. 2015). They are charismatic insects that provide cultural services (i.e. ecotourism, e.g. Lemelin 2007) and regulatory services (i.e. pest control, e.g. Sebastian et al. 1990). Their life history requirements are complex: adults require terrestrial environments whereas juvenile nymphs spend anywhere from several months to several years in the aquatic system (Corbet 1999). Odonata are one of the few groups of invertebrates that have been assessed by the International Union for Conservation of Nature (IUCN). Of the 26% of Odonata species worldwide included in the IUCN report, one in ten species are threatened, an extinction risk that is similar to birds (Clausnitzer et al. 2009). Based on IUCN assessments, the major threats to freshwater invertebrates in general include water pollution (threatening 41% of species) and habitat loss from urban development (threatening 19% of species) (Collen et al. 2012).

The threat of urban development is likely to increase. Over half of the global population now resides in urban areas (United Nations 2011). Cities are considered “ecological deserts” (*sensu* Hassall and Anderson 2015) and support low biodiversity because of lack of natural habitat, fragmentation and pollution (McKinney 2008). The major habitat change in cities is the creation of impervious surfaces, such as pavement and roof tops (Livingston and McCarron 1992). As a result, the hydrological cycle is altered by significant increases in the proportion of surface water runoff, thus creating a greater risk of flooding and erosion in cities (Livingston and McCarron 1992; Paul and Meyer 2001). One solution to this problem has been the construction of stormwater management ponds embedded in urban catchments (Marsalek and Chocat 2002; Scher and Thiéry 2005). While stormwater ponds are engineered for their hydrological services (Schueler 1992), they can attract wildlife such that some ponds can have similar biodiversity to natural ponds (Hassall and Anderson 2015; Perron and Pick 2020). However, stormwater ponds are subjected to urban stresses related to the predominance of non-native and invasive plants (McKinney 2004), water pollution (Frost et al. 2015) and surrounding land use (Goertzen and Suhling 2013) which collectively may simplify and homogenize biological communities (McKinney 2006).

With global declines in biodiversity, there is a pressing need to determine what habitat and landscape elements are required to support species even in secondary habitats such as cities (e.g. Lepczyk et al. 2017). This entails a full understanding of natural history requirements of species in order to determine whether a system can provide for all or only a restricted number of life stages. The objective of this study was to determine the relative importance of local-scale factors (of pond vegetation and water quality) to larger scale factors (of surrounding land cover) in determining adult and nymph Odonata community structure at urban stormwater ponds. First, I hypothesized that damselflies rely more on specific plant communities than dragonflies, given the differences in their modes of oviposition (endophytic vs. exophytic) (Westfall and May 1996; Corbet 1999). I predicted that there would be greater statistical associations between metrics of plant community structure and species composition of damselflies in comparison to dragonflies. I also hypothesized that dragonflies are influenced by the surrounding landscape to a greater extent that damselflies because of their wider dispersal abilities (Purse et al. 2003; Dolný et al. 2014) and predicted stronger associations between dragonfly community structure and land cover. I hypothesized that the relative importance of water quality, plant composition and landscape differ between Odonata life stages, given their biphasic lifecycle (aquatic and terrestrial life stages). I predicted that adults will be more influenced by plants, as adults are terrestrial and depend on plants for thermoregulation, oviposition, habitat selection and as perches (Corbet 1999); adults would be more influenced by landscape features, as this is their dispersal stage. In contrast, I predicted that nymphs would be more influenced by water quality as they spend several months to several years living in the aquatic environment. The overall goal of this study was to improve our understanding of the habitat elements that might help support biodiversity in cities.

5.3 Materials and methods

5.3.1 Site selection

Stormwater ponds (n=41, Fig. 5.1) were selected from the National Capital Region of Canada (NCRC) for a similar size (~1 ha) and a permanent body of water. Natural ponds (n=10, Fig. 5.1) were also selected from the NCRC to widen the gradient of environmental variables examined. Natural ponds followed the same selection criterion but had little to no impervious cover in the catchment basin (<0.04%) and were not man-made. All selected ponds were located at least one kilometer away from any lakes and/or rivers, as close proximity to these ecosystems may cause population overlap of lacustrine and riverine Odonata species (Dolný et al. 2014).

The stormwater ponds were located in residential (n=31) or commercial areas (n=9). One pond was located adjacent to a highway. Pond age ranged from one to 36 years post-construction. All ponds were sampled in 2015; an additional three stormwater ponds and five natural ponds were sampled in 2016 to widen the range of stormwater pond age and increase the sample size of natural ponds.

5.3.2 Odonata sampling

5.3.2.1 Adult sampling

Ponds were sampled twice for adult odonates, once in spring/early summer and once in late-summer to maximize the chances of encountering all early and late flying species (Oertli et al. 2005; Bracken and Lewis 2008). A 60-minute visual survey was conducted at each pond for both visits following methods from Perron and Pick (2020). If an individual could not be identified by eye, the individual was caught with an entomological sweep net and the time was stopped until the individual could be successfully identified using a hand lens and field guide (Jones et al. 2013).

5.3.2.2 Nymph sampling

Ponds were sampled once for nymphs in the spring (month of May), prior to emergence. The perimeter of each pond was divided into ten equal sections and within each section a random location along the littoral zone was selected for nymph sampling. Nymphs were collected using a framed net with a "Z-swipe" which accounted for individuals dwelling at the surface, the middle and the bottom of the pond (Hutchinson and Ménard 2016). Dragonfly and damselfly nymphs were then separated and preserved in 70% ethanol for subsequent identification. Dragonflies and damselflies were identified to genus using Hutchinson and Ménard (2016) and dragonflies were further identified to species using Walker (1958) and Walker and Corbet (1978). Nymphs could not be sampled at one natural pond, so sample size of reference ponds was reduced from ten to nine in the nymph analyses. Damselflies were not identified at three ponds due to the evaporation of ethanol from those samples, which made accurate identifications impossible. Only abundance was recorded for those samples.

5.3.3 Environmental variables

5.3.3.1 Plant communities

Plant communities were surveyed in spring/early summer along three interrupted belt transects perpendicular to the water's edge at each pond (encompassing submerged aquatics through to bank vegetation) following methods from Perron and Pick (2020). Four quadrats were randomly selected within each transect, plants were identified to species and their percent cover estimated. These same transects were re-sampled in late summer to verify the detection of all early and late flowering species (total of 24 quadrats per pond) (Dalton et al. 2015). Plants that were difficult to identify (e.g. graminoid species), were brought back to the lab and keyed out using Dore and McNeill (1980), Marie-Victorin et al. (2002), Barkworth et al. (2007) and Voss and Reznicek (2012). Plant habitat type was determined following Oldham et al. (1995). Obligate wetland plants have a 99% probability of being found in wetlands (i.e. hydric soils), facultative wetland plants a 67-99% probability of occurring in wetlands, facultative upland plants a 1-33% probability of occurring in wetlands and upland plants have less than a 1% chance of being found in wetlands (Oldham et al. 1995). Plant functional guilds (e.g. narrow-leaved emergent, floating, submerged, etc.) were assigned to each species based on adaptations from Golet (1976).

5.3.3.2 Water quality

Temperature, dissolved oxygen, pH and conductivity were measured *in situ* at the pond outlet (measurements taken every 0.5 m based on pond depth) several times throughout the field season with a HydroLab Mini Sonde.

Two surface water samples were also taken at the outlet of each pond (once in late spring/early fall, once in late summer) for water chemistry and planktonic chlorophyll *a* analyses. Water samples were taken at least two days after any precipitation to reduce the possibility of sampling ponds at peak levels. Nalgene bottles (1 L) were rinsed with pond water

(3 times) before sample was taken. Once the water sample was taken, it was moved to a cooler to transport back to the laboratory for processing. Water samples were mixed (~7 times) and subsampled for subsequent nutrient (reactive phosphate (RP), total phosphorus (TP) total Kjeldhal nitrogen (TKN), total nitrogen (TN), nitrate (NO_3^-)), metal (a full ICP scan [Ag, Al, As, B, Ba, Be, Bi, Cd, Cu, Cr, Co, Cu, Fe, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Th, Ti, V, W, Zn and Zr] and chloride ion (Cl^-) analyses. Water chemistry analyses were conducted at the Robert O. Pickard Environmental Centre of the City of Ottawa, a certified laboratory, following standard protocols for the analysis of surface waters (Standard Methods 2004; Ontario Ministry of Natural Resources 2007; Ontario Ministry of the Environment 2017). Chlorophyll *a* concentrations were measured from a subsample (500 ml) of each water sample following Jespersen and Christoffersen (1987).

5.3.3.3 Landscape features

Landscape features were analyzed in ArcMap version 10.5.1. Pond polygons were obtained from the City of Ottawa (2014); land cover data were obtained from the City of Ottawa (2011, 2014) and the Government of Canada (2000) (data file name: Canadian Landcover Circa Geobase series 2000). The land cover layer provided by the City of Ottawa is based upon 2011 aerial photography and LiDAR data collected from 2014. The land cover data provided by the Government of Canada was produced via the vectorization of raster thematic data from orthoimages. As the study was conducted in 2015, pond polygons and land cover data were manually updated using the Environmental Systems Research Institute (2015) World Imagery Satellite Base Map to reflect updated conditions in instances of new development surrounding the ponds. Land cover types were as follows: crop/pasture, grassland (e.g. fields), rock barren (exposed rock outcrops), sand/gravel (e.g. unpaved sand pits), settlement (any type of human development/infrastructure), transportation (roads), wetlands, other stormwater ponds, golf course ponds, water (rivers and lakes) and wooded area. Different landscape scales were tested for significance to determine if there was a scale-effect on the Odonata communities. In ArcMap, buffers were created around the perimeter of each pond at five different scales (100 m, 500 m, 1 km, 2 km and 5 km) using the "Buffer" tool (Analysis Toolbox). The "Intersect" tool (Analysis Toolbox) was then used to retrieve the land cover within each buffer. The "Dissolve" tool (Data Management Toolbox) was used to retrieve the percent of land cover types in each buffer for all ponds. The most significant scales were determined for: (i) adult dragonfly species composition, (ii) dragonfly nymph species composition, (iii) adult damselfly species composition and (iv) damselfly nymph genera composition.

5.3.4 Statistical analyses

The frequency of plant species occurrences was determined by dividing the number of ponds that a plant species was present at by the total number of ponds sampled. Averages of water quality variables were calculated for each pond. Odonata (family-level) average abundances with standard errors were plotted with grouped bar plots, using the *graphics* package (R Core Team 2017), to visualize the differences in adult and nymph abundance between the two pond types. Pearson's correlation and linear regression were used to test the relationship between Odonata nymph abundance (square root transformed to meet the assumptions of normality) and the species richness of obligate wetland plants at stormwater ponds with the *stats* package (R Core Team 2017).

For ordination analyses, rare species were removed to eliminate undo weighting in ordination space. These represented five rare adult Odonata species (with a single individual observed at a single site). The plant species matrix was reduced to the 50 most dominant species (found at five or more ponds and with over 6% of average cover) and the water quality variables that were below detection limit in >80% of samples were removed from the water quality data matrix.

Odonata community data were checked for spatial autocorrelation by analyzing Odonata community matrices against coordinates of ponds (in the *vegan* package, Oksanen et al. 2019). Spatial autocorrelation was not present in dragonfly nymph communities ($F=1.20$, $p=0.22$), adult damselfly communities ($F=1.61$, $p=0.09$) or damselfly nymph communities ($F=0.85$, $p=0.54$) but was present in adult dragonfly communities ($F=1.96$, $p=0.008$). As spatial autocorrelation was present in the adult dragonfly community matrix, spatial trends were analyzed with distance-based Moran's eigenvector map analysis (db-MEMs) (Legendre et al. 2012) using the *adespatial* package (Dray et al. 2017). However, as there were no significant MEM models, spatial trends were not included in variation partitioning models. Thus, for ordination analyses, spatial autocorrelation was removed from the adult dragonfly community matrix by eliminating any broad scale spatial trends to examine finer relationships between adult dragonflies and environmental variables (by regressing the adult dragonfly matrix against the pond coordinates and using the residual matrix for further analyses) using the *stats* package.

To determine the most significant spatial scales for dragonfly and damselfly community structure at both life stages, each scale (100 m, 500 m, 1 km, 2 km and 5 km) was tested for goodness of fit (adjusted R^2) against the four matrices: (i) detrended adult dragonfly species composition, (ii) dragonfly nymph species composition, (iii) adult damselfly species composition and (iv) damselfly nymph genera composition. Transformation-based redundancy analyses (tb-RDA) with a Hellinger transformation (to down weight the presence of zeros in the data set) (Legendre and Andersson 1999; Legendre and Gallagher 2001), with the *vegan* package, were used to analyze associations between the Odonata community matrix and the different buffer scales of surrounding land cover types (e.g. adult dragonfly community structure against land cover in a 100 m buffer around ponds). The significant land cover types ($p<0.05$) were selected using forward stepwise regression (with 9,999 permutations) to create an RDA model with only the significant land cover types and the goodness of fit (adjusted R^2 value). The RDA model and RDA axes were tested for significance ($p<0.05$). This procedure was repeated for each different scale against each of the four Odonata matrices; the scale, for each Odonata matrix, with the highest adjusted R^2 was retained for the final variation partitioning models.

The explanatory environmental features (related to plants, water quality and landscape) of Odonata community structure were examined using unbiased variation partitioning based on tb-RDA (with Hellinger transformation) with adjusted R^2 (Peres-Neto et al. 2006) with the *vegan* package. In total four different models were developed to identify the potential drivers of: (i) detrended adult dragonfly species composition, (ii) dragonfly nymph species composition, (iii) adult damselfly species composition and (iv) damselfly nymph genera composition, using three explanatory matrices: (a) plants, (b) water quality and (c) landscape (at the most significant scale of land cover surrounding the ponds). The environmental data were transformed (plant and landscape were square rooted, water quality data were scaled and centred to account for differences in measurement units). As a first step, to produce the most parsimonious tb-RDA models for each explanatory matrix (plants, water, landscape), only the environmental variables that were significant ($p<0.05$) in explaining Odonata community structure of each matrix (i-iv) (determined through forward stepwise regression with 9,999 permutations) were retained for final variation partitioning models. The variation partitioning analyses then calculated the contribution of plants, water quality and landscape in explaining each of the four Odonata community matrices (adult dragonflies, dragonfly nymphs, adult damselflies and damselfly nymphs). Variation partitioning calculated different fractions that represent the amount of variation in Odonata communities that can be explained by each individual environmental matrix alone (whether plants, water or landscape) as well as the shared variation among the matrices. Variation partitioning models and all testable fractions were analyzed for significance (p<0.05). All statistical analyses were conducted in R and RStudio version 0.99.902, 3.4.2 and 1.1.456.

5.4 Results

5.4.1 Odonata communities: adults versus nymphs

A total of 13,579 adult Odonata were identified and enumerated; 2,249 Odonata nymphs were collected and identified. There were 3,636 adults and 728 nymphs belonging to the Anisoptera (dragonfly) suborder. At the stormwater ponds, there were a total of 31 adult dragonfly species recorded with an average of 7 per pond (range 1-12) and a total of 18 dragonfly nymph species recorded with an average of 3 per pond (range 0-7). At the natural ponds, there were 21 adult dragonfly species recorded with an average of 10 per pond (range 4-11) and 13 dragonfly nymph species recorded with an average of 6 per pond (range 1-9).

There were 9,943 adults and 1,521 nymphs belonging to the Zygoptera (damselfly) suborder. At the stormwater ponds, there were 19 adult damselfly species recorded with an average of 7 per pond (range 2-11) and four genera of damselfly nymphs. At the natural ponds, there were 16 adult damselfly species recorded with an average of 5 per pond (range 3-7); the same four genera of damselfly nymphs that were present at the stormwater ponds were also present at the natural ponds.

Odonata represented seven major families (Fig. 5.2), four belonging to the suborder Anisoptera (Fig. 5.2a-d) and three belonging to the suborder Zygoptera (Fig. 5.2e-g). There were, on average, fewer adults and nymphs from the families Aeshnidae (Fig. 5.2a), Corduliidae (Fig. 5.2c), Libellulidae (Fig. 5.2d) and Lestidae (Fig. 5.2f) at the stormwater ponds compared to the natural ponds, with the differences in the average abundances of Libellulidae and Lestidae between pond types being the most evident. Stormwater ponds had similar abundances of Coenagrionidae adults and nymphs as the natural ponds (Fig. 5.2g), with slightly higher abundances of adults at the stormwater ponds. Gomphidae (Fig. 5.2b) and Calopterygidae (Fig. 5.2e) were extremely rare at all ponds, with just a few individuals recorded; Calopterygidae was only recorded at the adult stage.

5.4.2 Environmental variables

5.4.2.1 Plant Communities

Odonata communities were strongly associated with 27 plant species (Table 5.1). Adult dragonfly communities were specifically associated with six wetland plant species (one free-floating, two narrow-leaved emergent, three ground cover herbaceous) and three upland herbaceous species (Table 5.1). At the nymph stage, dragonflies were associated with six wetland plant species (one submerged, one floating, one narrow-leaved emergent, one robust emergent, two ground cover herbaceous) and three upland herbaceous species (Table 5.1). There were several species of dragonfly nymphs that were more closely associated with ponds containing a high proportion of wetland plants: the frosted whiteface (*Leucorrhinia frigida*), the autumn meadowhawk (*Sympetrum vicinum*), the American emerald (*Cordulia shurtlefii*), the racket-tailed emerald (*Dorocordulia libera*) and the chalk-fronted corporal (*Ladona julia*) were associated with ponds dominated by the three-way sedge (*Dulichium arundinaceum*) (Fig. S5.1). The white-faced meadowhawk (*Sympetrum obstrusum*), the Canada darner (*Aeshna canadensis*) and the horned clubtail (*Arigomphus cornutus*) were associated with ponds dominated by waterlilies (*Nymphaea odorata*) (Fig. S5.1). The green darner (*Anax junius)* was characteristic of ponds with cattails (*Typha angustifolia*) and pondweeds (*Stuckenia pectinata*) (Fig. S5.1). In contrast, the dot-tailed whiteface (*Leucorrhinia intacta*), the eastern pondhawk (*Erythemis simplicicollis*) and the twelve-spotted skimmer (*Libellula pulchella*) were more closely associated to ponds that had a high proportion of upland plants (Fig. S5.1).

Adult damselfly communities were specifically associated with seven wetland plant species (two narrow-leaved emergent, one robust emergent, three ground cover herbaceous, one tall shrub), four upland herbaceous species and one upland deciduous tree (Table 5.1). At the nymph stage, damselflies were associated with seven wetland plant species (one submerged, two robust emergent, three ground cover herbaceous, one deciduous tree) and two upland herbaceous species (Table 5.1). All damselfly nymph genera were associated with ponds containing wetland plants with the exception of nymphs from the genus *Lestes* not typically found in ponds with a high proportion of cattails (*Typha angustifolia*) (Fig. S5.2).

Adult dragonfly communities were not associated with the same plant species as their nymph communities (Table 5.1). In contrast, adult and nymph damselfly communities were both associated with the same three wetland plants: broadleaf arrowhead (*Sagittaria latifolia)*, swamp candle (*Lysimachia terrestris*) and fragrant bedstraw (*Galium triflorum*) (Table 5.1). Both adult dragonflies and damselflies were significantly associated with ponds containing the same five plant species: softstem bulrush (*Schoenoplectus tabernaemontani)*, swamp candle (*Lysmichia terrestris*), panicled aster (*Symphyotrichum lanceolatum*), Canada goldenrod (*Solidago canadensis*) and white sweetclover (*Melilotus alba*) (Table 5.1). Both dragonfly and damselfly nymphs were significantly associated with ponds containing the same four plant species: sago pondweed (*Stuckenia pectinata*), narrowleaf cattail (*Typha angustifolia*), fragrant bedstraw (*Galium triflorum*) and Canada thistle (*Cirsium arvense*) (Table 5.1). Total Odonata nymph abundance had a strong positive relationship with the species richness of obligate wetland plants at stormwater ponds (Fig. S5.3, R^2=0.373, p<0.001).

5.4.2.2 Water Quality

Adult dragonfly communities were related to five water quality variables: pH, B, Cr, Pb and TP (Table 5.2). Dragonfly nymph communities were related to seven variables: pH, conductivity, As, Ba, Zn, TP and chlorophyll *a* (Table 5.2). Adult damselfly communities were related to seven variables: pH, Mo, Ni, Se, Ti, NO_3^- and TN (Table 5.2). Damselfly nymph communities were related to three variables: Ti, TN and chlorophyll *a* (Table 5.2). Many of the metals/metalloids were highly correlated to one another (Fig. S5.4).

5.4.2.3 Landscape Features

Dragonfly adult (R^2_{adj}=0.125) and nymph (R^2_{adj}=0.125) communities were most significantly associated with land cover in a 2 km radius surrounding the study ponds (Table

S5.1, Table S5.2). Adult damselfly communities were most significantly associated with land cover at a smaller scale of a 500 m radius (Table S5.3, R^2_{adj}=0.188), whereas damselfly nymph communities were most significantly associated with land cover in a much larger scale of 5 km (Table S5.4, R^2_{adj}=0.076).

At the 500 m scale, the stormwater ponds were generally surrounded by a high proportion of settlement, whereas the natural ponds were surrounded by a high proportion of wooded area, wetland and rock barren (Fig. 5.3a). At the 2 km scale, the stormwater ponds were surrounded by a high proportion of settlement and crop/pasture, whereas the natural ponds were surrounded by a high proportion of wooded area and wetlands (Fig. 5.3b). At the 5 km scale, the stormwater ponds were generally surrounded by a high proportion of settlement, crop/pasture, and wooded area, whereas the natural ponds were surrounded by a high proportion of wooded area and crop/pasture (Fig. 5.3c).

Adult dragonfly community structure was significantly associated with surrounding wetlands, rock barren and wooded area at the 2 km scale (Table 5.3), whereas nymph community structure was significantly associated with surrounding transportation, settlement, golf course ponds and rock barren at the 2 km scale (Table 5.3). Adult damselfly community structure was significantly associated with surrounding stormwater ponds, rock barren and wooded area at the 500 m scale (Table 5.3), whereas nymph community structure was significantly associated with surrounding wetlands at the 5 km scale (Table 5.3).

5.4.3 Variation Partitioning

5.4.3.1 Dragonflies (Anisoptera)

Plants, water quality and landscape features contributed in total to 37.7% of the variation in adult dragonfly species composition (Fig. 5.4, F=2.78, $p<0.001$) and a similar amount of the variation (37.6%) in dragonfly nymph species composition (Fig. 5.5, F=2.56, $p<0.001$). Plant communities were the most dominant driver of dragonfly community structure, explaining 25.9% of the variation in adult dragonfly communities (Fig. 5.4) and 22.2% of the variation in dragonfly nymph communities (Fig. 5.5) across all shared fractions (12.4% of adult dragonfly communities and 11.2% of dragonfly nymph communities were explained exclusively by plants). Water quality was the second most important driver of dragonfly community structure, alone explaining 10.4% of the variation in adult dragonfly communities (Fig. 5.4) and 11.4% of the variation in dragonfly nymph communities (Fig. 5.5). Landscape features alone explained little variation in dragonfly community structure, explaining only 2.9% of the variation in adult dragonfly communities (Fig. 5.4) and 5.4% of the variation in dragonfly nymph communities (Fig. 5.5). Landscape features shared a small contribution with plant communities and together explained 5.7% of the variation in adult dragonfly communities (Fig. 5.4) and 1.7% of the variation in dragonfly nymph communities (Fig. 5.5). The shared contribution of plants, water and landscape together explained 4% of the variation in adult dragonfly communities (Fig. 5.4) and 6.8% of the variation in dragonfly nymph communities (Fig. 5.5).

5.4.3.2 Damselflies (Zygoptera)

Plants, water quality and landscape features contributed to 51.7% of the variation in adult damselfly species composition (Fig. 5.6, F=3.44, $p<0.001$) and 42.6% of the variation in damselfly nymph genera composition (Fig 5.7, F=3.62, $p<0.001$). As found for the dragonfly communities, plants explained the most variation in damselfly community structure, explaining 40.4% of the variation in adult damselfly communities (Fig. 5.6) and 38.6% of the variation in damselfly nymph communities (Fig. 5.7) across all shared fractions (13.9% of adult damselfly communities and 19.2% of damselfly nymph communities were explained exclusively by plants). Plants and water together explained 12.8% of the variation in adult damselfly communities (Fig. 5.6) and 11.8% of the variation in damselfly nymph communities (Fig. 5.7). Water quality alone explained a small proportion of the variation in damselfly community structure, explaining 6.2% of the variation in adult damselfly communities (Fig. 5.6) and 4% of the variation in damselfly nymph communities (Fig. 5.7). Landscape features alone explained even less variation in damselfly community structure of adults (2.4%) (Fig. 5.6) and nymphs (0.4%) (Fig. 5.7). Water quality and landscape shared a small contribution in explaining the variation in adult damselfly communities (2.8%) (Fig. 5.6); plants and landscape also shared a small contribution in explaining adult damselfly communities (1.6%) (Fig. 5.6) and damselfly nymph communities (4.7%) (Fig. 5.7). The shared contribution of plants, water and landscape together explained 12.1% of the variation in adult damselfly communities (Fig. 5.6) and 2.9% of the variation in damselfly nymph communities (Fig. 5.7).

5.5 Discussion

Plants, water and landscape features all had significant effects on dragonfly and damselfly community structure at both the adult and nymph life stage at the ponds. However, there were differences in the relative importance of the three main features between dragonflies and damselflies and between adults and nymphs.

5.5.1 Plants, water and landscape as potential drivers of Odonata community structure

Wetland plants were most strongly associated with Odonata community structure and, perhaps somewhat surprisingly, the most important driver at all life stages. Adult dragonflies were related to a variety of different plant guilds (i.e. free-floating, narrow-leaved emergent and herbaceous); adult damselflies were related to similar guilds but also related to deciduous trees and shrubs (Table 5.1) that provide canopy (shade). Adult dragonflies are not likely utilizing shaded areas (Remsburg et al. 2008). In contrast, damselflies, that are smaller bodied perchers, often require shaded/sunflecked microhabitats as they lack the thermoregulatory abilities of larger bodied dragonflies (May 1978; McKay and Herman 2008). In addition, adult Odonata require plants as cues for habitat selection (Samways and Steytler 1996; Ward and Mill 2005), for oviposition (Sawchyn and Gillott 1974; Westfall and May 1996) and as perches (Rouquette and Thompson 2005; Hykel et al. 2020). Pond plant communities were also highly important for the aquatic stages of Odonata. As nymphs, both dragonflies and damselflies were associated with ponds that supported diverse wetland plant species including submerged, floating and emergent plants (Table 5.1). Not only did plants influence the community structure of nymphs, but also had a strong association with total nymph abundance (Fig S5.3). Stormwater ponds that had diverse wetland plant communities supported large populations of nymphs. The presence of aquatic plants affects predator-prey relations (Thompson 1987; Remsburg and Turner 2009). Plants are also linked to Odonata egg hatching success, as eggs that are laid endophytically depend on plant tissues for protection (Fincke 1986; Bennett and Mill 1995).

Water quality (more specifically nutrients, pH, trace metals/metalloids and conductivity) was significantly associated with Odonata community structure (Table 5.2). Nutrients were associated with dragonfly and damselfly communities and are likely reflecting the overall productivity of the ponds (Keddy 2010). Higher nutrients would lead to more abundant resources in terms of more vegetation and more prey (mosquitoes and other flying dipterans) (Leisnham et al. 2004; Keddy 2010). Previous studies have also found that pH is correlated with Odonata species composition in ponds (Le Viol et al. 2009; Honkanen et al. 2011); the effect of pH may also be indirect through its influence on metal bioavailability (Starodub et al. 1987). Stormwater ponds generally have higher trace metals/metalloids than natural ponds within a same region (Frost et al. 2015). Tolerance towards metals is quite variable among Odonata species, but metals can have sub-lethal and lethal toxicological effects on aquatic invertebrates (Tollett et al. 2009). Pond water conductivity was also a significant predictor of dragonfly community structure. Conductivity affects the osmoregulation and development of Odonata nymphs (Wichard and Komnick 1974; Kefford et al. 2006). However, conductivity did not affect damselflies in the present study, suggesting that damselflies may have increased tolerances. In temperate regions, stormwater ponds typically have significantly higher conductivity than natural waters due to increased inputs of road salt from winter road maintenance (Hassall and Anderson 2015). Water salinity can be a predictor of the distribution of dragonfly species among freshwater habitats as shown by Cannings and Cannings (1987).

Landscape was also significantly related to adult dragonfly and damselfly communities, but at different scales. As adults, dragonflies responded to land cover at a larger scale (1 and 2 km) around ponds (Table S5.1) whereas damselflies were mostly influenced by landcover at much smaller scales (100 m and 500 m) (Table S5.3). The larger scale of effect recorded for adult dragonflies likely reflects their greater dispersal abilities. Mark-release and recapture studies have shown that dragonflies regularly displace over 1 km around breeding sites (Dolný et al. 2014) whereas damselflies rarely displace more than 500 m, with regular movements between 50-300 m around habitats (Purse et al. 2003). The land cover types of wooded areas and rock barren (exposed rock outcrop) were significant for both dragonfly and damselfly communities (Table 5.3). Wooded areas can be important to Odonata as foraging grounds and for roosting (Cordero Rivera 2006). Rocks are important perching sites and aid in the insects' thermoregulation (McGeoch and Samways 1991; Osborn and Samways 1996). In addition to wooded areas and rock barren, both dragonfly and damselfly communities were associated with the presence of adjacent lentic habitats (other stormwater ponds, golf course ponds or wetlands) (Table 5.3). These results could be indicative of Odonata metapopulations in urban areas and the importance of pond networks for population dynamics. There has been documentation of a threatened species of dragonfly in the Czech Republic (*Leucorrhinia pectoralis*) forming metapopulations in highly fragmented habitats of mining ponds (Harabiš and Dolný 2012).

5.5.2 Local-scale versus large-scale contributions to Odonata community structure

The relative importance of the three factors varied across the two suborders and the different life stages. I predicted that adult damselflies would be mostly associated with plants, adult dragonflies would be associated with landscape features and damselfly and dragonfly nymphs would be mostly associated with water quality. The results did not entirely support these predictions as plant communities consistently explained the highest variation in Odonata community structure, regardless of the suborder or life stage, with water quality being of second importance and landscape features being of little importance (<5%) (Fig. 5.4-5.7).

As predicted, plants explained a higher proportion of the variation in adult damselfly communities compared to dragonfly communities (Fig. 5.4, Fig. 5.6). All damselflies are obligate endophytes, which means they lay their eggs directly inside plant tissue (Westfall and

May 1996). In contrast, most dragonflies (apart from the family Aeshnidae) are exophytes, laying their eggs freely into the environment and thus are inherently less dependent on plants for reproduction (Corbet 1999). The greater importance of plants to damselfly communities is likely a reflection of egg hatching success and oviposition site selection. Egg hatching success relies on the physical properties of plants and if plant stems have suitable features for both protection and hatching (Bennett and Mill 1995; Purse and Thompson 2009). Perron and Pick (2020) found that ponds with a high species richness of obligate wetland plants had higher abundances of adult Odonata. Odonata as adults use plant communities as visual cues for habitat selection (Wildermuth 1992). Plants also offer shelter and roosting sites and individuals have been shown to select plants based on their morphological characteristics to increase their protection from predators (O'Farrell 1971; Rouquette and Thompson 2005). Plants are also important perching sites for adults and the presence of suitable perches can affect community structure (May 1976; Hykel et al. 2020).

Contrary to the prediction that water quality would be the most important driver for nymphs, plants also explained the most variation in nymph community structure. Damselfly nymphs, in particular, were more closely related to the plant communities than dragonfly nymphs were. This again is likely a reflection of the adult oviposition mode as damselfly eggs hatch out of plant tissues (Westfall and May 1996; Corbet 1999). Plants, for both damselfly and dragonfly nymph communities, are important for creating structural complexity in the aquatic environment (Remsburg and Turner 2009). The presence of macrophytes may influence Odonata nymph community composition. Nymphs that mainly burrow into the sediments, such as the dragonfly genus *Arigomphus*, are less likely to be affected by plant communities whereas nymphs that are known to clasp to aquatic vegetation, such as the dragonfly genus *Celithemis*, likely rely more on the presence of plants (Remsburg and Turner 2009). In addition, the presence of macrophytes decreases the rate of Odonata nymph predation by offering refuge (Baker and Dixon 1986; Thompson 1987). Emergent vegetation is also critical as nymphs require a vertical substrate to successfully emerge into their adult phase (Corbet 1999; Bried et al. 2018).

Water quality alone did explain some of the variation in Odonata nymph communities, particularly for dragonfly nymphs suggesting a greater sensitivity of dragonflies to water quality than damselflies. This is in contrast to studies from more tropical lotic waters that show increased sensitivity of damselflies to habitat degradation and disturbances (Monteiro Júnior et al. 2015; Miguel et al. 2017). In North America, it is suspected that the majority of dragonfly species require a minimum of two years in the nymph stage until they are ready to emerge into adults (Tennessen 2019). Damselflies have a shorter duration of nymph development, most likely ranging from a few months to over a year (Walker 1953). The results from this study suggest a response of dragonfly nymph communities to increased pond water conductivity. In the present ponds, specific damselfly taxa appeared quite tolerant of high conductivity; the eastern forktail (*Ischnura verticalis*) was the dominant species at most of the stormwater ponds. A previous study showed that this same species can maintain large populations, even under conditions of poor water quality (Hart and Fuller 1974).

As adult dragonflies have a larger home range, I predicted that they would be more influenced by landscape features than damselflies; however, landscape explained much less variation in both adult dragonfly and damselfly communities compared to water quality and plants. There was some shared contribution between plant communities and landscape features, perhaps suggesting that landscape might have a small influence in determining the plants present at ponds. Land use practices can affect the abundance and distribution of wetland plant propagules (Houlahan et al. 2006).

On average, 58% of the variation in Odonata community structure was unaccounted for in the models and this could be due to sampling error and/or could be caused by other biotic (e.g. predator-prey relations) and/or abiotic (e.g. climate, water fluctuations) factors that were not included in the present study. Predation from fish was not quantified, fish/minnows were recorded at all ponds and could have been important in suppressing nymph abundance (Šigutová et al. 2015). Changes in water levels were also not considered; stormwater ponds are known to have rapid increases in their water levels and frequent fluctuations as a function of precipitation or snow melt events (Shaw et al. 1997). However, some of this hydrological variability may have been captured through the analysis of land cover type as a greater proportion of roads would lead to greater fluctuations in water levels (Schueler 1992; Brabec et al. 2002). Another factor that I was unable to account for in this dataset was the influence of previous life stages on the present communities. One would expect that adult odonates would be predictive of the nymph communities present at a pond, if the adults were in fact successful in reproducing. To test the effect of adult Odonata communities on nymph communities, temporal data spanning over several years would be needed, given the lengthiness of the nymph stage. Although, there may be some variation present in these models that is a lagged effect from the previous life stage, for example landscape factors on nymphs.

In any ecological study, error (i.e. sampling error) always contributes to the unexplained variation in models. Given that I was able to explain such a high proportion of variation in Odonata communities with three environmental features contributes to the validity of these models and just how important plants and water are to these communities. Local scale habitat features appeared relatively more important than larger scale features for Odonata community structure with plant communities being the most important characteristic for all life stages of Odonata (Fig. 5.4-5.7). The greater relative importance of local scale habitat characteristics over larger-landscape scale characteristics has been observed for other invertebrate communities. Grassland butterflies respond more to local habitat quality characteristics (the number of native versus non-native species, types of grasses present), while no significant relationships were found between butterfly species richness or composition and surrounding landscape variables (i.e. percent of surrounding urbanization) (Collinge et al. 2003). Most insect communities from prairie habitats respond to local scale habitat characteristics with some predatory insects (*Coccinellidae*) also related to larger scale characteristics (i.e. habitat fragmentation) (Stoner and Joern 2004). Thornhill et al. (2017) determined that local factors (related to macrophyte coverage) were more important for benthic macroinvertebrates than larger landscape factors in urban ponds of the United Kingdom, which is consistent with the results of this study of Odonata in stormwater management ponds. Based on the results of the present study, management efforts should be directed at improving local habitat pond features, in particular pond plant communities and water quality.

5.6 Conclusions

As urban growth is expected to accelerate in the future, there is a pressing need to make cities more sustainable. There has been much research on the benefits of green spaces in cities for biodiversity (e.g. MacGregor-Fors et al. 2016), however little attention has been given to the potential for “bluespaces” to provide similar benefits (Higgins et al. 2019). In this study, pond plant communities proved to be the most important feature for dragonflies and damselflies at both aquatic and terrestrial life stages. Pond water quality was also of high importance for dragonfly nymphs in particular, who appeared to be more sensitive to certain variables (i.e. conductivity) than damselflies. Although landscape features explained little variation in Odonata community structure, results point to the potential importance of pond-networks in cities for regional diversity as adjacent lentic waters significantly affected Odonata community structure. Initial pond design should include providing suitable environments for the establishment of wetland plants and reducing the amount of impervious surface in pond catchment basins. Stormwater ponds can be important habitat for species in cities if designed and maintained properly.

See Appendix D for Supplementary Material

Table 5.1

Plant species influencing Odonata communities (dragonflies and damselflies) at the adult stage and the nymph stage at study ponds. Plant species are described by their functional guild, plant habitat type and how frequently they were found at the study ponds as well as a range of the average percent the species covered at ponds. *p*-values (significance level $p<0.05$) were obtained through forward stepwise regression (with 9,999 permutations) based on transformation-based redundancy analyses (tb-RDA with Hellinger transformation) for each adult dragonfly species composition (n=51 ponds), dragonfly nymph species composition (n=50 ponds), adult damselfly species composition (n=51 ponds) and damselfly nymph genera composition (n=47 ponds), *ns* refers to no significant relationship to the plant species ($p>0.05$).

Plant species	**Functional Guild**	**Plant Habitat Type**	**Frequency in ponds (%)**	**Cover range (%)**	**Adult Dragonfly (*p*-value)**	**Dragonfly Nymph (*p*-value)**	**Adult Damselfly (*p*-value)**	**Damselfly Nymph (*p*-value)**
Stuckenia pectinata	Submerged	Obligate Wetland	55	0-10	*ns*	*0.010*	*ns*	*0.005*
Lemna minor	Free-Floating	Obligate Wetland	43	0-14	*0.015*	*ns*	*ns*	*ns*
Nymphaea odorata	Floating	Obligate Wetland	14	0-32	*ns*	*0.025*	*ns*	*ns*
Eleocharis acicularis	Narrow-leaved Emergent	Obligate Wetland	12	0-14	*0.005*	*ns*	*ns*	*ns*
Eleocharis palustris	Narrow-leaved Emergent	Obligate Wetland	55	0-6	*ns*	*ns*	*0.005*	*ns*
Dulichium arundinaceum	Narrow-leaved Emergent	Obligate Wetland	16	0-15	*ns*	*0.005*	*ns*	*ns*
Schoenoplectus tabernaemontani	Narrow-leaved Emergent	Obligate Wetland	65	0-7	*0.005*	*ns*	*0.015*	*ns*
Typha angustifolia	Robust Emergent	Obligate Wetland	57	0-29	*ns*	*0.020*	*ns*	*0.025*
Sagittaria latifolia	Robust Emergent	Obligate Wetland	14	0-15	*ns*	*ns*	*0.030*	*0.020*
Lythrum salicaria	Ground Cover	Obligate Wetland	96	0-12	*ns*	*ns*	*ns*	*0.025*
Galium palustre	Ground Cover	Obligate Wetland	57	0-12	*0.025*	*ns*	*ns*	*ns*
Lysimachia terrestris	Ground Cover	Obligate Wetland	18	0-8	*0.030*	*ns*	*0.030*	*0.045*
Thelypteris palustris	Ground Cover	Facultative Wetland	14	0-10	*ns*	*ns*	*0.010*	*ns*
Symphyotrichum lanceolatum	Ground Cover	Facultative Wetland	51	0-6	*0.040*	*ns*	*0.045*	*ns*
Symphyotrichum novae-angliae	Ground Cover	Facultative Wetland	67	0-7	*ns*	*ns*	*ns*	*0.035*
Euthamia graminifolia	Ground Cover	Facultative Wetland	59	0-11	*ns*	*0.015*	*ns*	*ns*
Vitis riparia	Ground Cover	Facultative Wetland	25	0-6	*ns*	*0.015*	*ns*	*ns*
Oenothera biennis	Ground Cover	Facultative Upland	29	0-9	*0.030*	*ns*	*ns*	*ns*
Solidago canadensis	Ground Cover	Facultative Upland	73	0-19	*0.015*	*ns*	*0.035*	*ns*
Melilotus albus	Ground Cover	Facultative Upland	33	0-11	*0.005*	*ns*	*0.015*	*ns*
Galium triflorum	Ground Cover	Facultative Upland	39	0-10	*ns*	*0.005*	*0.010*	*0.035*
Cirsium arvense	Ground Cover	Facultative Upland	73	0-20	*ns*	*0.025*	*ns*	*0.005*
Pastinaca sativa	Ground Cover	Upland	35	0-13	*ns*	*0.010*	*ns*	*ns*
Vicia cracca	Ground Cover	Upland	80	0-19	*ns*	*ns*	*0.005*	*ns*
Alnus incana	Tall Shrub	Obligate Wetland	22	0-11	*ns*	*ns*	*0.015*	*ns*
Fraxinus americana	Deciduous Tree	Facultative Upland	16	0-22	*ns*	*ns*	*0.025*	*ns*
Salix alba	Deciduous Tree	Facultative Wetland	14	0-15	*ns*	*ns*	*ns*	*0.025*

Table 5.2

Water quality variables influencing Odonata communities (dragonflies and damselflies) at the terrestrial adult stage and the aquatic nymph stage at study ponds. Averages and range are included for water quality variables, DL refers to measurements that were less than detection level. *p*-values (significance level $p<0.05$) were obtained through forward stepwise regression (with 9,999 permutations) based on transformation-based redundancy analyses (tb-RDA with Hellinger transformation) for each adult dragonfly species composition (n=51 ponds), dragonfly nymph species composition (n=50 ponds), adult damselfly species composition (n=51 ponds) and damselfly nymph genera composition (n=47 ponds), *ns* refers to no significant relationship to the water quality variable ($p>0.05$).

Water Quality Variable	**Mean (Range)**	**Adult Dragonfly (*p*-value)**	**Dragonfly Nymph (*p*-value)**	**Adult Damselfly (*p*-value)**	**Damselfly Nymph (*p*-value)**
pH	7.56 (5.77-9.23)	*0.018*	*0.040*	*0.002*	*ns*
Conductivity (µS/cm)	1285.3 (43.45-5761)	*ns*	*0.045*	*ns*	*ns*
As (µg/L)	0.36 (DL-1.45)	*ns*	*0.005*	*ns*	*ns*
B (µg/L)	38.05 (5.40-146.40)	*0.002*	*ns*	*ns*	*ns*
Ba (µg/L)	62.66 (11.95-151.80)	*ns*	*0.005*	*ns*	*ns*
Cr (µg/L)	0.52 (DL-1.60)	*0.004*	*ns*	*ns*	*ns*
Mo (µg/L)	1.57 (DL-8.45)	*ns*	*ns*	*0.018*	*ns*
Ni (µg/L)	2.10 (DL-5.00)	*ns*	*ns*	*0.008*	*ns*
Pb (µg/L)	0.14 (DL-1.1)	*0.006*	*ns*	*ns*	*ns*
Se (µg/L)	0.24 (DL-2.20)	*ns*	*ns*	*0.022*	*ns*
Ti (µg/L)	4.24 (DL-33.95)	*ns*	*ns*	*0.012*	*0.004*
Zn (µg/L)	2.85 (DL-14.2)	*ns*	*0.005*	*ns*	*ns*
TP (mg/L)	0.039 (0.009-0.187)	*0.012*	*0.025*	*ns*	*ns*
NO_3^- (mg/L)	0.31 (DL-3.28)	*ns*	*ns*	*0.004*	*ns*
TN (mg/L)	1.08 (0.37-4.49)	*ns*	*ns*	*0.004*	*0.048*
Chlorophyll *a* (mg/L)	0.0113 (0.0005-0.0630)	*ns*	*0.040*	*ns*	*0.002*

Table 5.3

Land cover types influencing Odonata communities (dragonflies and damselflies) at the terrestrial adult stage and the aquatic nymph stage at study ponds. *p*-values (significance level $p<0.05$) were obtained through forward stepwise regression (with 9,999 permutations) based on transformation-based redundancy analyses (tb-RDA with Hellinger transformation) for adult dragonfly species composition at a 2 km spatial scale (n=51 ponds), dragonfly nymph species composition at a 2 km spatial scale (n=50 ponds), adult damselfly species composition at a 500 m spatial scale (n=51 ponds) and damselfly nymph genera composition at a 5 km spatial scale (n=47 ponds), *ns* refers to no significant relationship to the land cover type ($p>0.05$).

Land Cover Type	**Adult Dragonfly (*p*-value)**	**Dragonfly Nymph (*p*-value)**	**Adult Damselfly (*p*-value)**	**Damselfly Nymph (*p*-value)**
Transportation	*ns*	*0.002*	*ns*	*ns*
Settlement	*ns*	*0.012*	*ns*	*ns*
Golf Course Pond	*ns*	*0.016*	*ns*	*ns*
Stormwater Pond	*ns*	*ns*	*0.030*	*ns*
Wetland	*0.014*	*ns*	*ns*	*0.006*
Rock Barren	*0.002*	*0.006*	*0.002*	*ns*
Wooded Area	*0.032*	*ns*	*0.002*	*ns*

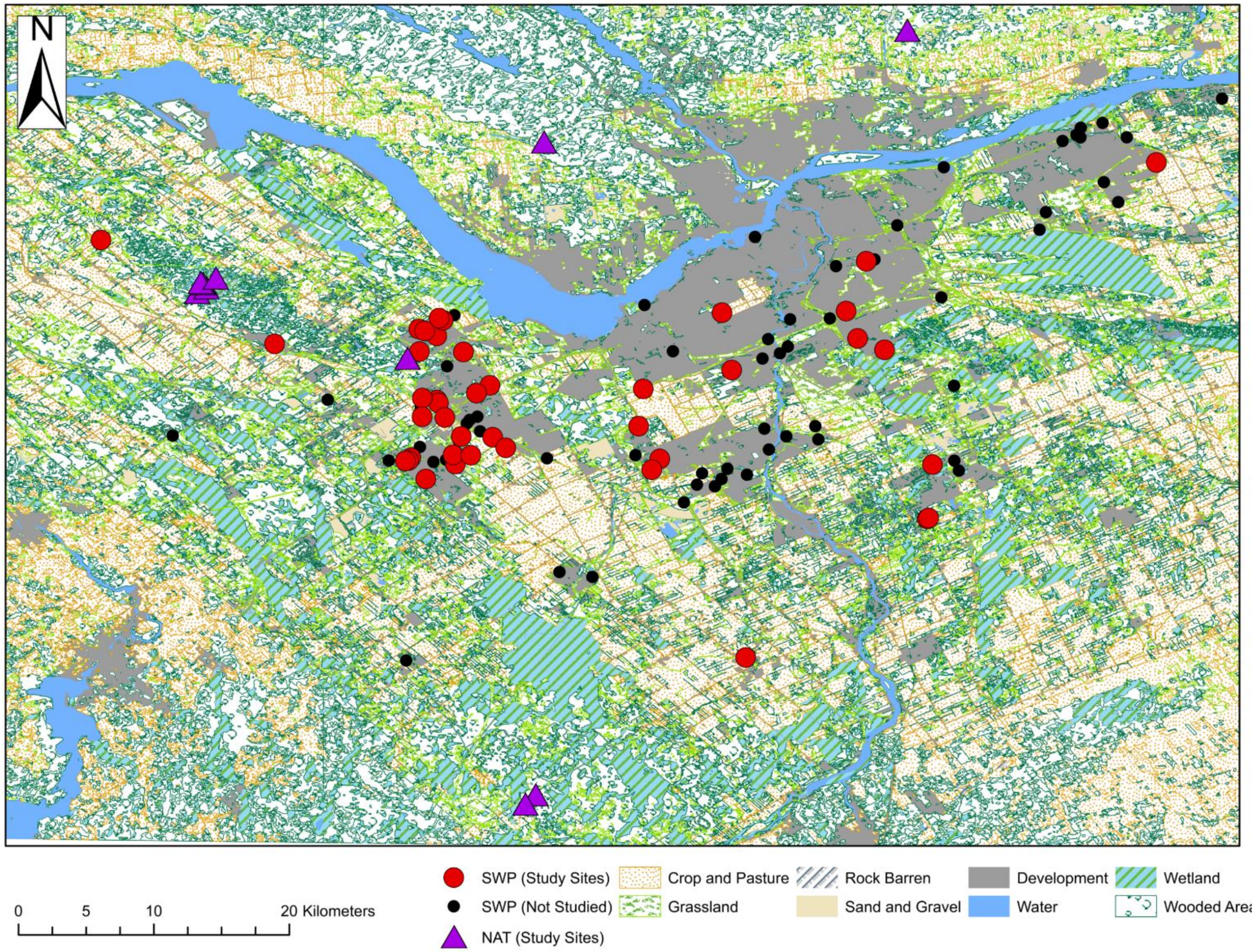

Figure 5.1 Land cover map of the stormwater ponds (SWP in red circles, n=41) and natural ponds (NAT pink triangles, n=10) studied including other stormwater ponds (wet ponds) that were not studied (SWP black circles, n=55) in the National Capital region of Canada (NCRC) (Ottawa, Ontario and Gatineau, Québec). Land cover data for Ottawa, Ontario was provided by the City of Ottawa (2014). Land cover data for Gatineau, Québec was provided by the Government of Canada (2000) and represents the circa 2000 land cover dataset. All land cover data were updated manually to reflect 2015 conditions. Land cover classes were summarized to represent major land cover types. Map was created using ArcMap version (10.5.1).

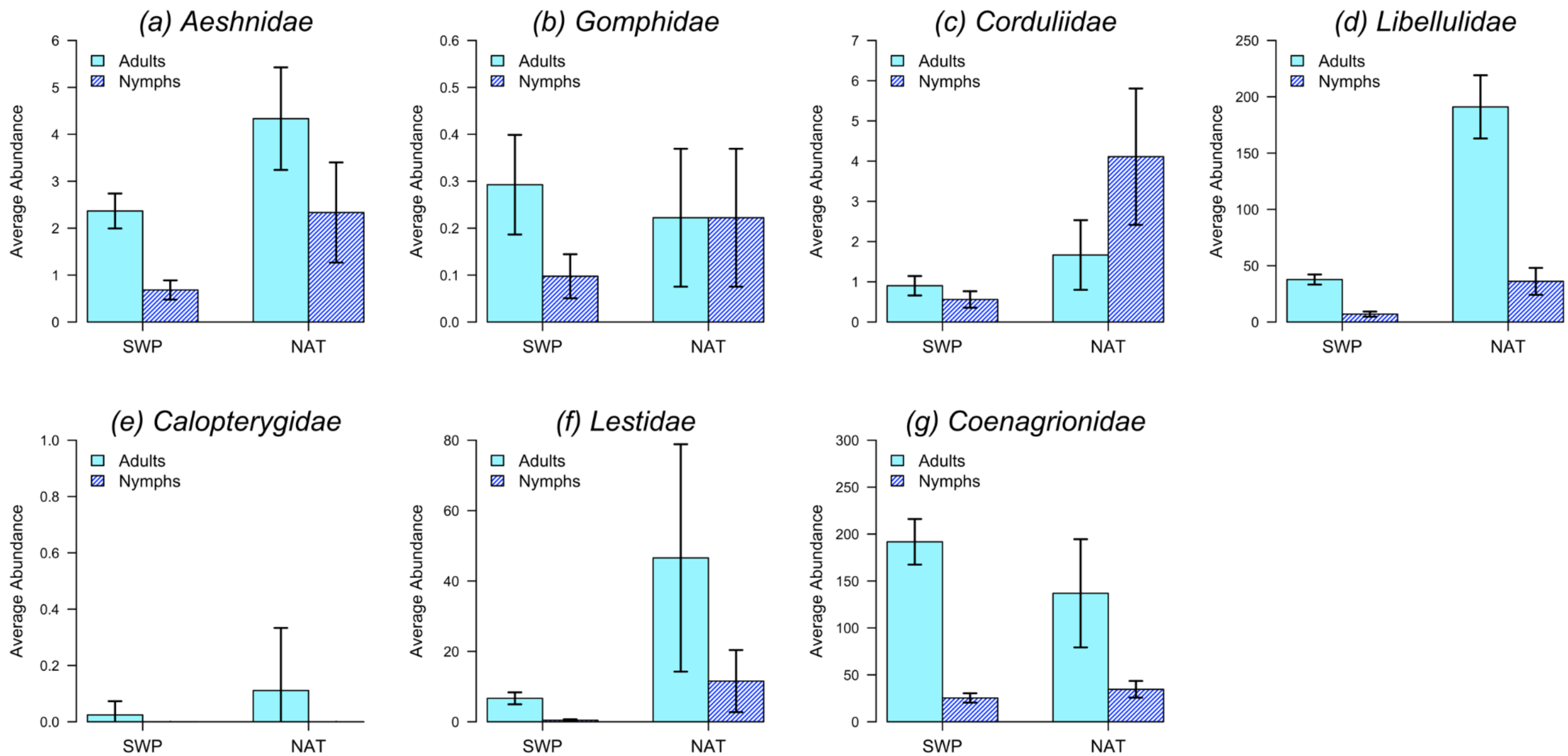

Figure 5.2 Average adult and nymph abundances with standard errors for the four Anisoptera (dragonfly) families (a-d) and the three Zygoptera (damselfly) families (e-g) at the stormwater ponds (SWP). Sample size of stormwater ponds for corresponding analyses: dragonfly and damselfly adults n=41, dragonfly nymphs n=40 and damselfly nymphs n=39. Sample size of the natural ponds (NAT) for corresponding analyses: dragonfly and damselfly adults n=10, dragonfly nymphs n=9 and damselfly nymphs n=6: (a) Aeshnidae (darners), (b) Gomphidae (clubtails), (c) Corduliidae (emeralds), (d) Libellulidae (skimmers), (e) Calopterygidae (jewelwings), (f) Lestidae (spreadwings) and (g) Coenagrionidae (pond damsels).

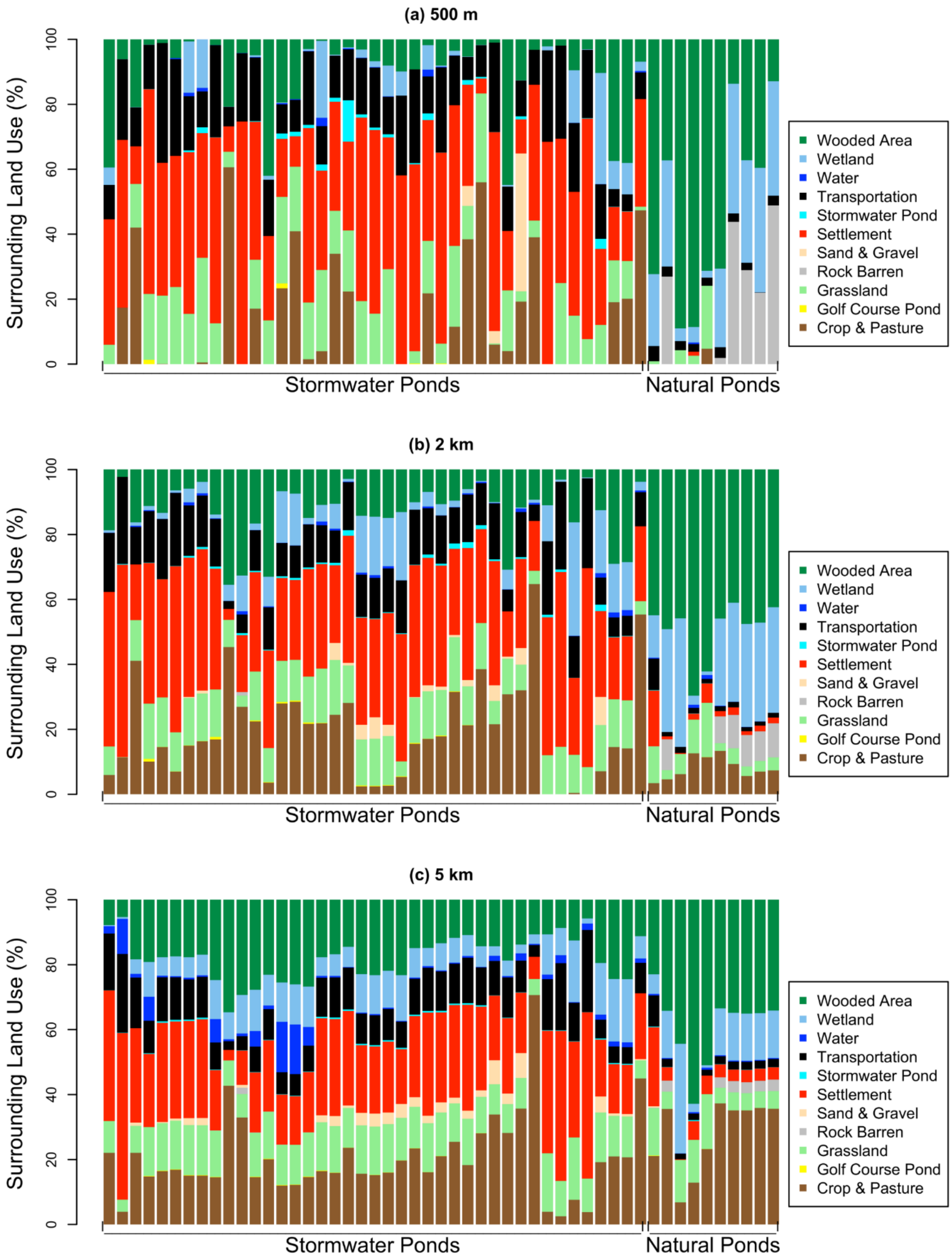

Figure 5.3 Percent of land cover types surrounding stormwater ponds (n=41) and natural ponds (n=10) at a (a) 500 m spatial scale, (b) 2 km spatial scale and (c) 5 km spatial scale. Each bar represents an individual pond.

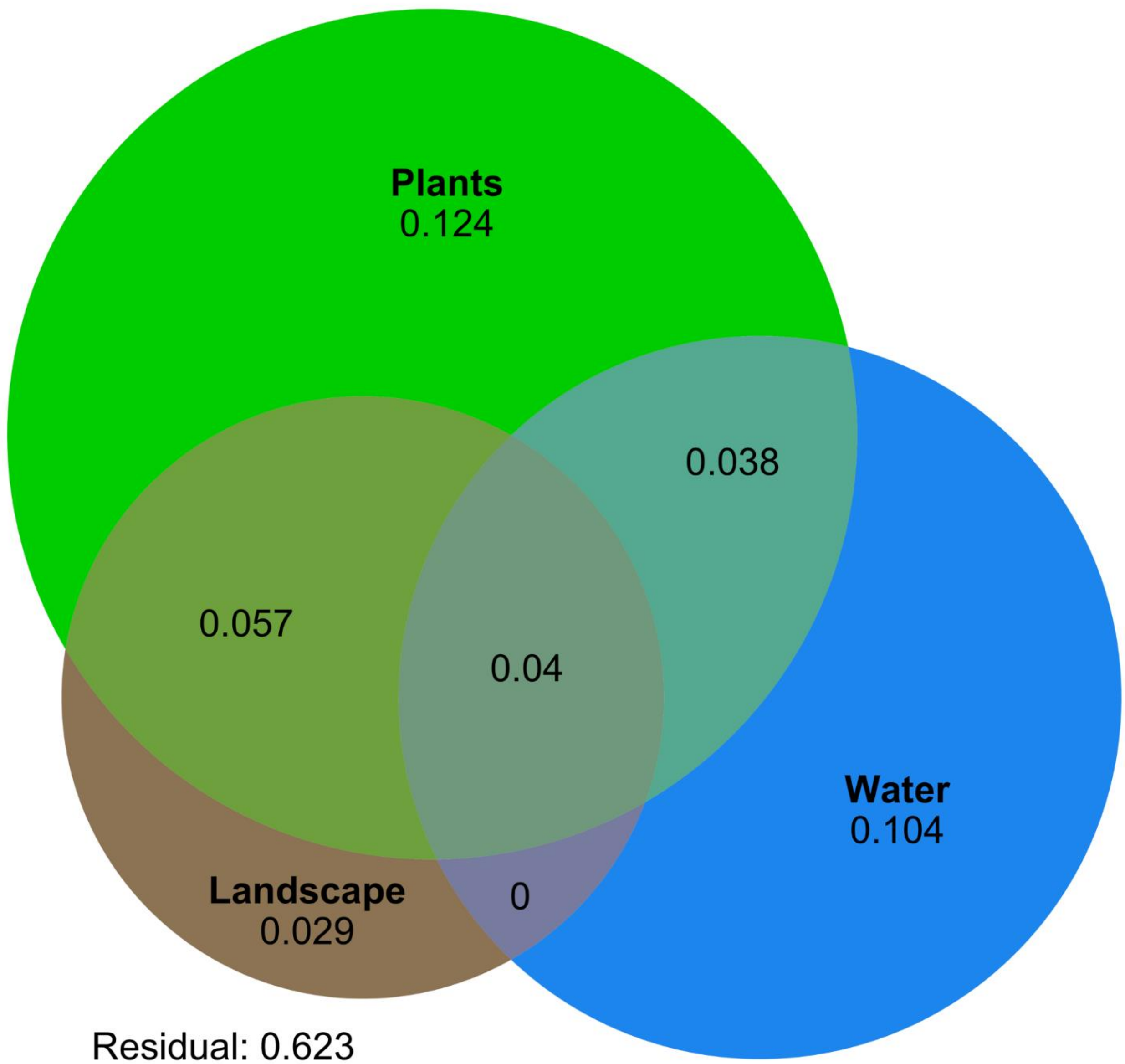

Figure 5.4 Variation partitioning analysis showing the contribution of three explanatory matrices (plants, water and landscape) to explain variation in adult dragonfly community structure at study ponds (stormwater ponds n=41, natural ponds n=10). Significant variables ($p<0.05$) for each explanatory matrix (see Tables 5.1, 5.2 and 5.3) determined through transformation-based redundancy analyses (tb-RDA with Hellinger transformation).

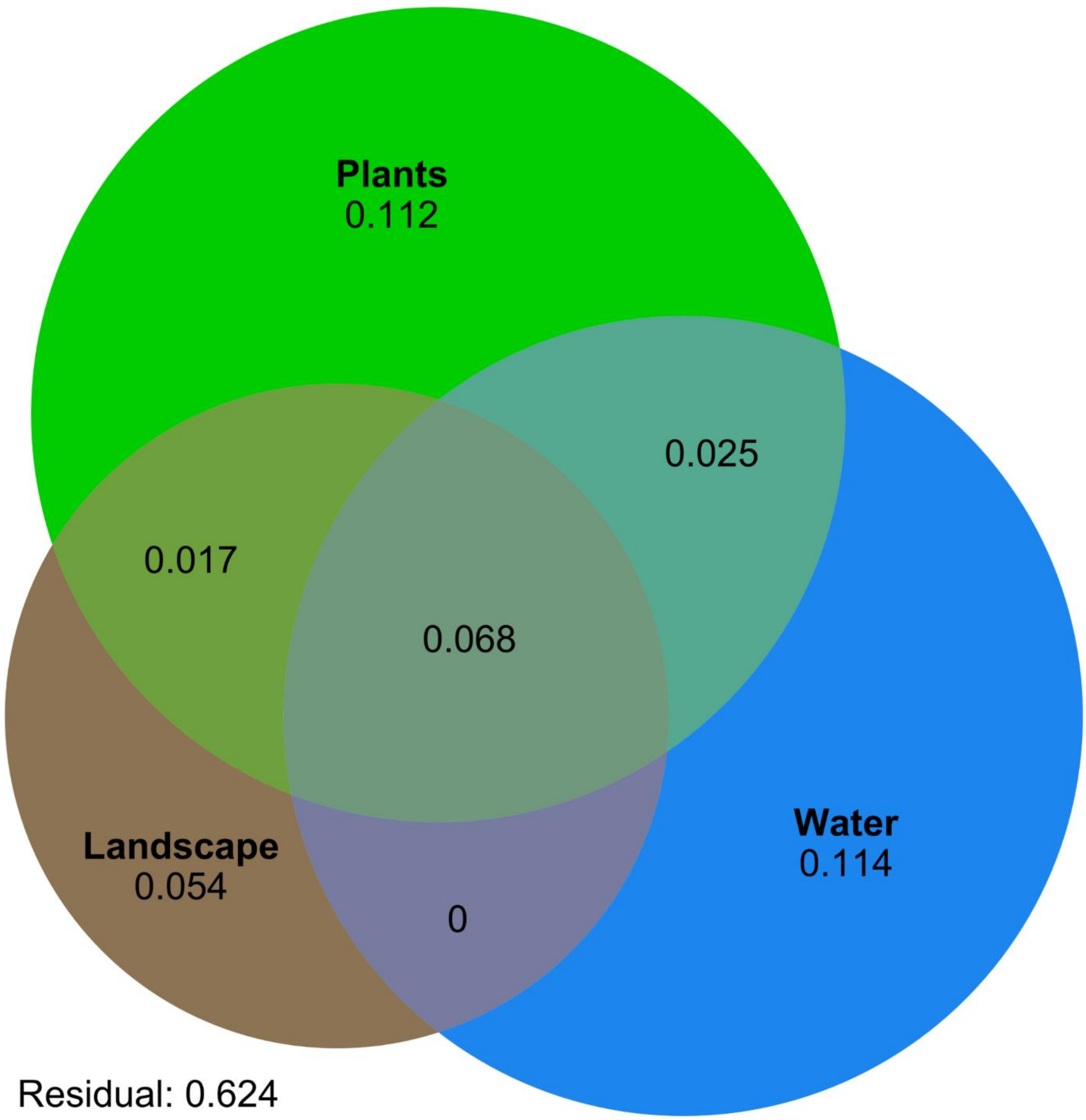

Figure 5.5 Variation partitioning analysis showing the contribution of three explanatory matrices (plants, water and landscape) to explain variation in dragonfly nymph community structure at study ponds (stormwater ponds n=41, natural ponds n=9). Significant variables (p<0.05) for each explanatory matrix (see Tables 5.1, 5.2 and 5.3) determined through transformation-based redundancy analyses (tb-RDA with Hellinger transformation).

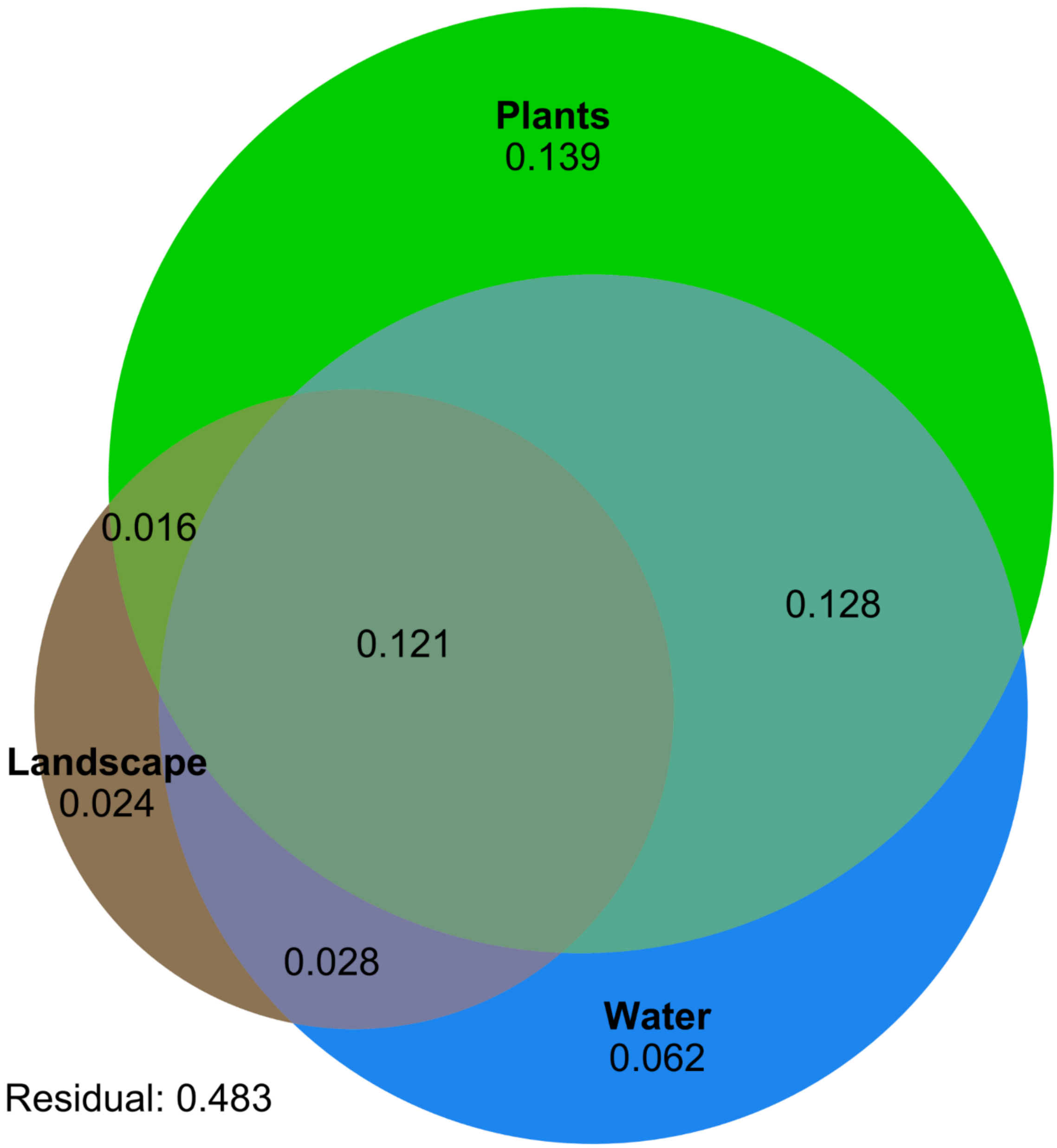

Figure 5.6 Variation partitioning analysis showing the contribution of three explanatory matrices (plants, water and landscape) to explain variation in adult damselfly community structure at study ponds (stormwater ponds n=41, natural ponds n=10). Significant variables (p<0.05) for each explanatory matrix (see Tables 5.1, 5.2 and 5.3) determined through transformation-based redundancy analyses (tb-RDA with Hellinger transformation).

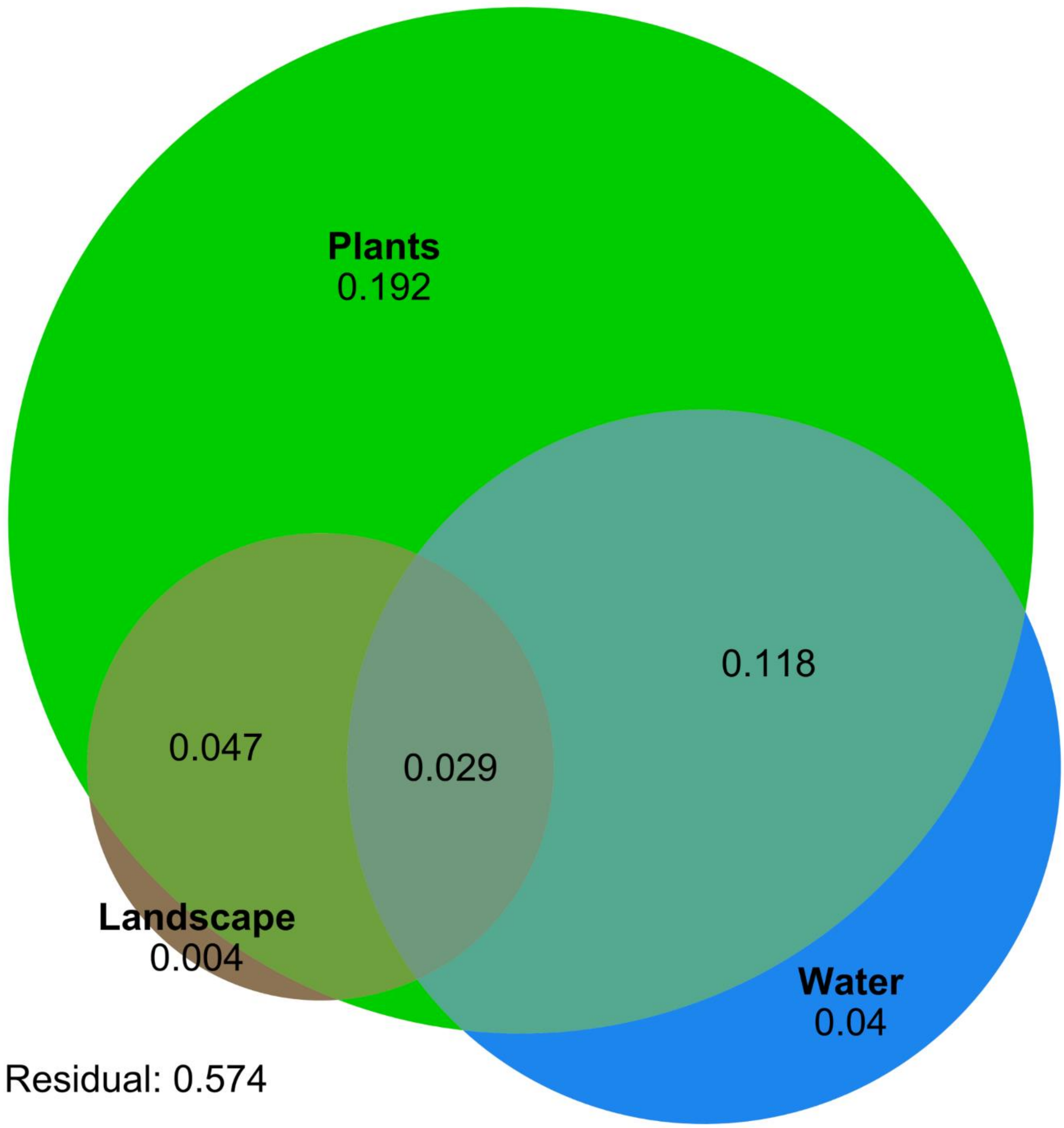

Figure 5.7 Variation partitioning analysis showing the contribution of three explanatory matrices (plants, water and landscape) to explain variation in damselfly nymph community structure at study ponds (stormwater ponds n=40, natural ponds n=6). Significant variables (p<0.05) for each explanatory matrix (see Tables 5.1, 5.2 and 5.3) determined through transformation-based redundancy analyses (tb-RDA with Hellinger transformation).

Chapter 6: General Conclusion

6.1 Summary of research findings

The major conclusion of this thesis is that stormwater ponds have the potential to provide wildlife habitat in cities, in addition to their original purpose of flood control. The wetland plant community of the littoral zone and to a lesser extent pond water quality were the primary features explaining Odonata community structure (abundance, diversity, species assemblages).

Stormwater ponds had most of the same Odonata species as those encountered at natural ponds across the same region (National Capital Region of Canada) and supported a total of 49 different species, representing nearly 60% of the pond species known regionally. The assemblage included both generalists (e.g. the dot-tailed whiteface, *Leucorrhinia intacta*) as well as less common species such as the amber-winged spreadwing (*Lestes eurinus*), a provincially vulnerable damselfly species (S3 ranked) and the horned clubtail (*Arigomphus cornutus*), a provincially and nationally vulnerable dragonfly species (S3, G3 ranked) (Ontario Ministry of Natural Resources 2018). Stormwater ponds also supported migratory dragonfly species (e.g. the green darner, *Anax junius*, Figure 6.1) and resident species (e.g. the familiar bluet damselfly, *Enallagma civile*). However, stormwater ponds were not all equal in providing suitable habitat for Odonata. Some ponds had only a few species (<5 species) while others had many (upwards of ~20). The explanation for this variation was most likely the result of differences in plant community structure between the ponds.

Wetland plant communities were a significant predictor of adult Odonata community structure (Chap. 2). Previous research had documented the relationship between the physical structure of plants and particular species of Odonata in natural ecosystems (e.g. Rouquette and Thompson 2005). This study is the first to demonstrate the close relationship specifically between the quality of plant communities (native wetland plants) and Odonata community structure (Perron and Pick 2020); this relationship with plants may be the most important one for Odonata (Chap. 5). Stormwater ponds with plant communities similar to natural ponds characterized by a high proportion of native and wetland plants also had similar Odonata communities. Furthermore, ponds with many species of obligate wetland plants and native plants supported larger populations of Odonata at both the adult and nymph stages. In particular, damselflies were linked to specific wetland plant species, likely because of their mode of oviposition.

Despite the wide variation in water chemistry across natural and stormwater ponds, the aquatic nymph communities were not as closely related to water quality as expected (Chap. 3). Less than 25% of community structure could be explained by water quality variables associated with pH, conductivity, nutrients and metals. On average, stormwater ponds, had higher concentrations of metals/metalloids and chloride or conductivity, but similar nutrient concentrations to natural ponds. Surprisingly, estimations of the water quality index developed by the Canadian Council of Ministers of the Environment (CCME) suggested that the stormwater ponds were of "good" quality, whereas the natural ponds were only of "fair" quality. Overall, the stormwater ponds posed little toxicological risk to dependent wildlife as contaminant concentrations were often below guidelines for the protection of aquatic life. This finding is important for future research on residential/commercial stormwater ponds, as they are assumed to have toxic contaminant loads (Wren et al. 1997; Bishop et al. 2000a, b). The two major exceptions were copper and chloride concentrations, which were both above CCME guidelines at 77% and 68% of the stormwater ponds respectively. Copper may originate from vehicular erosion (e.g. brake wear) (Davis et al. 2001), whereas high chloride concentrations are a result of road salt usage for winter road maintenance (Marsalek 2003; Stone and Marsalek 2011). There are few studies providing evidence of biological effects caused by chloride and conductivity *in situ*. This study identified that dragonflies are more sensitive to conductivity and chloride, likely from road salts, whereas damselflies appeared more tolerant. This research contrasts with previous studies claiming that damselflies are more sensitive to disturbances and habitat degradation than dragonflies (Monteiro Júnior et al. 2015; Miguel et al. 2017).

Despite the fact that some of the stormwater ponds had poor water quality, dragonflies were still reproducing successfully at rates similar to those estimated at natural ponds (Chap. 4). This suggests that stormwater ponds are not necessarily acting as ecological traps, a concern raised in recent studies (e.g. Oertli and Parris 2019). However, there was once again a range in the suitability of stormwater ponds as breeding habitats for Odonata. Ponds that attracted many adult dragonfly species and high abundances supported the lifecycle completion of a proportionally higher number of species and individuals, whereas ponds that attracted few species and low abundance only supported the emergence of a few species and individuals. Out of the five stormwater ponds studied, one pond in particular attracted a relatively low number of adult dragonfly species and this was consistently observed over the four years of sampling. Unlike the other ponds in the subset, this pond was completely hardscaped with rock gabion walls and little littoral zone. This suggests that the ponds that are overly hardscaped are much less attractive to Odonata. One outcome of this study, relevant to sampling methods, was that more species were encountered through exuviae collections than through adult surveys; direct on-site quantitative sampling of exuviae was a more efficient approach than the use of artificial emergence screens.

This research identified habitat requirements of all the life stages of Odonata. This research demonstrated that local habitat features were more important than large scale/landscape level features in structuring Odonata communities (Chap. 5). Plants and water quality were significantly more important for Odonata communities at stormwater ponds than surrounding land cover types. Plant communities explained the highest variation in dragonfly and damselfly community structure (between 22% and 40% of the variation). Water quality was of secondary importance, even for the aquatic nymph communities. Interestingly, the order of these features did not change between Odonata suborder or life stage, with plants always being of greatest importance followed by water quality and then landscape features. This research showed for the first time the relative importance of plants across the complete lifecycle of Odonata. This research also suggest that the water quality of stormwater ponds may not have the negative effects implied in previous studies (e.g. Helfield and Diamond 1997; Wren et al. 1997). Although landscape features explained little variation in Odonata community structure, the presence of adjacent lentic waters (ponds, wetlands) was a significant result and may be an indication of Odonata metapopulations in cities. With ~100 stormwater ponds in this study region alone, pond networks could be used as patch habitats and support the persistence of regional populations, despite the fact that some stormwater ponds are of poorer quality. However, further research is needed to determine if pond networks are indeed supporting metapopulations.

In summary, this thesis is the first research to examine the entire lifecycle of Odonata in relation to major environmental factors associated with both primary and secondary habitats. I concluded that plants matter more than water chemistry for these semi-aquatic insects, and that stormwater ponds embedded in residential and small-scale commercial areas generally appear to pose a low toxicological risk to these animals. This research contributes to the growing field of urban ecology in demonstrating how and under what conditions cities can support critical wetland habitat and biodiversity.

6.2 Contribution to ecological theory

Plants, water and landscape explained a significant amount of the variation in the distribution of Odonata in pond systems. The results do not support the neutral theory of species diversity (Hubbell 2001) and are more suggestive of a non-stochastic distribution of Odonata diversity, largely determined by pond plant communities. Other studies have also suggested that Odonata follow a niche-based distribution (e.g. Arrowsmith et al. 2018). Functional trait-based research should be conducted for Odonata in the future to further study niche models (e.g. McGill et al. 2006). In addition, the results from this thesis do not provide evidence in support of the biotic homogenization hypothesis associated with urbanization (McKinney 2006). Instead, I found that urban ponds exhibit a range of Odonata biodiversity, with some ponds supporting fewer and more common species while others supported unique assemblages including specialist species, some that are provincially and regionally vulnerable. This is due to the array of differences between stormwater pond habitats, thus suggesting that stormwater ponds follow source-sink theory (Pulliam 1988). In addition, this research provided valuable information regarding the theory of ecological traps (Hutto 1985; Robertson and Hutto 2006). There was no evidence that the stormwater ponds (n=5) were acting as ecological traps and the ponds that were studied were in fact important breeding habitats for urbanized areas. These finding do not entirely refute the possibility of stormwater ponds as ecological traps as other groups of organisms need to be studied in similar detail over their entire lifecycle. Although not directly tested, results from this study likely support metapopulation theory (Levins 1969), whereby pond habitats act as patches for populations that are connected through dispersal.

There are possibilities for this research to contribute to ecological theory that go beyond what was specifically tested. For example, stormwater ponds with high plant richness may increase ecological functions such as the removal of contaminants from urban runoff (e.g., Brisson et al. 2020).

6.3 Management implications and future directions

Results from this study suggest that stormwater ponds can serve additional purposes, apart from their hydrological benefits. Stormwater ponds can clearly provide habitat for species in cities. As this study has demonstrated the primary importance of native wetland plant communities for the Odonata lifecycle, one important management recommendation would be to focus on the initial design of ponds to enhance wetland habitat. Bank slope is a major determinant of wetland plant communities (He et al. 2019); a gradual sloping bank instead of steep banks and rock/concrete banks are important for the formation of hydric soils and the establishment of wetland habitat. Native wetland plants should be planted or hydric soils with a native seed bank should be applied when a pond is first constructed. The mitigation of non-native plant species should be practiced, which will add conservation value to urban systems (e.g. Narango et al. 2017). Within the city of Ottawa, this has only been undertaken in the case of toxic plants such as giant hogweed or wild parsnip (City of Ottawa 2020). Future research on stormwater ponds should include how to best sustain native wetland plant communities in an urban setting. In this research, a positive relationship was found between pond age since construction and the percentage of native plant species in the plant communities (Fig. S2.6). There could be a few potential explanations for this relationship: (1) that stormwater ponds undergo succession which stabilizes plant communities through time providing better habitat for native plants, or (2) differences in pond design over time, with older designs supporting more native plants. This relationship needs to be further studied and may provide insights into offering optimal conditions for native plants in urban ponds.

In terms of water quality, there were few contaminants that reached concentrations high enough to pose risks to wildlife in these residential/commercial ponds. However, only major ions, metals and nutrients were measured. Persistent organic contaminants not measured included petroleum products (including PAHs) from cars or home heating and pesticides. However, cosmetic pesticide (including herbicide) use is increasingly being regulated in urban areas. Further research of stormwater pond quality should be directed to measuring these other potential contaminants.

Of all the elements measured, chloride from road salting reached the highest concentrations in stormwater ponds relative to natural ponds. High chloride is likely negatively affecting Odonata in the stormwater ponds of the National Capital Region (Chap. 3). Road salt contamination is becoming the biggest freshwater pollutant in temperate regions, with little regulations in many locations (Oberts et al. 2000; Marsalek 2003). In Ontario and in many regions in North America, there are minimal or no restrictions on the use of road salts for residential streets, parking lots and sidewalks (Stone and Marsalek 2011). Enforcing regulations on the amount of road salts applied to residential and commercial areas (e.g. limiting the amount per m^2) is recommended and more environmentally friendly alternatives should be developed. Reducing the area of imperviousness in pond catchment basins (e.g. green road shoulders, narrower roads) will also improve water quality of ponds in addition to providing better water infiltration (more flood control).

The construction of stormwater ponds is expected to increase with increasing development; it is important to design these ponds with their use for biodiversity in mind. Apart from the wet ponds studied here, there are also dry ponds constructed in cities which do not hold a permanent body of water. These ponds can also be important for wildlife; there are specific species of Odonata that require temporary ponds for development (Corbet 1999). The combination of wet and dry constructed pond systems in cities can have substantial implications for regional diversity and potential metapopulations.

6.4 Importance of wildlife habitat in cities

As the amount of natural wetland habitat continues to decrease, especially with urbanization, the use of stormwater ponds for wetland species may prove to be critical for the conservation of biodiversity. In addition to plant and Odonata diversity, I documented the presence of many other species (including butterflies, birds, fish, amphibians, reptiles, mammals) that used the ponds and adjacent areas for nesting, foraging and resting (Table 6.1). Stormwater ponds should not only be designed to attain their hydrological benefits but be considered amenities to biodiversity in cities. This means designing and maintaining them with habitat quality in mind; this may also increase their societal value. There is increasing evidence of the value of bluespaces in cities and stormwater ponds can contribute to the bluescape. While the benefits of "bluespaces" in cities are not as well understood as those of greenspaces (Higgins et al. 2019), this study provides evidence of habitat services for biodiversity which is typically linked to other ecological and societal benefits (Brown and Grant 2005; Cadotte et al. 2008). Stormwater ponds can provide cultural services for urbanites through the opportunity to view and appreciate freshwater habitats as well as in offering recreation and overall health benefits through associated walking trails and greenspace.

Dragonflies can be flagship species for conservation; they are charismatic insects appreciated by people for their colourful appearance and flight behaviour (Corbet 1999; Lemelin 2007). There are currently five Odonata species designated as endangered in Canada by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (Cannings 2019). However, the status of most Odonata populations is unknown and this level of uncertainty is the same for most insects around the world. E.O. Wilson (1987) designated invertebrates as the "little things that run the world" and suggested the demise of the human species if their populations were ever to go extinct. Over three decades later, there is still an urgent need for research on invertebrate conservation (Donaldson et al. 2016). Scientists from around the world have recently published a "roadmap" for insect conservation and recovery identifying current gaps in knowledge and strategic plans for conservation (Harvey et al. 2020). This strategy includes the mitigation of invasive species, reducing water pollution and increasing habitat heterogeneity and microhabitats through landscapes, among other things. This strategy also calls to engage citizen scientists in collecting data on insects and increasing awareness of insect conservation (Harvey et al. 2020). Connecting people to stormwater ponds through dragonfly biodiversity could help promote a broader appreciation of wetland ecosystems and also contribute to the conservation of insect biodiversity.

Table 6.1

Incidental wildlife encounters at the stormwater ponds (n=41) from 2015-2018, Ottawa, Ontario, Canada.

Common name	**Scientific name**
Green frog	*Lithobates clamitans*
Northern leopard Frog	*Lithobates pipiens*
American bullfrog	*Lithobates catesbeianus*
American toad	*Anaxyrus americanus*
Midland painted turtle	*Chrysemys picta marginata*
Snapping turtle	*Chelydra serpentina*
Red-bellied snake	*Storeria occipitomaculata*
Garter snake	*Thamnophis sirtalis*
Red-winged blackbird	*Agelaius phoeniceus*
Mourning dove	*Zenaida macroura*
American robin	*Turdus migratorius*
Blue jay	*Cyanocitta cristata*
Song sparrow	*Melospiza melodia*
Belted kingfisher	*Ceryle alcyon*
Goldfinch	*Carduelis tristis*
Osprey	*Pandion haliaetus*
Green heron	*Butorides virescens*
Great blue heron	*Ardea herodias*
American bittern	*Botaurus lentiginosus*
Great egret	*Ardea alba*
Common merganser	*Mergus merganser*
Hooded merganser	*Lophodytes cucullatus*
Mallard	*Anas platyrhynchos*
Canada goose	*Branta canadensis*
Ground hog	*Marmota monar*
Beaver	*Castor canadensis*
White-tailed deer	*Odocoileus virginianus*
Red fox	*Vulpes vulpes*
Northern pike	*Esox lucius*
Pumpkin seed	*Lepomis gibbosus*
Giant water bug	*Belostoma* sp.
Garden spider	*Argiope* sp.
Monarch	*Danaus plexippus*
Black swallowtail	*Papilio polyxenes*

Figure 6.1 A teneral green darner (*Anax junius*) with its exuviae found at a stormwater pond (SWF-1809) in Ottawa, Ontario, Canada.

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Appendix A: Supplementary Material for Chapter 2

Table S2.1

Description of stormwater ponds chosen as study sites across the National Capital Region of Canada (NCRC) (n=41). * n=38, missing impervious cover data for three stormwater ponds.

Pond characteristics	**Range**	**Mean**
Age	1-36 years	~14 years
Area	577.8-14,798.4 m^2	4,786.9 m^2
Perimeter	93.7-839.1 m	349.5 m
Impervious surfaces in catchment area*	8.3-74.3%	44.0%

Table S2.2

Occurrences of Odonata (Zygoptera and Anisoptera) species at urban stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10) with abbreviations used in Fig. 2.5 and Fig. 2.6. "✓" indicates species was present and "X" indicates that species was absent at ponds.

Scientific name	**Abbreviation**	**SWP**	**NAT**
Suborder: Zygoptera			
Calopteryx maculata	CALMAC	✓	✓
Lestes congener	LESCON	✓	✓
Lestes disjunctus	LESDIS	✓	✓
Lestes dryas	LESDRY	✓	✓
Lestes eurinus	LESEUR	✓	✓
Lestes rectangularis	LESREC	✓	✓
Lestes unguiculatus	LESUNI	✓	✓
Argia fumipennis violacea	ARGFUM	✓	X
Chromagrion conditum	CHRCON	✓	X
Coenagrion resolutum	COERES	✓	✓
Enallagma annexum	ENAANN	✓	✓
Enallagma antennatum	ENAANT	✓	X
Enallagma aspersum	ENAASP	X	✓
Enallagma boreale	ENABOR	✓	✓
Enallagma civile	ENACIV	✓	X
Enallagma ebrium	ENAEBR	✓	✓
Enallagma hageni	ENAHAG	✓	✓
Ischnura verticalis	ISCVER	✓	✓
Nehalennia irene	NEHIRE	✓	✓
Suborder: Anisoptera			
Aeshna canadensis	AESCAN	✓	✓
Aeshna constricta	AESCON	✓	✓
Aeshna tuberculifera	AESTUB	X	✓
Aeshna umbrosa	AESUMB	✓	X
Anax junius	ANAJUN	✓	✓
Arigomphus cornutus	ARICOR	✓	X
Dromogomphus spinosus	DROSPI	✓	✓
Epitheca cynosura	EPICYN	✓	X
Epitheca canis	EPICAN	✓	✓
Epitheca princeps	EPIPRI	✓	X
Cordulia shurtleffi	CORSHU	✓	✓
Dorocordulia libera	DORLIB	✓	✓
Celithemis elisa	CELELI	✓	✓
Erythemis simplicicollis	ERYSIM	✓	X
Leucorrhinia frigida	LEUFRI	✓	✓
Leucorrhinia intacta	LEUINT	✓	✓
Leucorrhinia proxima	LEUPRO	✓	✓
Pachydiplax longipennis	PACLON	✓	X
Perithemis tenera	PERTEN	✓	X
Ladona julia	LADJUL	✓	✓
Libellula luctuosa	LIBLUC	✓	✓
Libellula pulchella	LIBPUL	✓	✓
Libellula quadrimaculata	LIBQUA	✓	✓
Plathemis lydia	PLALYD	✓	✓
Sympetrum costiferum	SYMCOS	✓	X
Sympetrum internum	SYMINT	✓	✓
Sympetrum obtrusum	SYMOBT	✓	✓
Sympetrum semicinctum	SYMSEM	✓	✓
Sympetrum vicinum	SYMVIC	✓	✓

* rare species with only one individual at a single site removed included: *Libellula incesta, Gomphus fratenus, Gomphus spicatus,* and *Lestes forcipatus.*

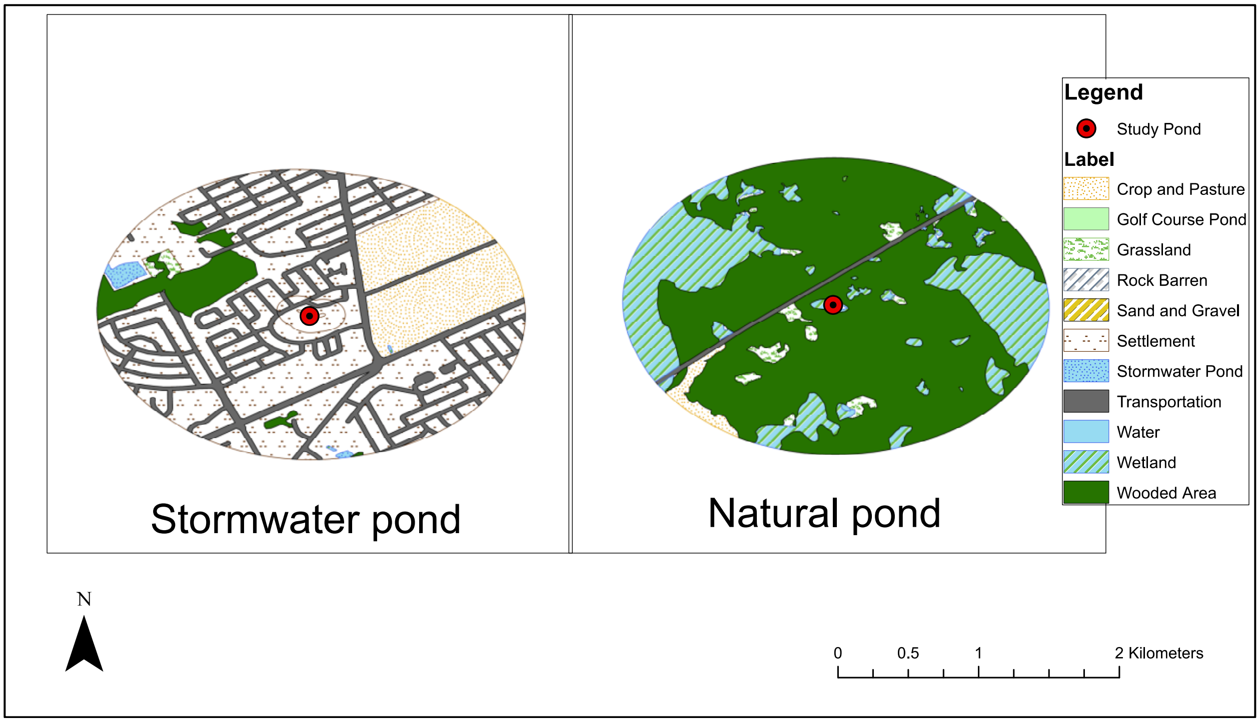


Figure S2.1 Examples of land cover types within a 1 km buffer from study pond perimeter of both a stormwater pond (SWP-1133) and natural pond (NAT-3), for location of sites see Fig. 2.1.

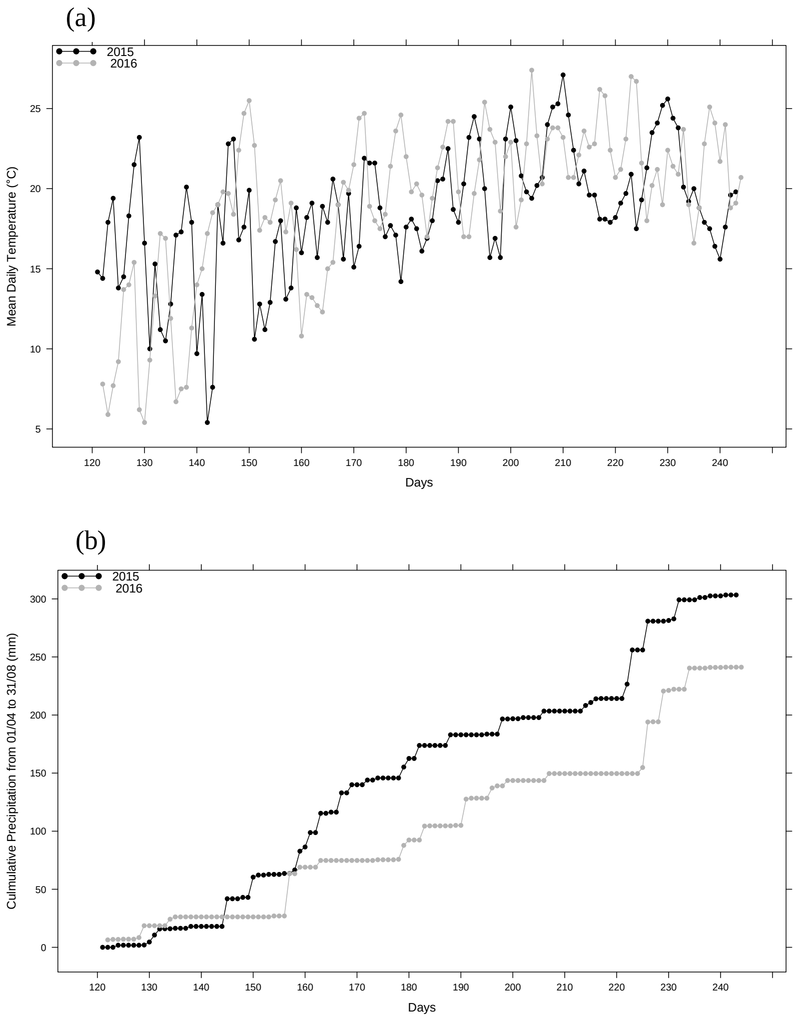


Figure S2.2 (a) Mean daily temperature data (°C) from the 2015 (black) and 2016 (grey) field season (April 1st to August 31st), and (b) cumulative total precipitation (mm) from the 2015 (black) and 2016 (grey) field season (April 1st to August 31st). Data from Environment Canada 2015 and 2016.

Environment Canada (2015) Daily Data Report 2015-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada (2016) Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

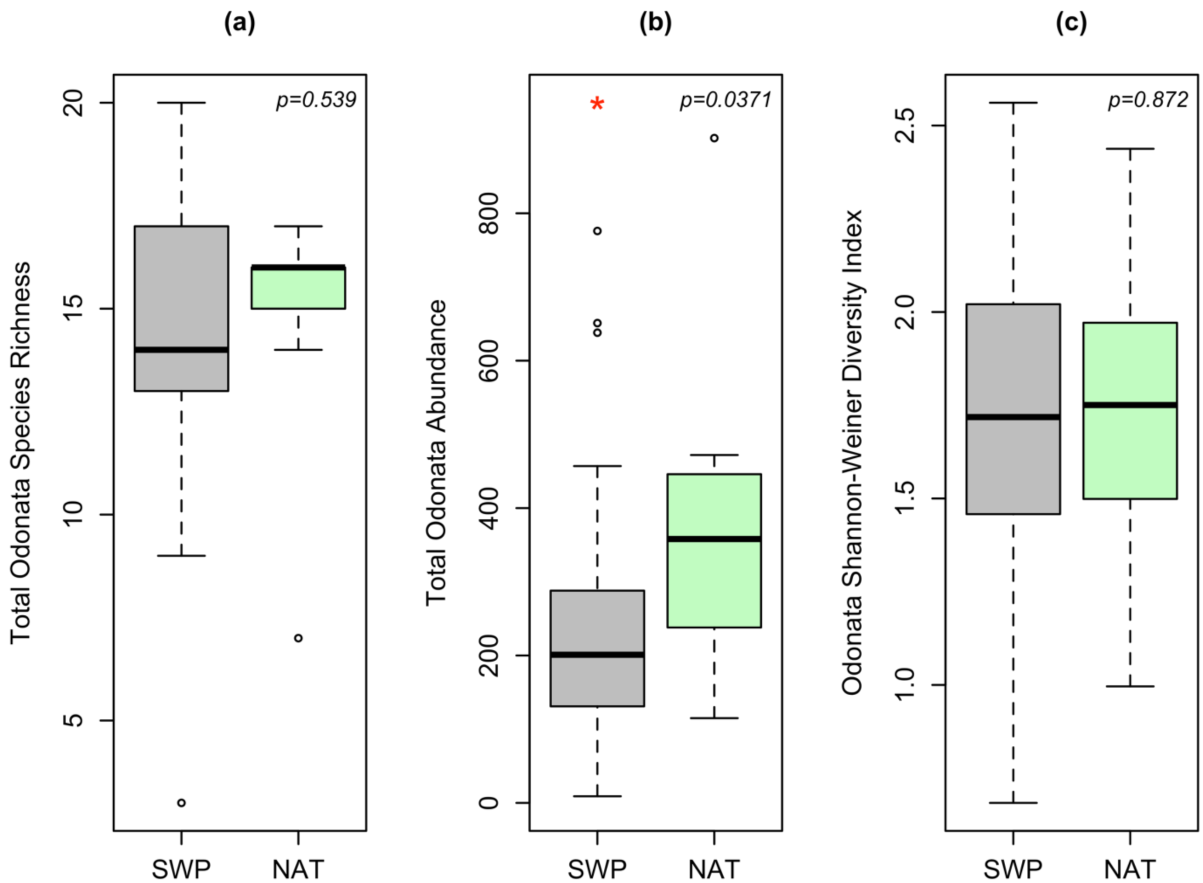


Figure S2.3 Odonata community structure patterns in urban stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10); (a) Odonata species richness (b) Odonata total abundance, and (c) Odonata Shannon-Weiner diversity.

(a) (b)

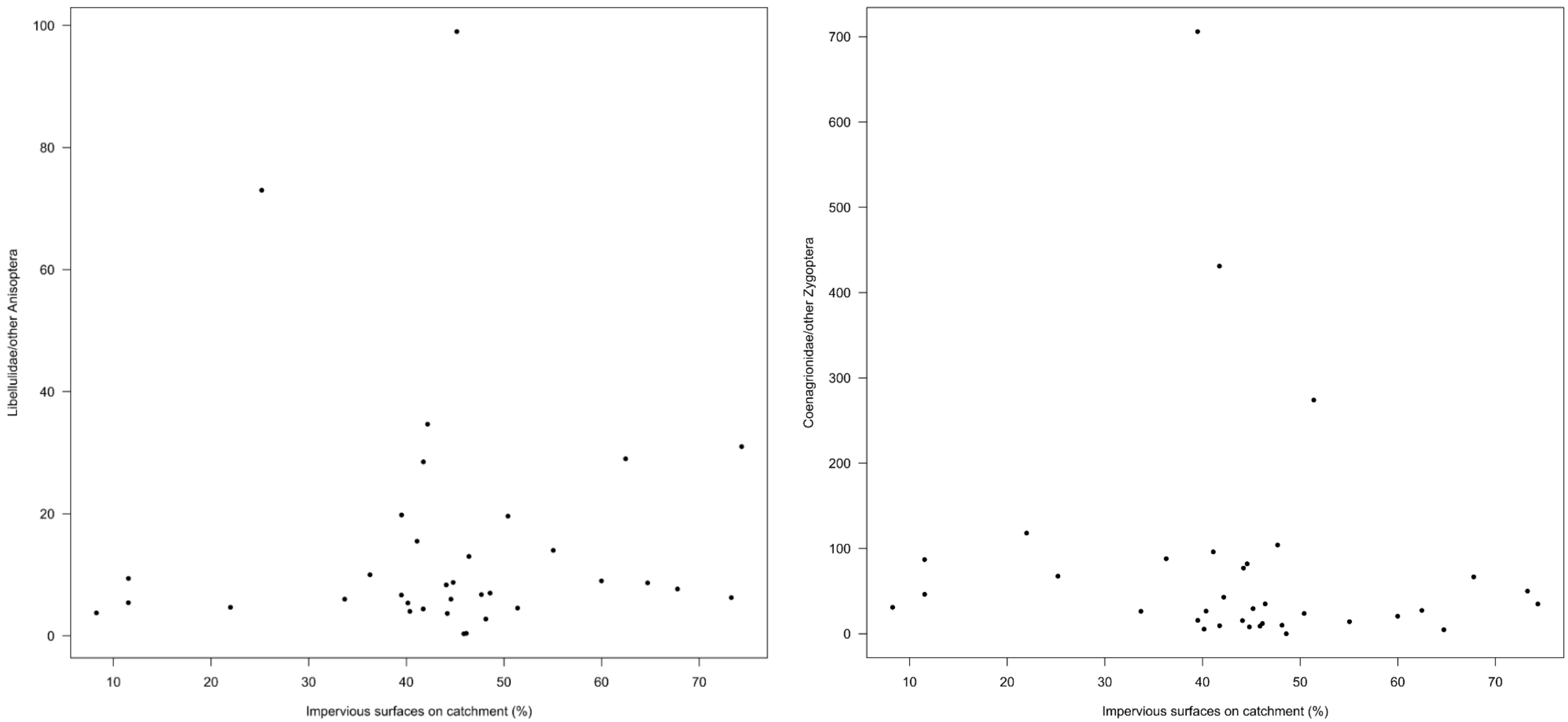


Figure S2.4 No significant relationship between the percent of impervious surfaces on the catchment basin of stormwater ponds (n=38) and (a) the Libellulidae/other Anisoptera ratio and (b) the Coenagrionidae/other Zygoptera ratio.

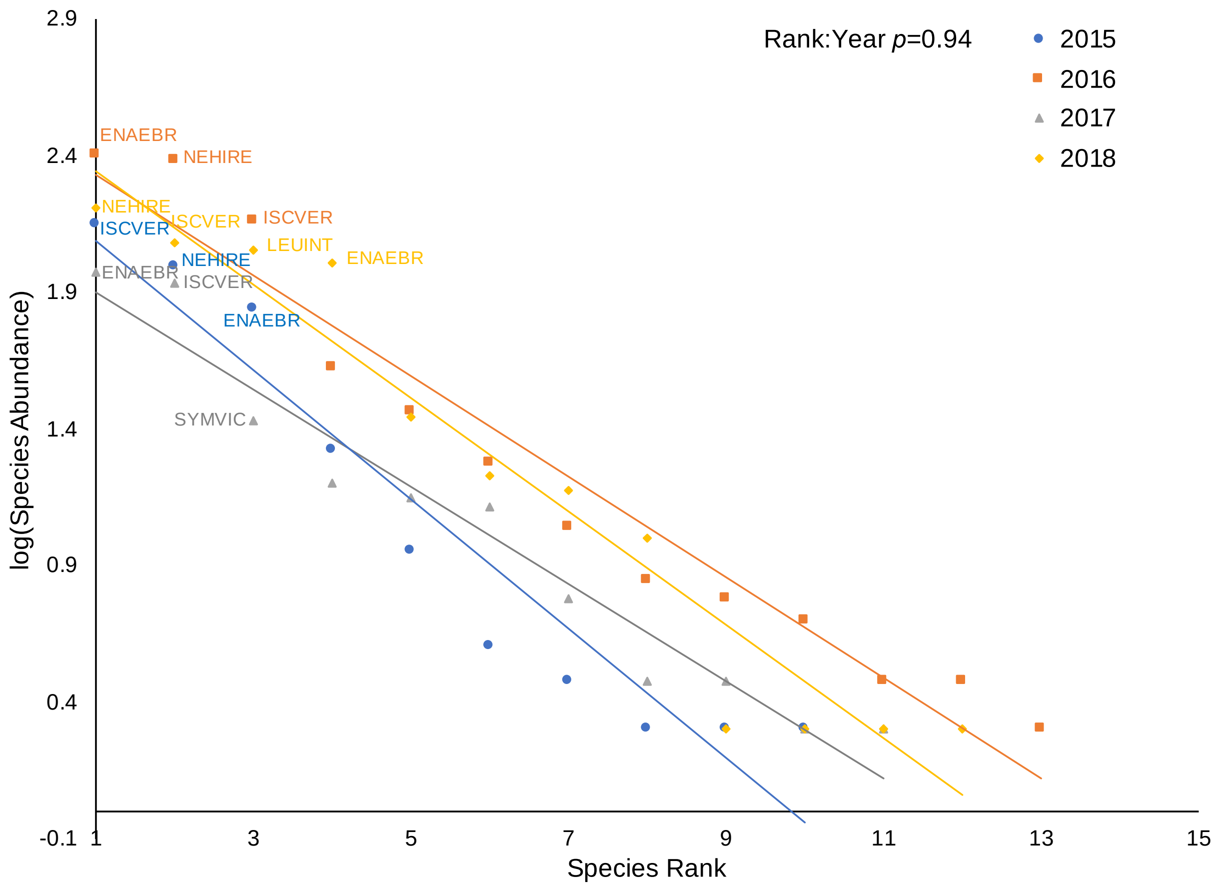


Figure S2.5 Example of a rank-abundance curve showing the community structure of adult Odonata in the same pond (SWF-1204) over a four-year period (part of the subset of ponds n=5 studied through time). Species rank refers to the most to least abundant species and abundance of species are on a log scale. Labels have been created for species representing 75% of total abundance and abbreviations can be found in Table S2.2. The *p*-value for Rank:Year interaction is >0.05 demonstrating that there is no significant difference between the community structure of Odonata between the years (results from ANCOVA). Rare species (one individual) were removed as this represented the detection limit.

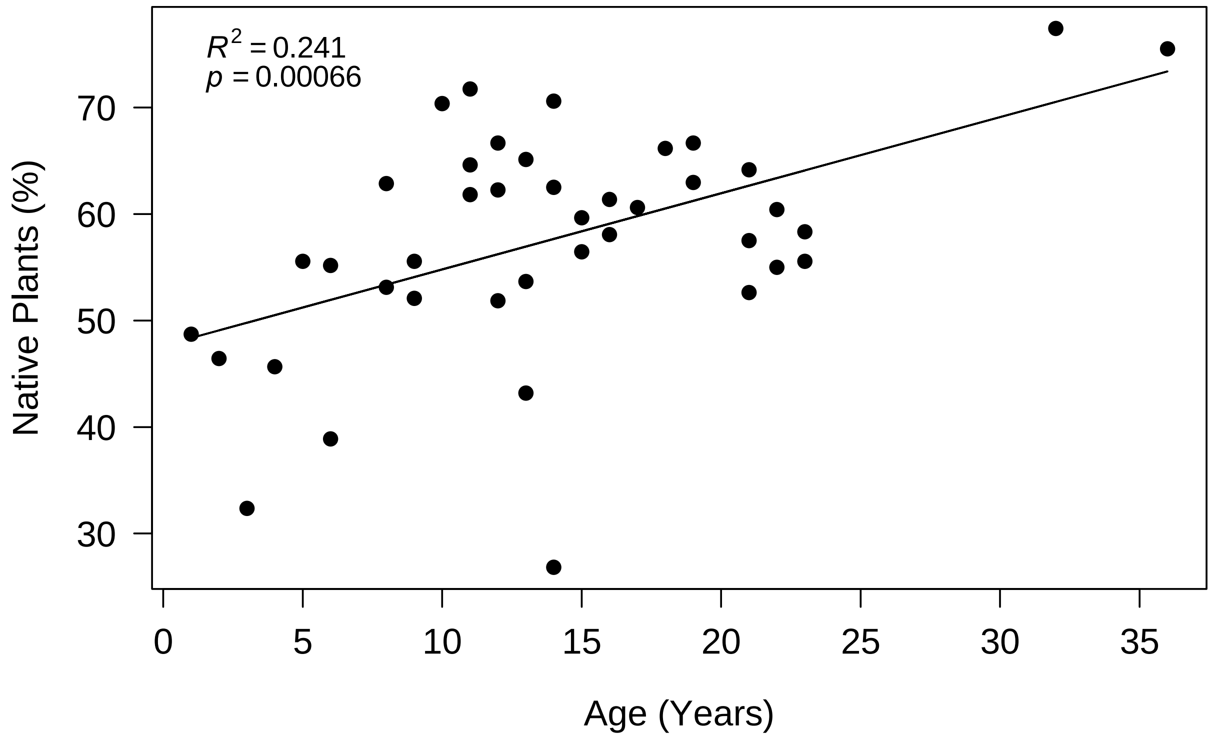


Figure S2.6 Relationship between stormwater pond age and the percentage of native plant species present at stormwater ponds (n=41).

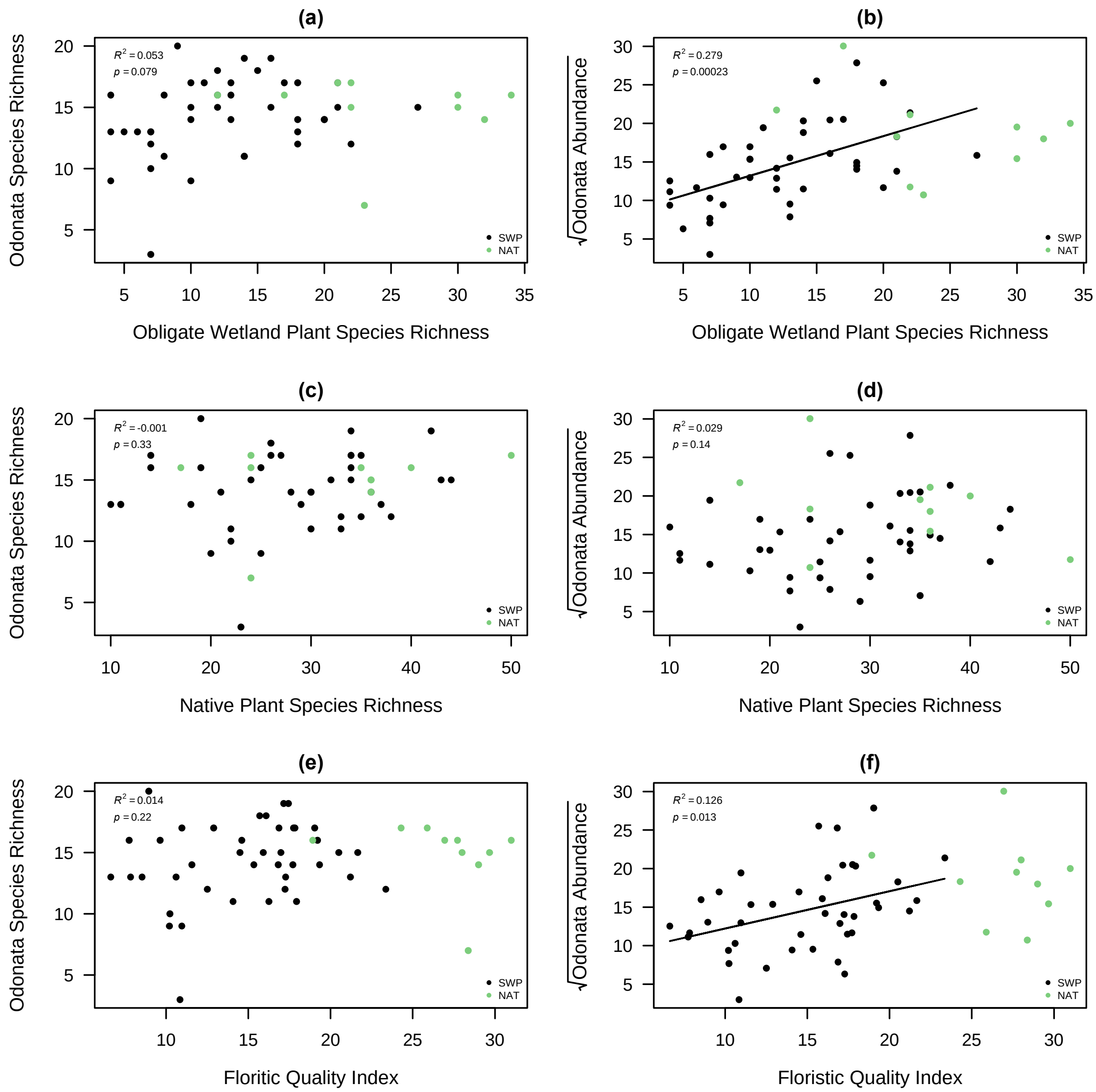


Figure S2.7 Total Odonata species richness and abundance in relation to plant community metrics at stormwater ponds. Regression models based on stormwater ponds exclusively (SWP in black, n=41) with natural ponds (NAT in green, n=10) indicated for reference only. Relationships between Odonata species richness and (a) obligate wetland plant species richness, (c) native plant species richness, (e) Floristic Quality Index, and relationships between total Odonata abundance and (b) obligate wetland plant species richness, (d) native plant species richness, (f) Floristic Quality Index * all plant metrics are assigned based on Oldham et al. (1995).

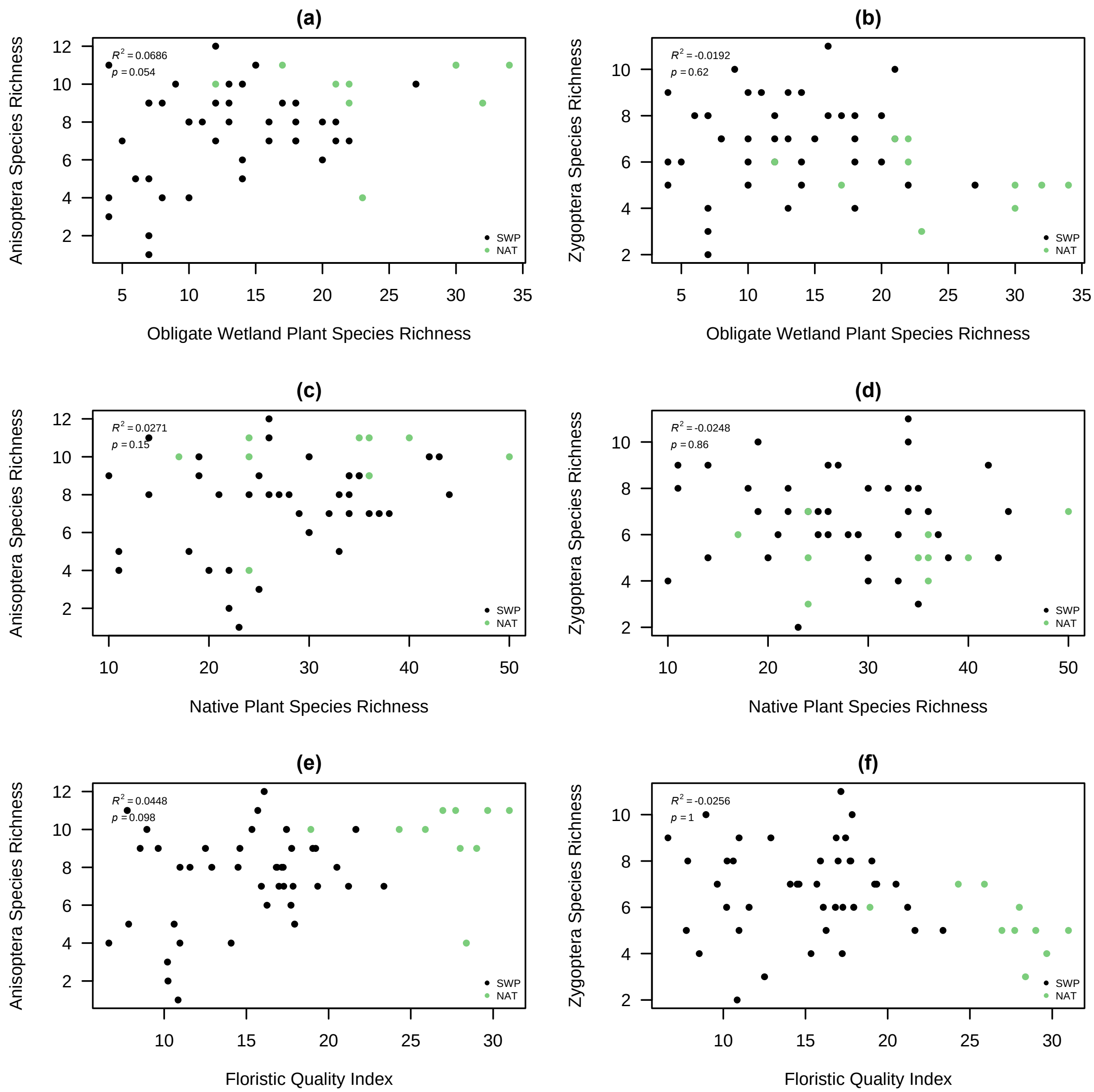


Figure S2.8 Odonate species richness and plant relationships at stormwater ponds. Regression models based on stormwater ponds exclusively (SWP in black, n=41) with natural ponds (NAT in green, n=10) indicated for reference only. Relationships between anisopteran species richness and (a) obligate wetland plant species richness, (c) native plant species richness, (e) Floristic Quality Index, and relationships between zygopteran species richness and (b) obligate wetland plant species richness, (d) native plant species richness, (f) Floristic Quality Index * all plant metrics are assigned based on Oldham et al. (1995).

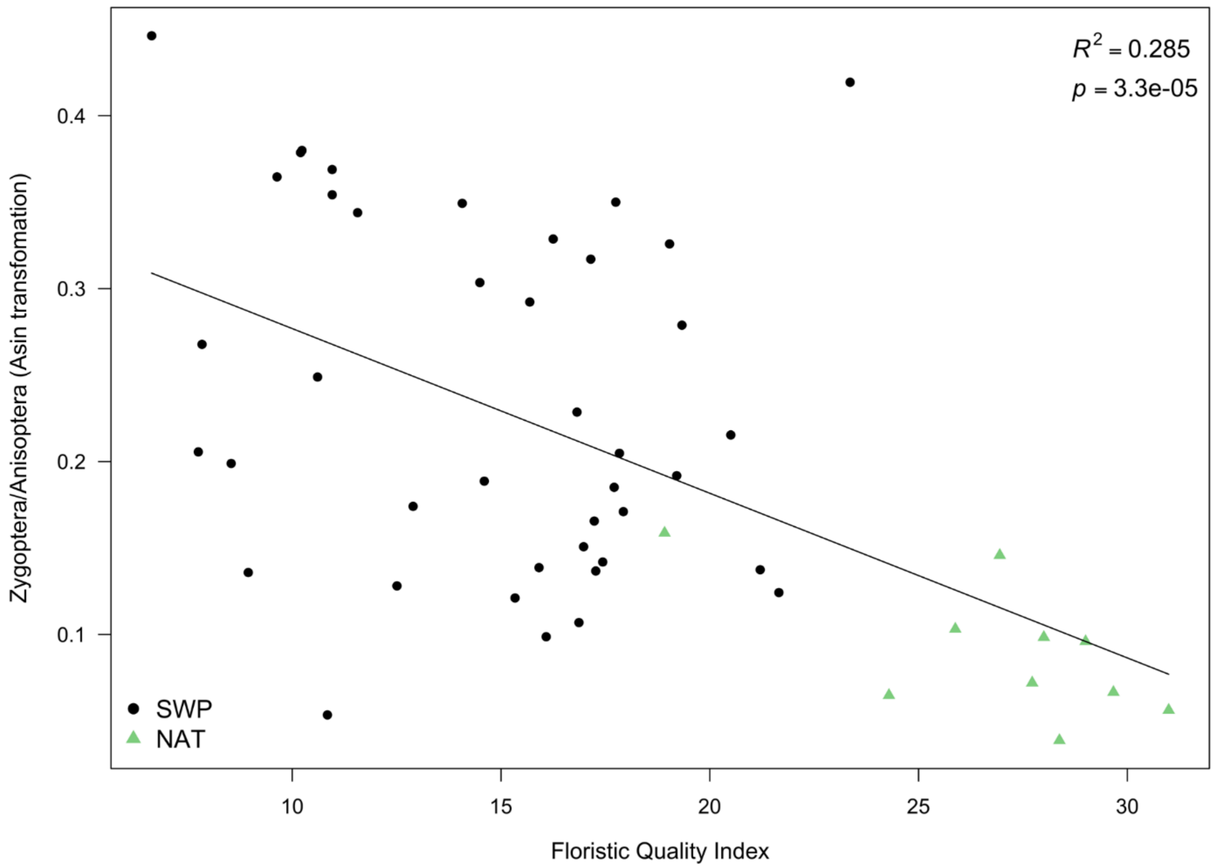


Figure S2.9 The relationship between the Zygoptera/Anisoptera ratio and the Floristic Quality Index (FQI) at study sites (n_{SWP}=41, n_{NAT}=10). The FQI of ponds is assigned based on Oldham et al. (1995).

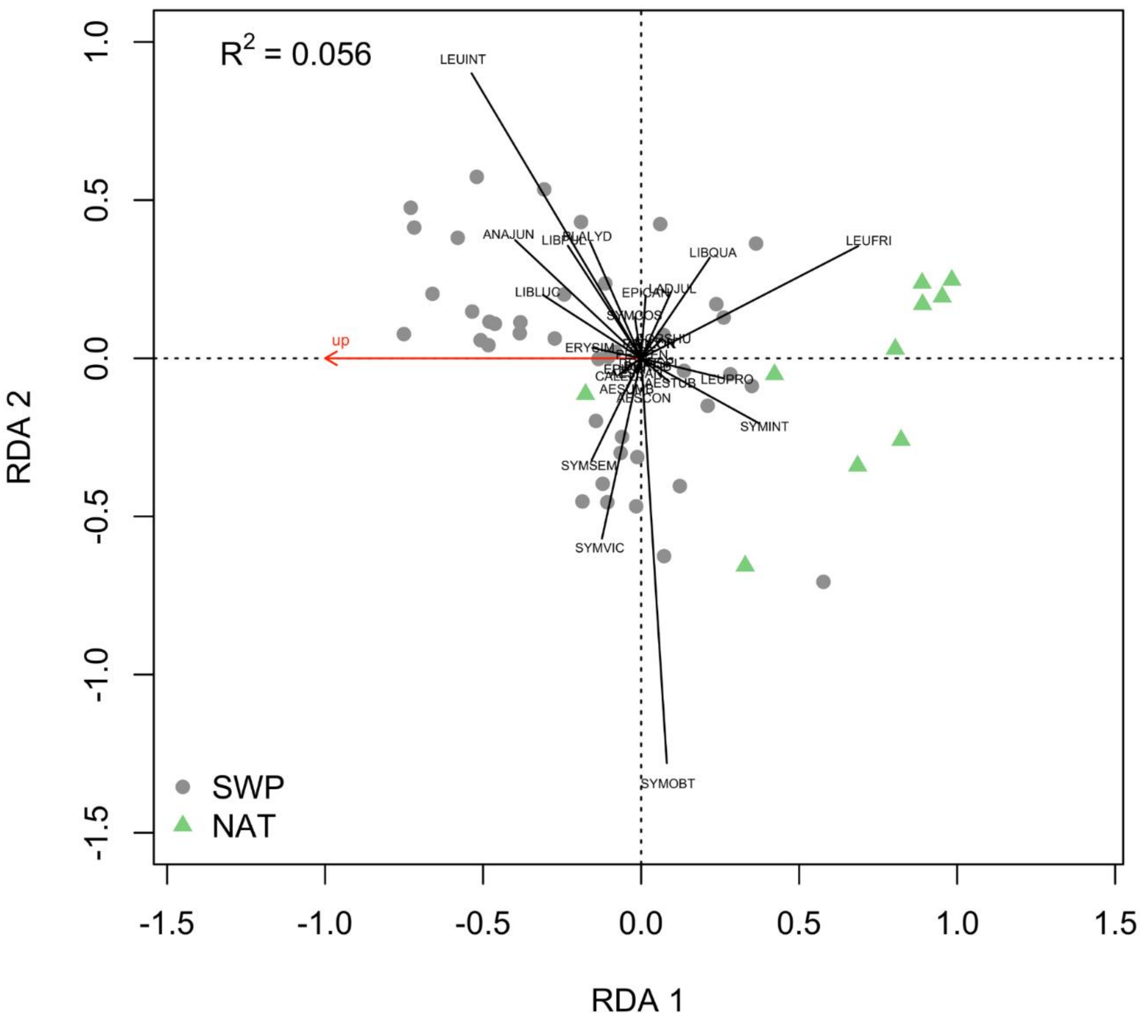


Figure S2.10 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between Anisoptera (dragonfly) species composition (represented by black vectors without arrows, species abbreviations can be found in Table S2.2) and the average cover of significant (*p*<0.05) plant functional guilds (represented by red vectors with arrows, up=upland herbaceous plants) at urban stormwater ponds (SWP, n=41) in grey circles and natural ponds (NAT, n=10) in green triangles. Data plotted in scaling type 2, appropriate for interpreting distance among communities.

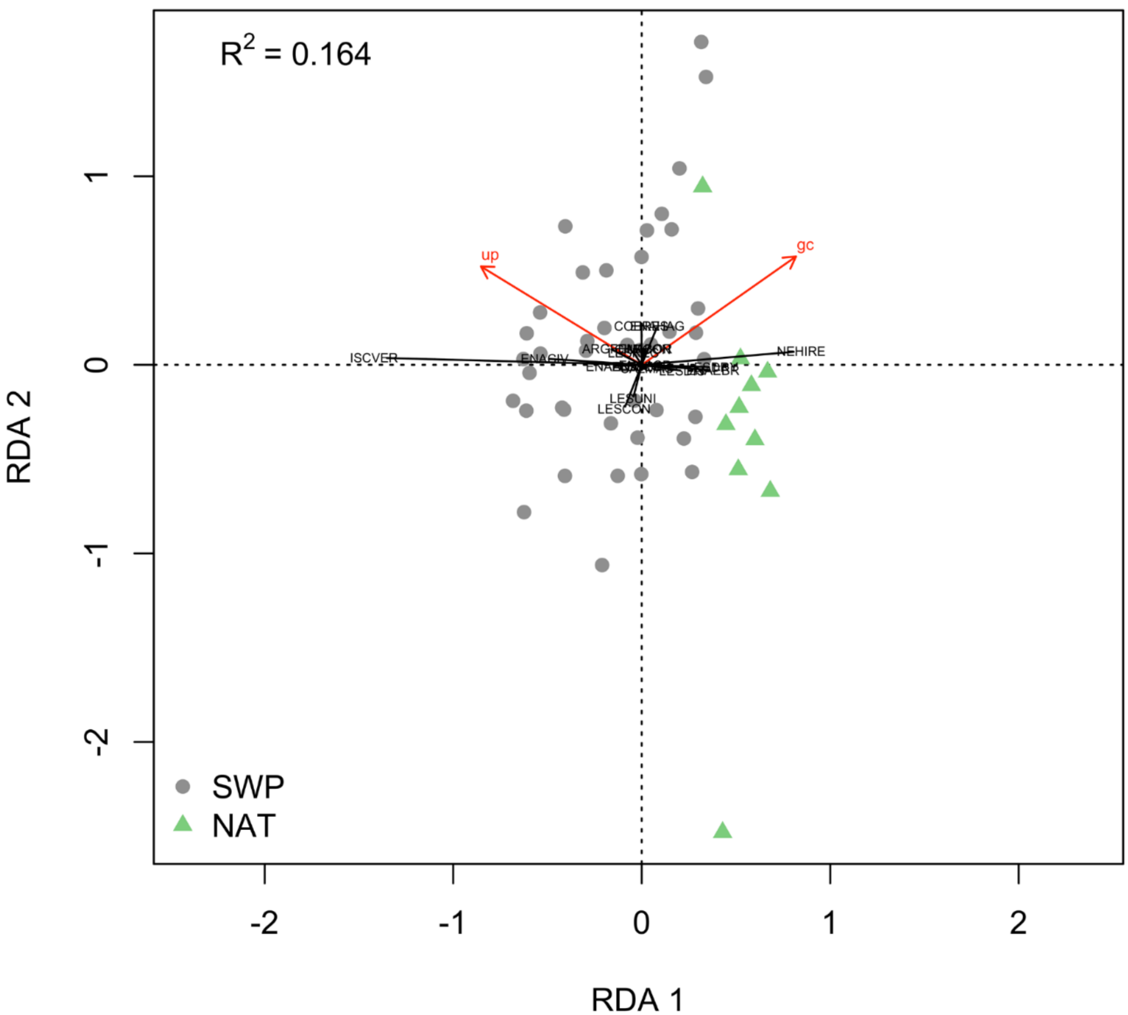


Figure S2.11 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between Zygoptera (damselfly) species composition (represented by black vectors without arrows, species abbreviations can be found in Table S2.2) and the average cover of significant (*p*<0.05) plant functional guilds (represented by red vectors with arrows, up=upland herbaceous plants and gc=wetland herbaceous plants) at urban stormwater ponds (SWP, n=41) in grey circles and natural ponds (NAT, n=10) in green triangles. Data plotted in scaling type 2, appropriate for interpreting distance among communities.

Appendix B: Supplementary Material for Chapter 3

Table S3.1

Physical characteristics of the stormwater ponds (SWF, n=41) and natural ponds (NAT, n=10), including location of pond (latitude and longitude), pond age since construction, pond and catchment basin areas with the percent of imperviousness of the catchment. Ponds were sampled in 2015 and ponds with * were sampled in 2016, na signifies that data were unavailable.

Pond	X, Y coordinates	Age (years)	Area (m^2)	Catchment area (km^2)	Imperviousness of the catchment (%)
SWF-1127	45.33017974, -75.72884265	32	10063	1.471	59.99
SWF-1133	45.36830783, -75.73526815	16	2725	0.373	55.05
SWF-1134	45.31763596, -75.78754088	21	860	0.066	48.58
SWF-1204	45.34220373, -75.90694549	19	2935	0.100	74.34
SWF-1205	45.32004202, -75.88933103	19	3306	0.452	40.16
SWF-1206	45.31482398, -75.89826439	16	8800	0.460	41.75
SWF-1207	45.31016948, -75.92453807	17	11191	0.745	44.20
SWF-1208	45.30832635, -75.92350697	21	6799	0.562	67.77
SWF-1209	45.31152481, -75.93421663	13	2578	0.215	39.51
SWF-1215	45.35286907, -75.92465466	11	3057	1.353	46.41
SWF-1220	45.41657243, -76.1476066	9	578	0.032	na
SWF-1221	45.3475836, -76.03235259	12	1081	0.078	42.17
SWF-1227	45.35740207, -75.9365356	14	8154	0.441	45.89
SWF-1228	45.34245843, -75.93618021	9	7974	0.197	50.41
SWF-1234	45.36322865, -75.92050455	8	5244	0.087	39.49
SWF-1235	45.36465947, -75.92307613	8	5236	0.259	51.39
SWF-1236	45.35621585, -75.93269977	6	1914	0.182	64.72
SWF-1253	45.29948854, -75.93429083	3	2131	0.210	21.99
SWF-1306	45.2854921, -75.88745844	13	5267	0.695	36.28
SWF-1310	45.27005163, -75.9433316	15	3334	0.447	41.10
SWF-TIM2	45.26972619, -75.945565	15	5867	na	na
SWF-1311	45.27185572, -75.94189199	14	3512	0.087	47.69
SWF-1312	45.25775185, -75.93188827	21	2761	0.909	44.80
SWF-1314	45.26769323, -75.91223575	14	7804	0.419	44.09
SWF-1316	45.29861425, -75.91925322	23	4474	0.483	73.29
SWF-1320	45.2738277, -75.91380184	18	1143	0.233	45.18
SWF-1325	45.27357088, -75.90201709	5	10311	0.454	44.57
SWF-1347	45.2860605, -75.90843208	6	1553	0.040	62.46
SWF-1352*	45.27847676, -75.87882062	2	13823	na	na
SWF-1428*	45.27107658, -75.77661898	4	10415	na	na
SWF-1439	45.29284369, -75.79058015	23	5805	0.140	8.26
SWF-1444*	45.26420368, -75.78128195	1	14798	na	na
SWF-1501	45.13916237, -75.719499	36	1267	0.157	25.19
SWF-1610	45.3512119, -75.64518557	22	2905	0.157	46.14
SWF-1616	45.36931473, -75.65283607	13	2996	0.502	33.69
SWF-1621	45.34360175, -75.62729094	12	3506	0.315	48.14
SWF-1622	45.40248832, -75.639495	22	2765	0.210	40.36
SWF-1802	45.26743492, -75.59547947	10	2450	0.186	41.73
SWF-1808	45.23123898, -75.59896445	11	1060	0.018	11.53
SWF-1809	45.23180344, -75.59808048	11	722	0.054	11.54
SWF-1914	45.46813473, -75.44680814	12	8268	0.033	na
NAT-1	45.33810824, -75.94407793	na	1908	0.483	0.000
NAT-2	45.38493452, -76.07759461	na	4750	2.142	0.005
NAT-3	45.04808296, -75.85889868	na	4874	1.001	0.008
NAT-4	45.48190875, -75.85336602	na	4028	1.378	0.034
NAT-5	45.55612795, -75.61218458	na	1570	13.513	0.019
NAT-6*	45.38193056, -76.08365175	na	2963	2.954	0.002
NAT-7*	45.39146021, -76.071336	na	7999	2.142	0.005
NAT-8*	45.046375, -75.858456	na	1383	1.001	0.008
NAT-9*	45.38772056, -76.07981221	na	1586	2.081	0.0003
NAT-10*	45.38854686, -76.08141043	na	9379	2.081	0.0003

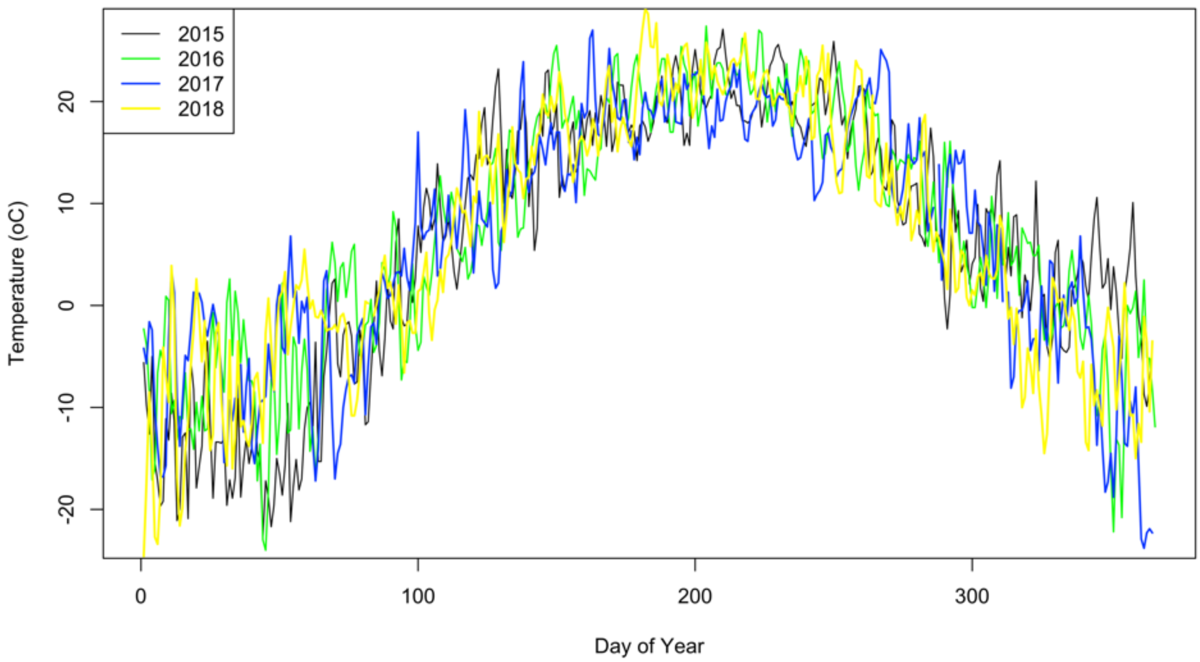


Figure S3.1 Mean daily air temperature from 2015 to 2018 measured at Ottawa International airport (YOW).

Environment Canada, 2015. Daily Data Report 2015-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada, 2016. Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada, 2017. Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada, 2018. Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

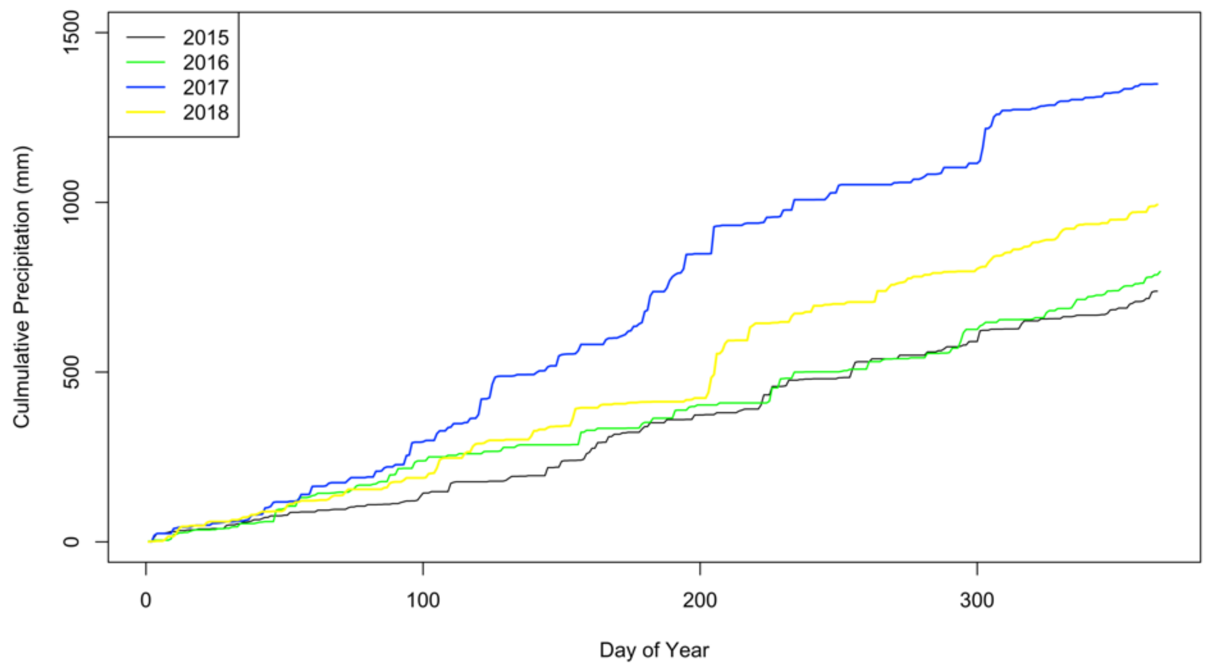


Figure S3.2 Cumulative precipitation (mm) from 2015 to 2018 measured at Ottawa International airport (YOW).

Environment Canada, 2015. Daily Data Report 2015-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada, 2016. Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada, 2017. Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

Environment Canada, 2018. Daily Data Report 2016-monthly. Ottawa, ON, Canada. Ottawa International Airport. TC ID: YOW. WMO ID: 71628. Climate ID: 6106001

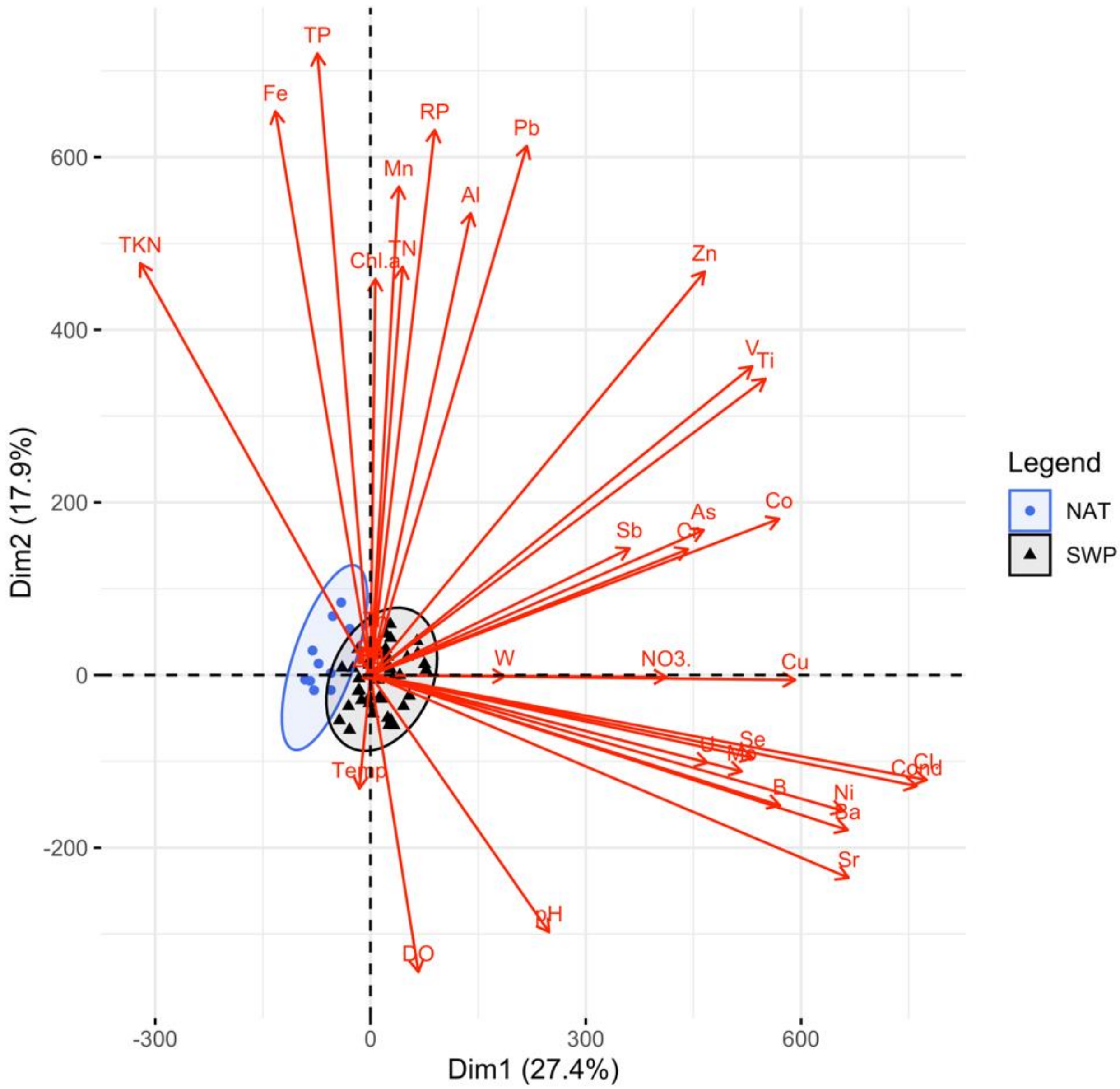


Figure S3.3 Principal Component Analysis (PCA) of 38 ranked water quality variables sampled in stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10) with 95% confidence ellipses based on pond type (SWP, NAT) rank means. Water quality variables were ranked (with tied values assigned average rank values) as measures under detection limit were present (especially for Ag, Cd, Be, Bi, Sn, Th, W and Zr that were 80-100% under detection) as a non-parametric way to display data.

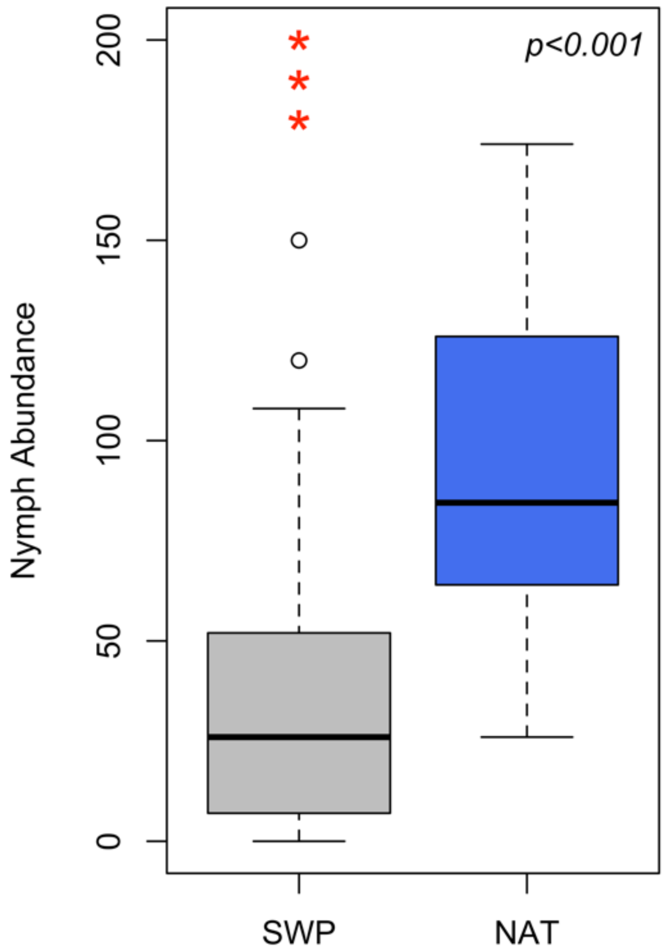


Figure S3.4 Comparison (unpaired t-test) between total nymph abundance in stormwater ponds (SWP, n=41) and natural ponds (NAT, n=10).

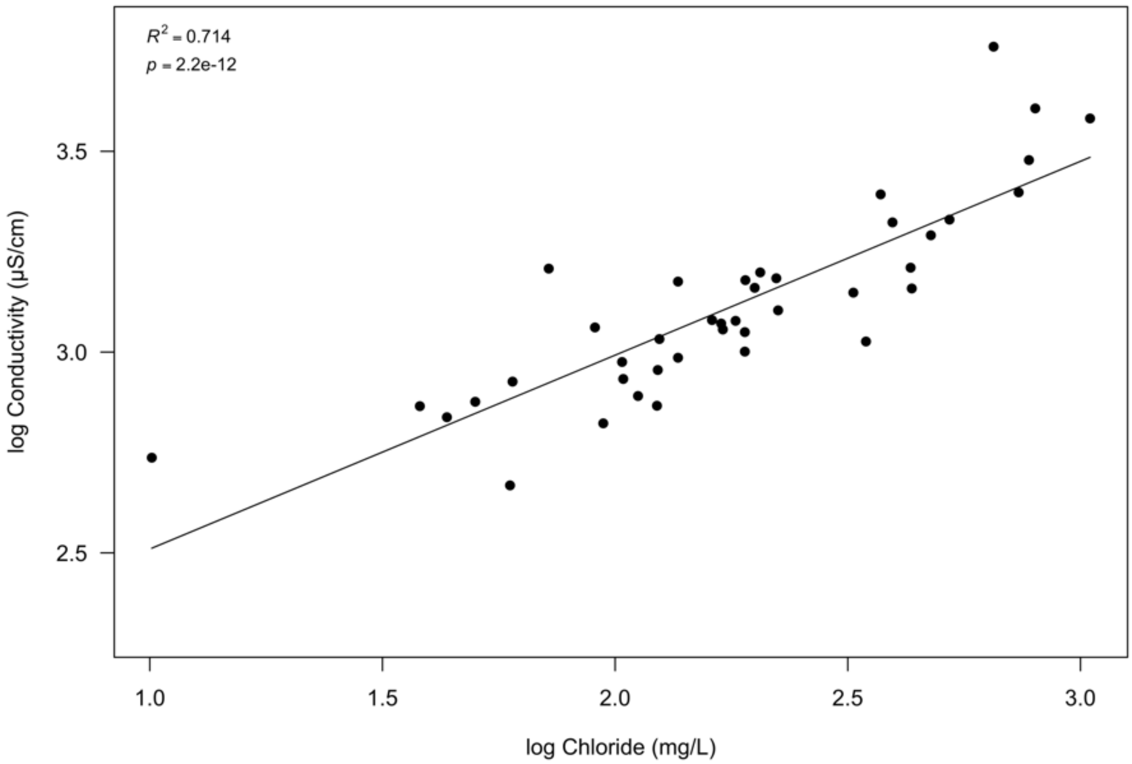
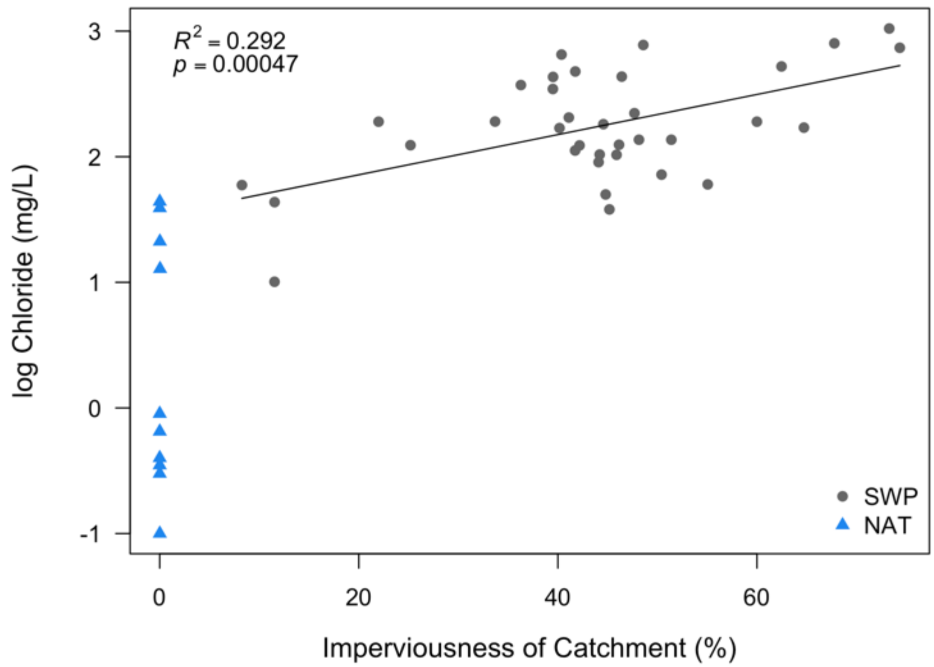


Figure S3.5 Linear regression between chloride concentrations and conductivity measures in stormwater ponds (n=41).

(a)



(b)

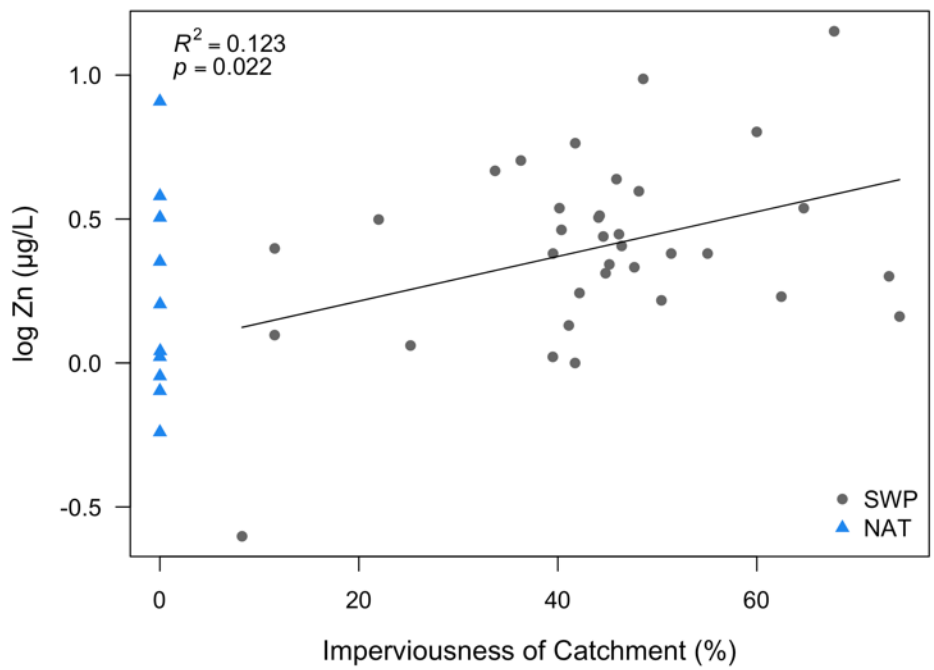


Figure S3.6 Relationships between the percent imperviousness of pond catchments and (a) chloride concentrations and (b) zinc concentrations in urban stormwater ponds. Regression models based on stormwater ponds exclusively (SWP, n=35, grey circles), with natural ponds (NAT, n=10, blue triangles) indicated for reference only.

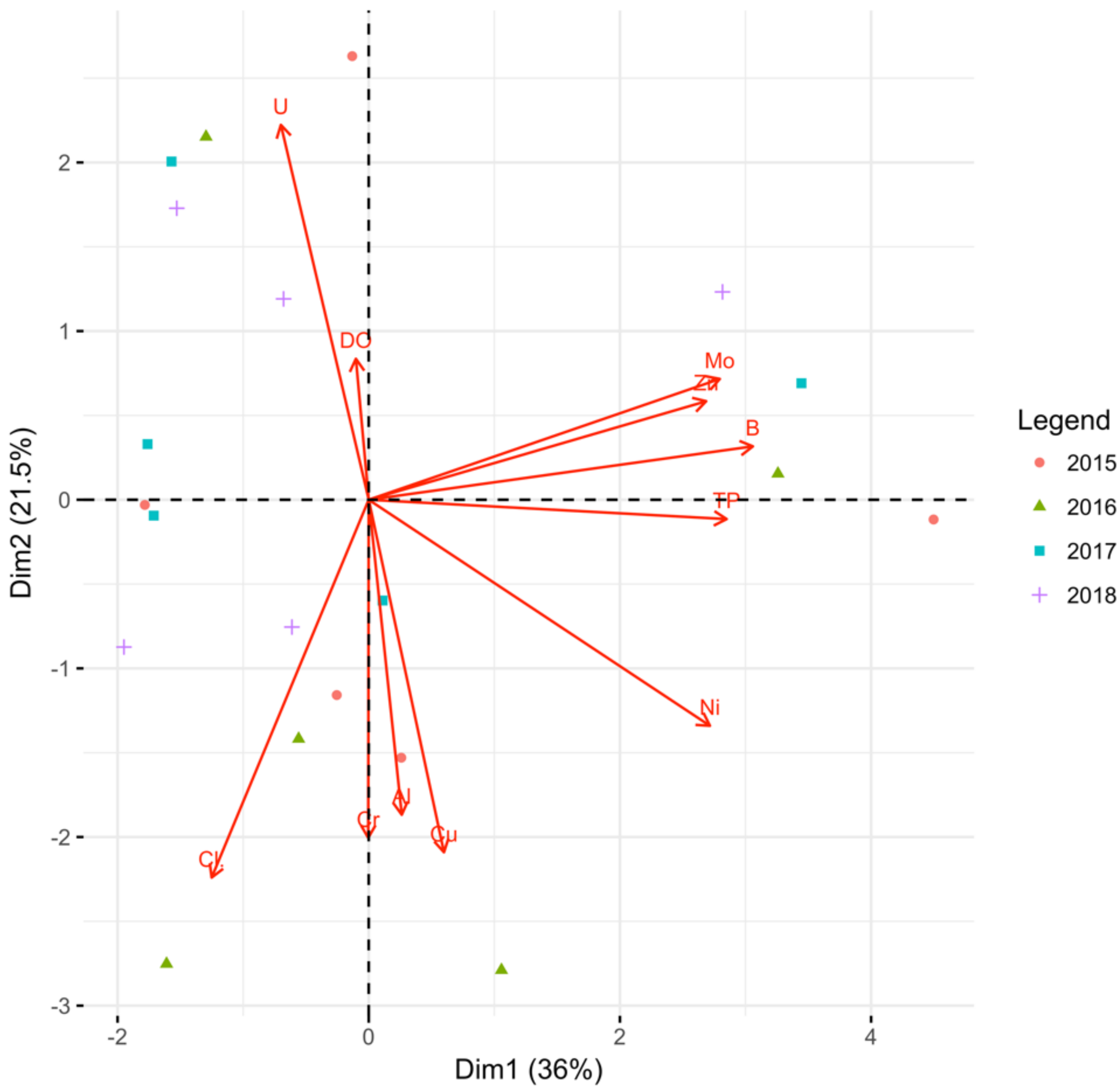
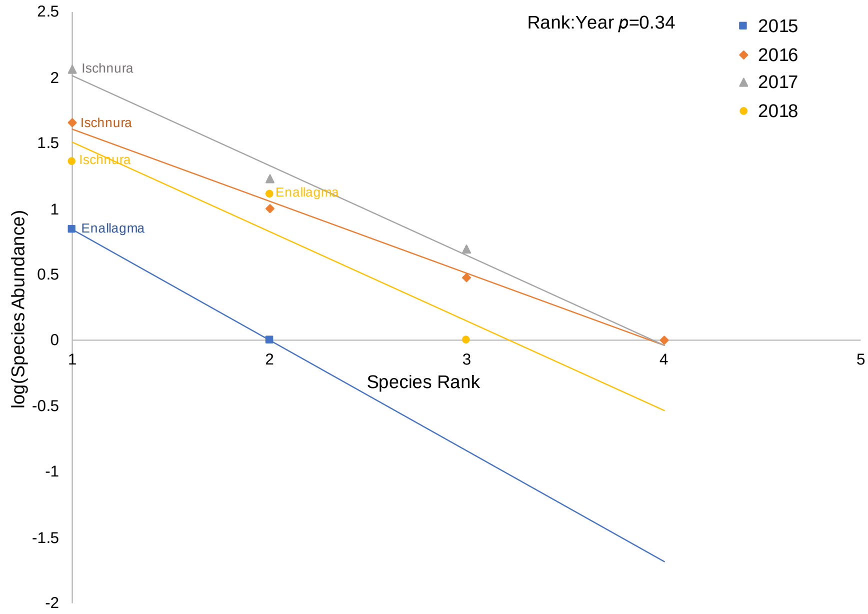


Figure S3.7 Principal Component Analysis (PCA) of 12 water quality variables, displayed by year, sampled in stormwater ponds (N_{pond}=5) over a four-year period (N_{time}=4). The number of water quality variables were reduced by removing the highly correlated variables. Water quality measures that were below detection limit were replaced with half the value of the corresponding detection limit. Water quality variables were scaled and centered as units differed between measures.

(a)



(b)

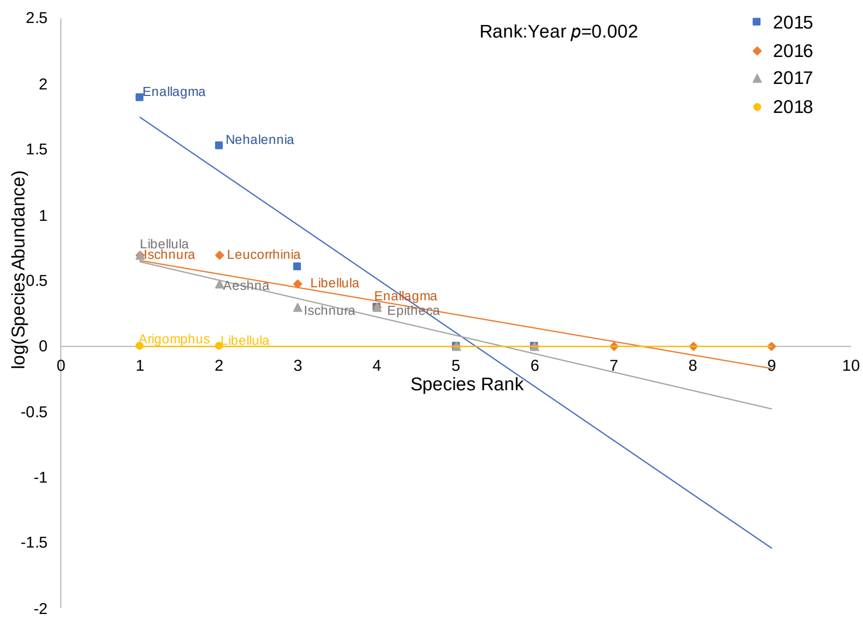


Figure S3.8 Rank-abundance curves of the community structure of Odonata nymphs in the same ponds over a four-year period (part of the subset of ponds n=5 studied through time). Rank is ordered from most to least abundant genus and abundance of genera are on a log scale. Labels have been created for genera representing 75% of the total abundance. (a) SWF-1616 with no significant interaction between the community structure over a four year period (Rank:Year) and (b) SWF-1204 with a significant interaction between the community structure over a four year period (Rank:Year).

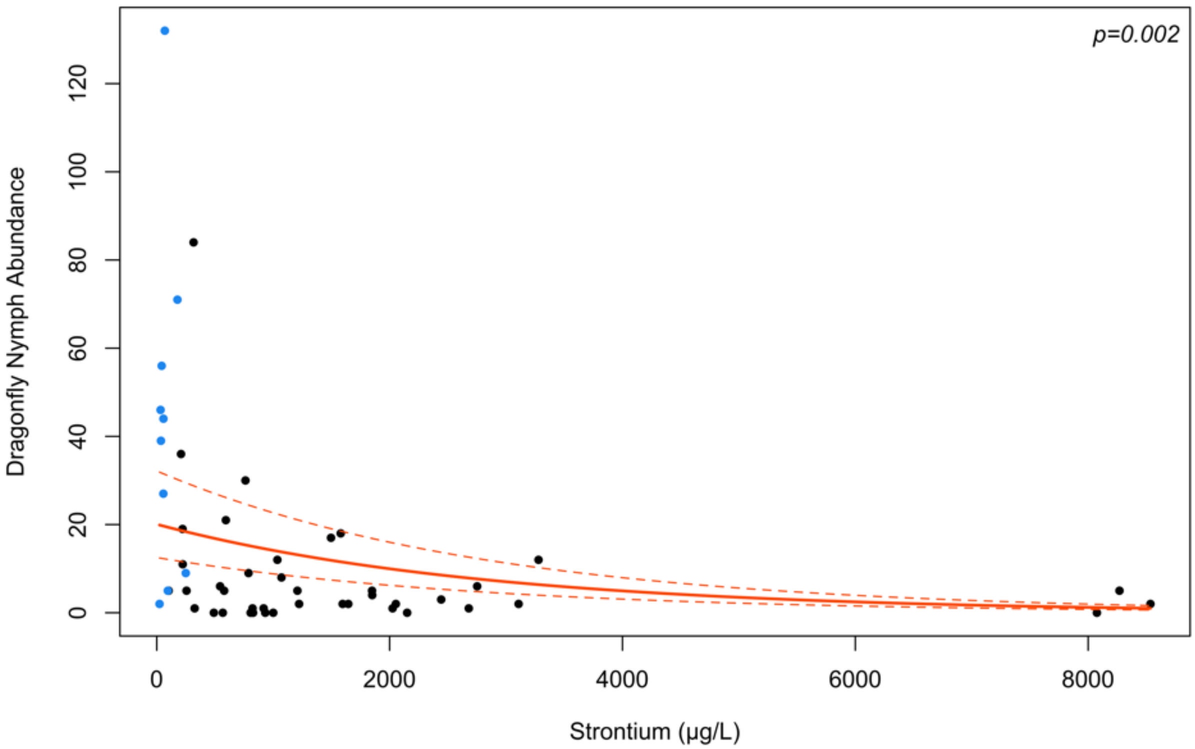


Figure S3.9 Negative binominal generalized linear model of the relationship between strontium concentrations (µg/L) and dragonfly nymph abundance in stormwater ponds (black, n=41) and natural ponds (blue, n=10).

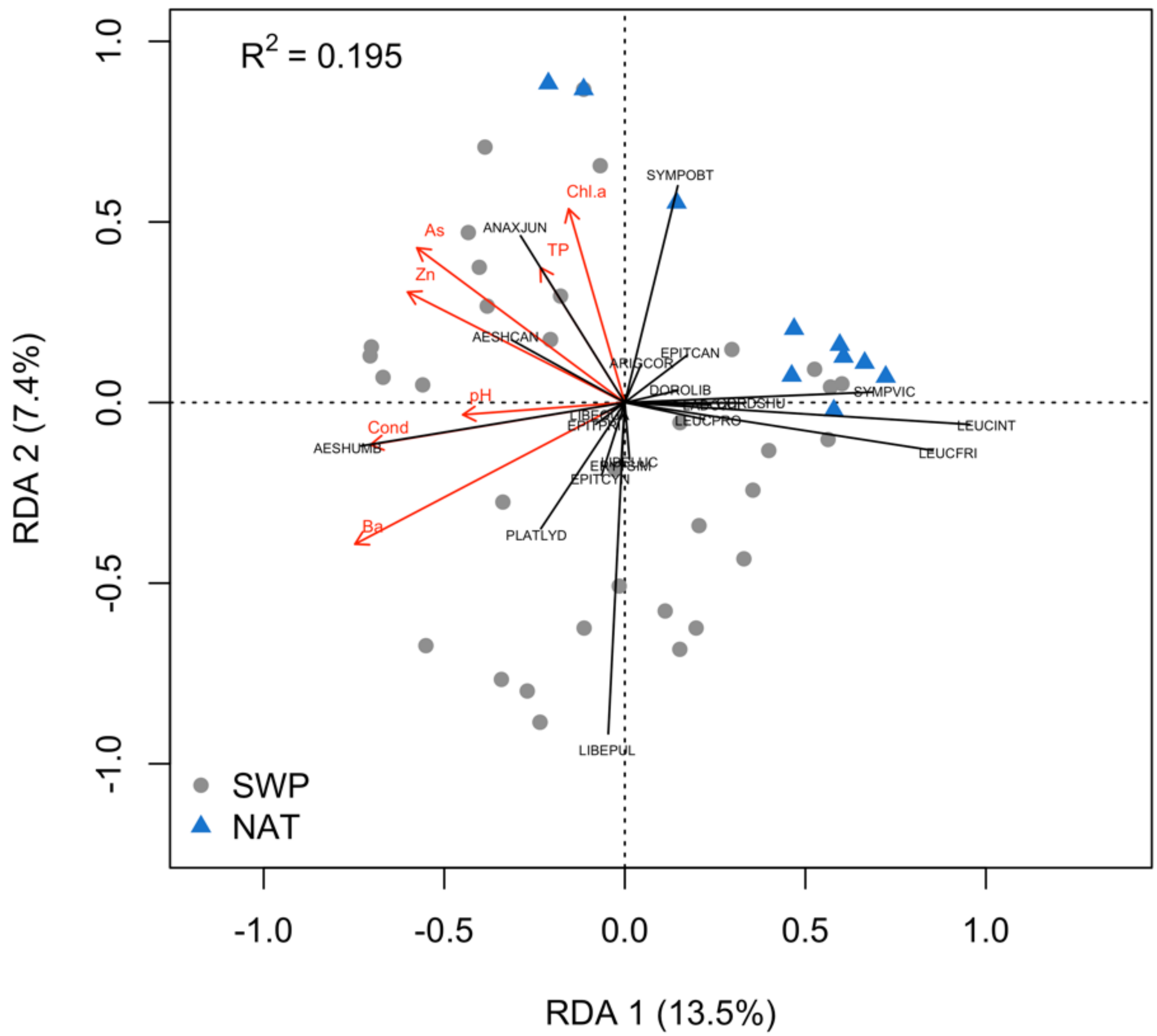


Figure S3.10 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between dragonfly (Anisoptera) species composition (represented by black vectors without arrows) and significant (p<0.05) water quality variables determined through forward stepwise regression (represented by red vectors with arrows) at stormwater ponds (SWP, grey circles, n=41) and natural ponds (NAT, blue triangles, n=10). Data plotted in scaling type 2, appropriate for interpreting distance among communities. Species abbreviations are as follow: AESH = *Aeshna* (AESHCAN= *A. canadensis*, AESHUMB= *A. umbrosa*, AESHTUB= *A. tuberculifera*), ANAXJUN= *Anax junius*, ARIGCOR= *Arigomphus cornutus*, EPIT= *Epitheca (EPITCAN= E. canis*, EPITCYN= *E. cynosura*, EPITPRI= *E. princeps*, EPITSPI= *E. spinigera*), CORDSHU= *Cordulia shurtlefii*, DOROLIB= *Dorocordulia libera*, LADOJUL= *Ladona julia*, PLATLYD= *Plathemis lydia*, LIBE= *Libellula* (LIBEPUL= *L. pulchella*, LIBELUC= *L. luctuosa*, LIBEQUA= *L. quadrimaculata*) SYMP= *Sympetrum* (SYMPOBT= *S. obstrusum*, SYMPVIC= *S. vicinum*), LEUC= *Leucorrhinia* (LEUCINT= *L. intacta*, LEUCFRI= *L. frigida*, LEUCPRO= *L. proxima*), ERYTSIM= *Erythemis simplicicollis.*

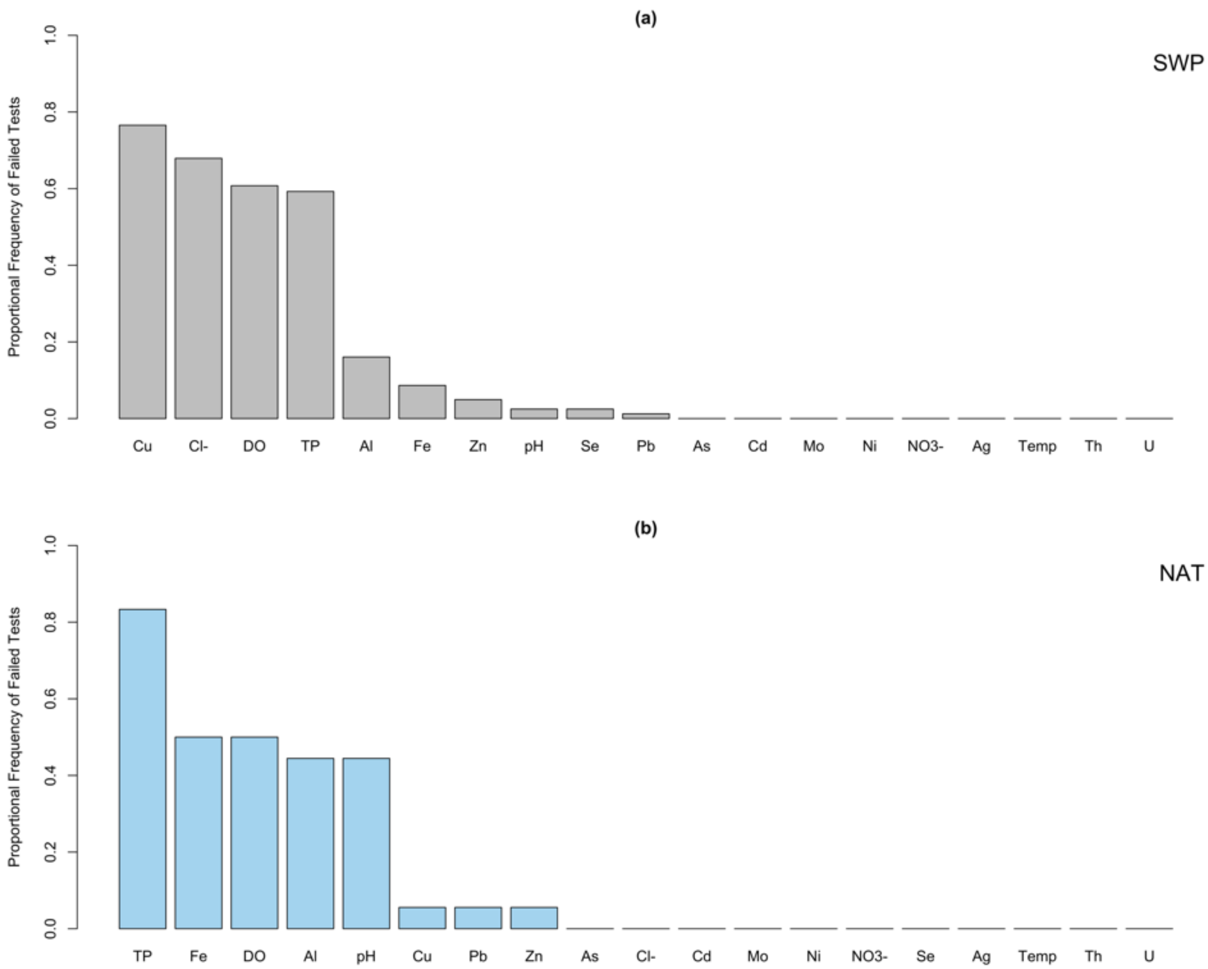


Figure S3.11 The proportional frequency of each water quality variable that did not meet the Canadian Council of Ministers of the Environment (CCME) water quality guideline for the protection of aquatic life used for the calculation of the CCME Water Quality Index for: (a) stormwater ponds (SWP) and (b) natural ponds (NAT).

Appendix C: Supplementary Material for Chapter 4

(a) **(b)**

Figure S4.1 Photos demonstrating differences in stormwater pond design: (a) pond SWF-1227 with hardscaped bank containing rock gabion walls, and (b) pond SWF-1209 with gradual sloping vegetated bank.

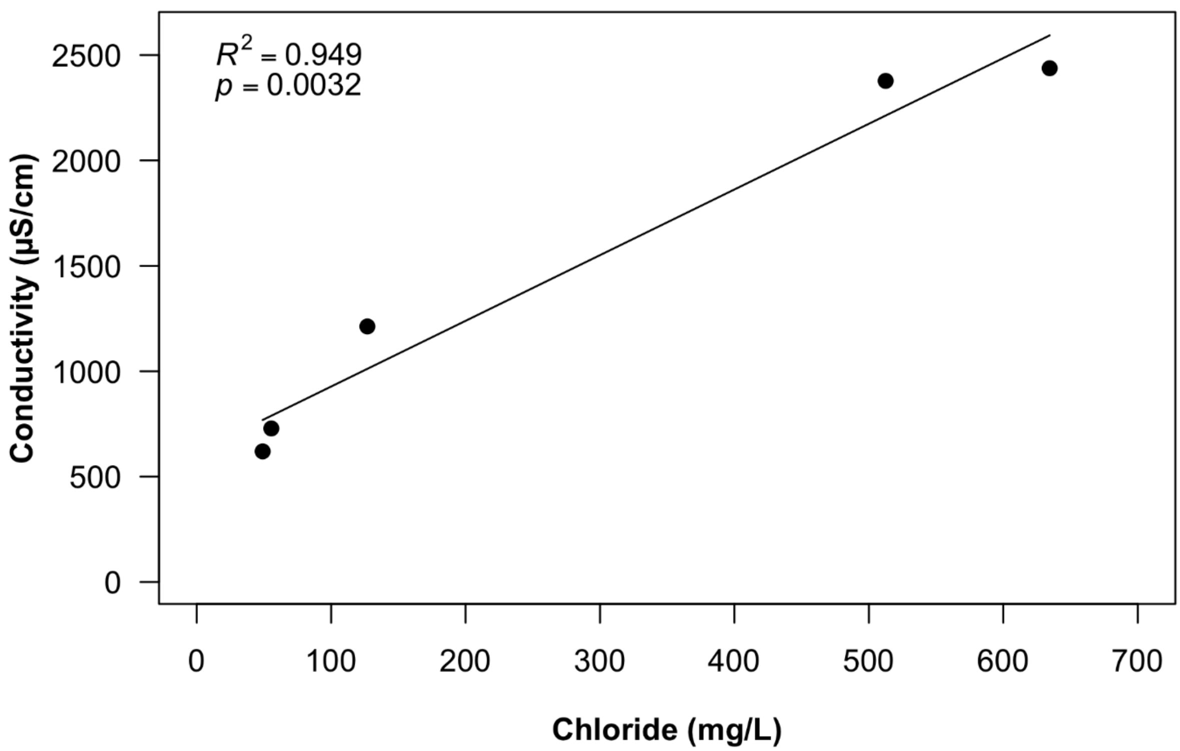


Figure S4.2 The relationship between chloride concentrations and conductivity in stormwater ponds (n=5) from Ottawa, Ontario, Canada.

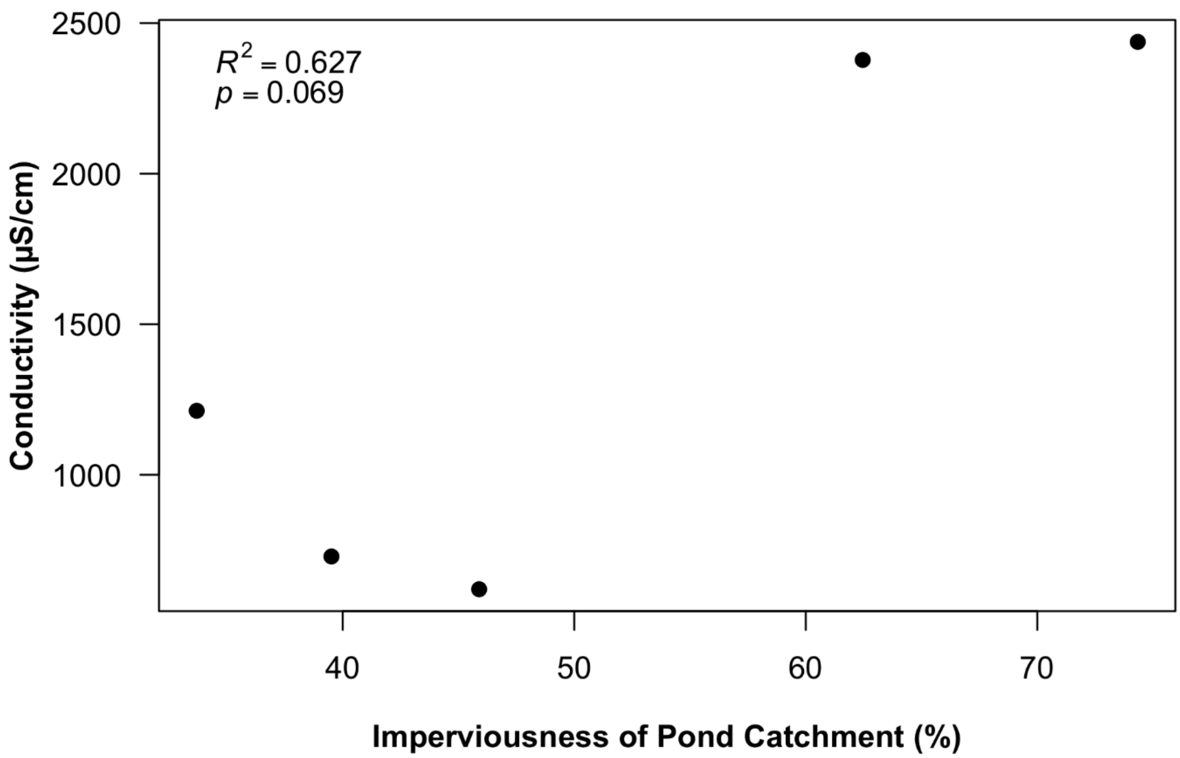


Figure S4.3 The relationship between the imperviousness of the pond catchment basin and the conductivity of stormwater ponds (n=5) from Ottawa, Ontario, Canada.

(a) (b)

Figure S4.4 The artificial emergence screens used to collect Odonata exuviae at ponds. Each screen was 0.8 x 1 m with 0.2 m legs used to secure screen in sediments: (a) side view, and (b) face view.

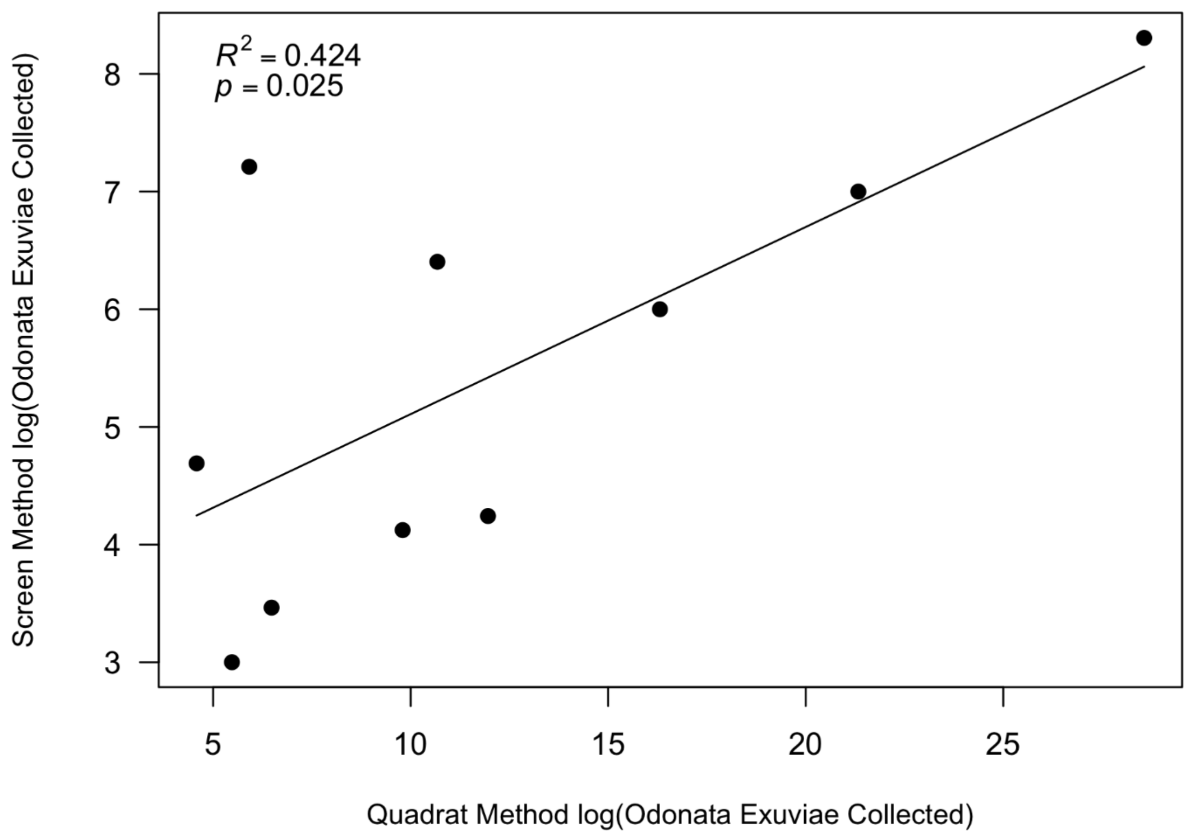


Figure S4.5 The relationship between the number of Odonata exuviae collected at study ponds (n=10) using the quadrat method compared to the number collected using the artificial emergence screen method.

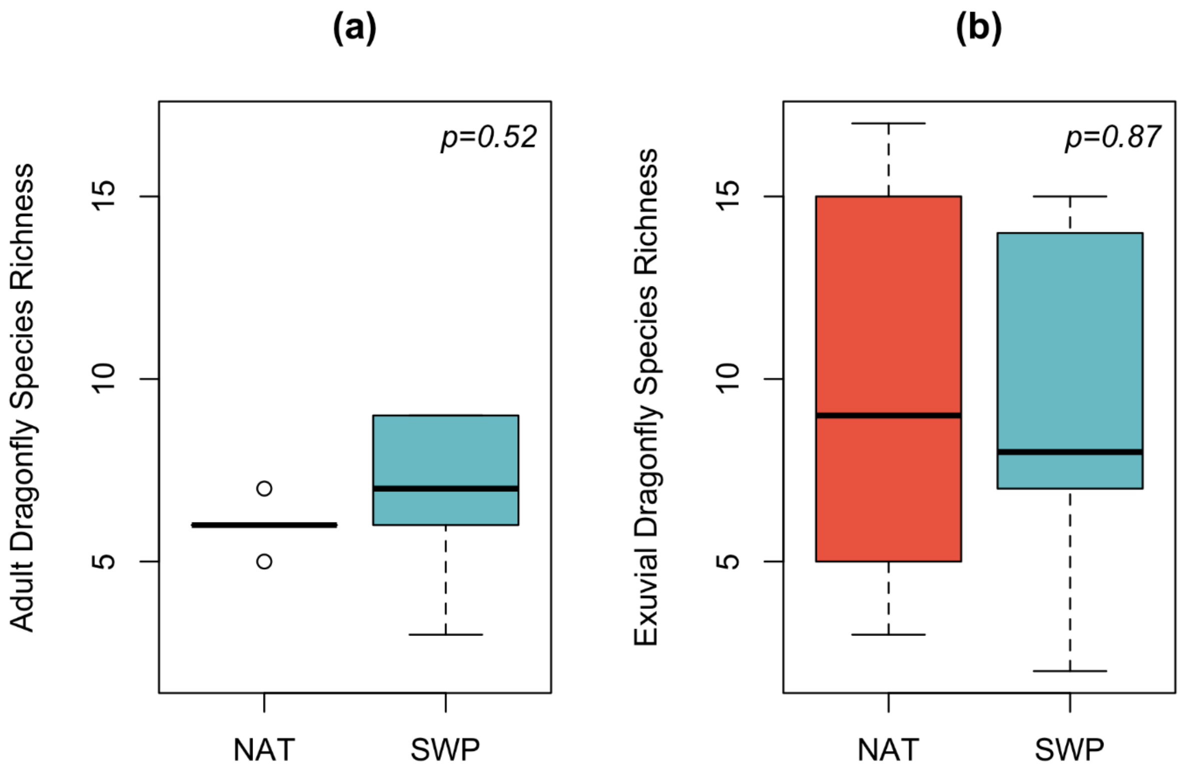


Figure S4.6 Average dragonfly species richness at stormwater ponds (SWP, n=5) and natural ponds (NAT, n=5) of (a) adults and (b) exuviae, with statistics from unpaired t-test.

Appendix D: Supplementary Material for Chapter 5

Table S5.1

The scale of effect of land cover types (bolded) determined for adult dragonfly species composition at 51 study ponds (stormwater ponds n=41, natural ponds n=10) in the National Capital Region of Canada. The goodness of fit (adjusted R^2 value) obtained from transformation-based redundancy models (tb-RDA with Hellinger transformation) of significant land cover types at a 100 m, 500 m, 1 km, 2 km and 5 km scale (buffer) around study ponds. Significant land cover types for each scale model were obtained through stepwise forward regression using 9,999 permutations.

Scale	Significant landcover types	*p*-values	$R^2_{adjusted}$
100 m	Wetland	0.002	0.082
	Water	0.042	
500 m	Settlement	0.002	0.085
	Rock Barren	0.022	
1 km	Rock Barren	0.002	0.116
	Transportation	0.008	
	Settlement	0.024	
2 km	**Rock Barren**	**0.002**	**0.125**
	Wetland	**0.008**	
	Wooded Area	**0.018**	
	Golf Course Pond	**0.048**	
5 km	Rock Barren	0.004	0.059
	Wooded Area	0.038	

Table S5.2

The scale of effect of land cover types (bolded) determined for dragonfly nymph species composition at 50 study ponds (stormwater ponds n=41 and natural ponds n=9) in the National Capital Region of Canada. The goodness of fit (adjusted R^2 value) obtained from transformation-based redundancy models (tb-RDA with Hellinger transformation) of significant land cover types at a 100 m, 500 m, 1 km, 2 km and 5 km scale (buffer) around study ponds. Significant land cover types for each scale model were obtained through stepwise forward regression using 9,999 permutations.

Scale	Significant landcover types	*p*-values	$R^2_{adjusted}$
100 m	Settlement	0.004	0.064
	Grassland	0.006	
500 m	Wetland	0.002	0.042
1 km	Rock Barren	0.002	0.072
	Settlement	0.014	
2 km	**Transportation**	**0.002**	**0.125**
	Rock Barren	**0.008**	
	Settlement	**0.012**	
	Golf Course Pond	**0.024**	
5 km	Transportation	0.002	0.060

Table S5.3

The scale of effect of land cover types (bolded) determined for adult damselfly species composition at 51 study ponds (stormwater ponds n=41 and natural ponds n=10) in the National Capital Region of Canada. The goodness of fit (adjusted R^2 value) obtained from transformation-based redundancy models (tb-RDA with Hellinger transformation) of significant land cover types at a 100 m, 500 m, 1 km, 2 km and 5 km scale (buffer) around study ponds. Significant land cover types for each scale model were obtained through stepwise forward regression using 9,999 permutations.

Scale	Significant landcover types	*p*-values	$R^2_{adjusted}$
100 m	Wooded Area	0.002	0.187
	Rock Barren	0.004	
	Stormwater Pond	0.026	
500 m	**Wooded Area**	**0.002**	**0.188**
	Rock Barren	**0.004**	
	Stormwater Pond	**0.032**	
1 km	Wooded Area	0.002	0.170
	Grassland	0.002	
2 km	Wooded Area	0.002	0.151
5 km	Wooded Area	0.002	0.159
	Golf Course Pond	0.020	
	Sand and Gravel	0.050	

Table S5.4

The scale of effect of land cover types (bolded) determined for damselfly nymph genera composition at 46 study ponds (stormwater ponds n=40 and natural ponds n=6) in the National Capital Region of Canada. The goodness of fit (adjusted R^2 value) obtained from transformation-based redundancy models (tb-RDA with Hellinger transformation) of significant land cover types at a 100 m, 500 m, 1 km, 2 km and 5 km scale (buffer) around study ponds. Significant land cover types for each scale model were obtained through stepwise forward regression using 9,999 permutations.

Scale	Significant landcover types	*p*-values	$R^2_{adjusted}$
100 m	none significant	NA	NA
500 m	none significant	NA	NA
1 km	none significant	NA	NA
2 km	none significant	NA	NA
5 km	**Wetland**	**0.008**	**0.076**

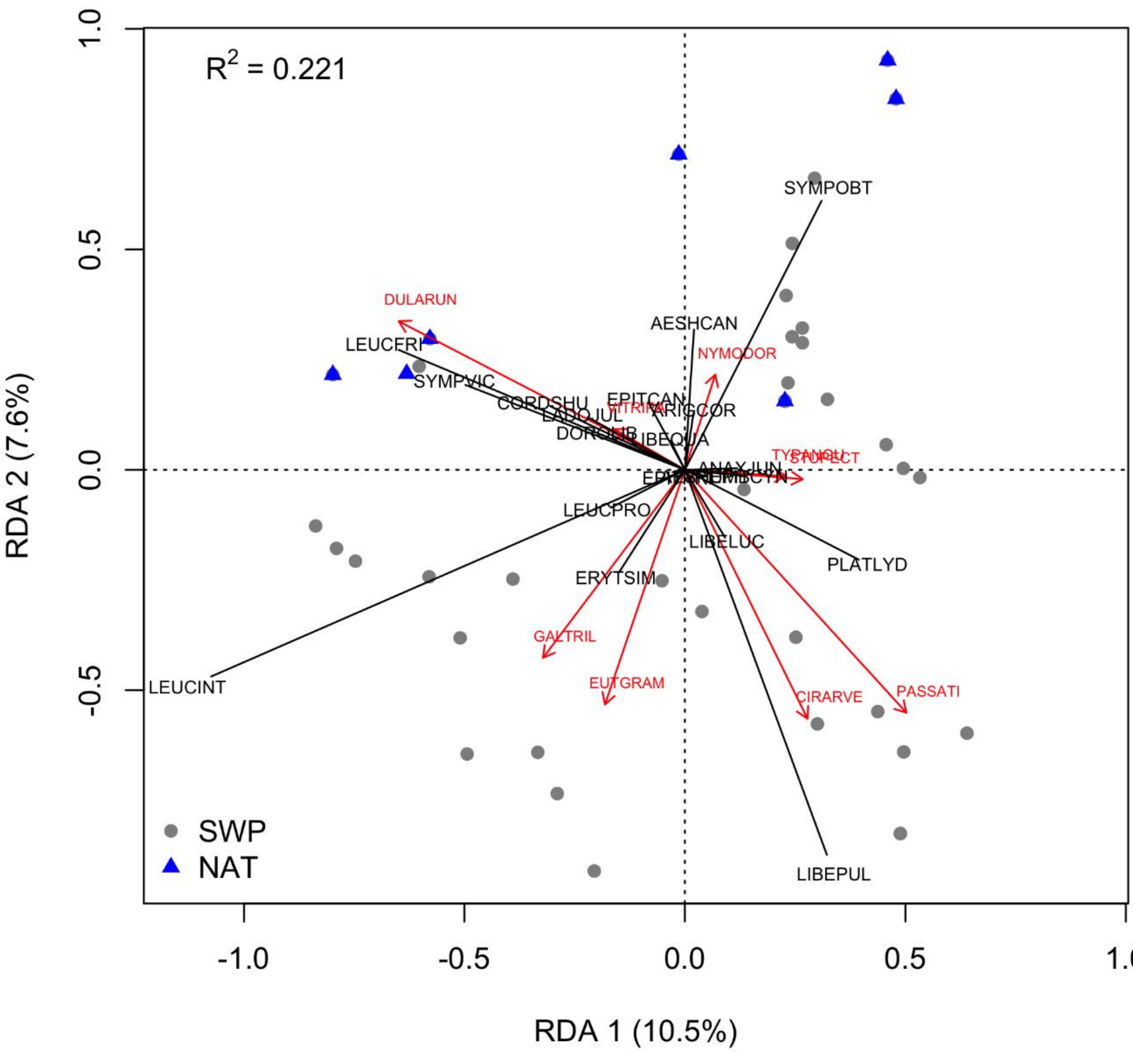


Figure S5.1 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between dragonfly (Anisoptera) nymph species composition (represented by black vectors without arrows, species abbreviations can be found in Table S2.2) and significant (*p*<0.05) plant species [DULARUN= *Dulichium arundinaceum*, VITRIPA= *Vitis riparia*, NYMODOR= *Nymphaea odorata*, TYPANGU= *Typha angustifolia*, STUPECT= *Stuckenia pectinata*, PASSATI= *Pastinaca sativa*, CIRARVE= *Cirsium arvense*, EUTGRAM= *Euthamia graminifolia*, GALTRIL= *Galium triflorum*] determined through forward stepwise regression with 9,999 permutations (represented by red vectors with arrows) at stormwater ponds (SWP, grey circles, n=41) and natural ponds (NAT, blue triangles, n=9). Data plotted in scaling type 2, appropriate for interpreting distance among communities.

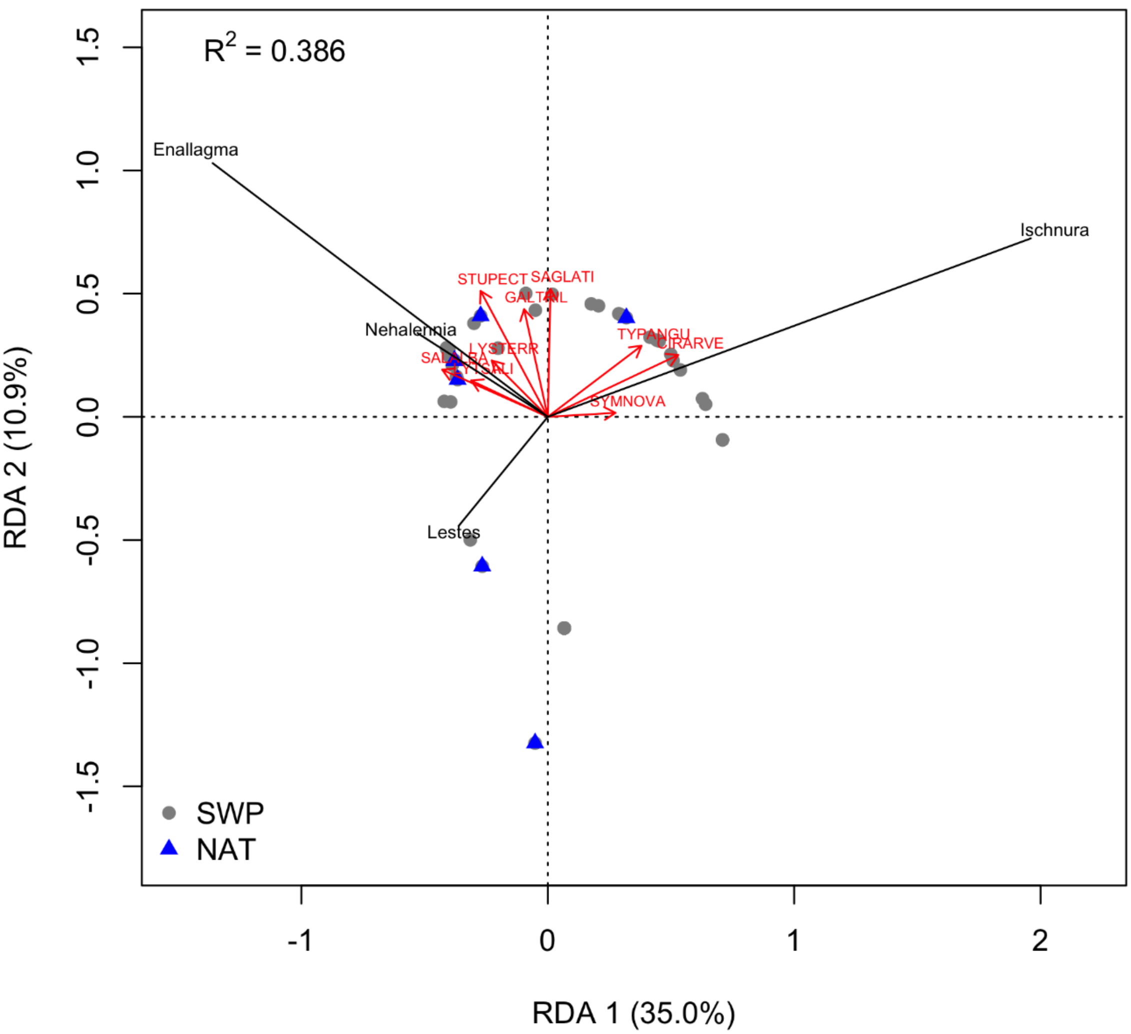


Figure S5.2 A transformation based-redundancy analysis (tb-rda) (with Hellinger transformation) of the relationship between damselfly (Zygoptera) nymph genera composition (represented by black vectors without arrows, species abbreviations can be found in Table S2.2) and significant (p<0.05) plant species [STUPECT= *Stuckenia pectinata*, GALTRIL= *Galium triflorum*, SAGLATI= *Sagittaria latifolia*, TYPANGU= *Typha angustifolia*, CIRARVE= *Cirsium arvense*, SYMNOVA= *Symphyotrichum novae-angliae*, SALABLA= *Salix alba*, LYTSALI= *Lythrum salicaria*, LYSTERR= *Lysimachia terrestris*] determined through forward stepwise regression with 9,999 permutations (represented by red vectors with arrows) at stormwater ponds (SWP, grey circles, n=40) and natural ponds (NAT, blue triangles, n=6). Data plotted in scaling type 2, appropriate for interpreting distance among communities.

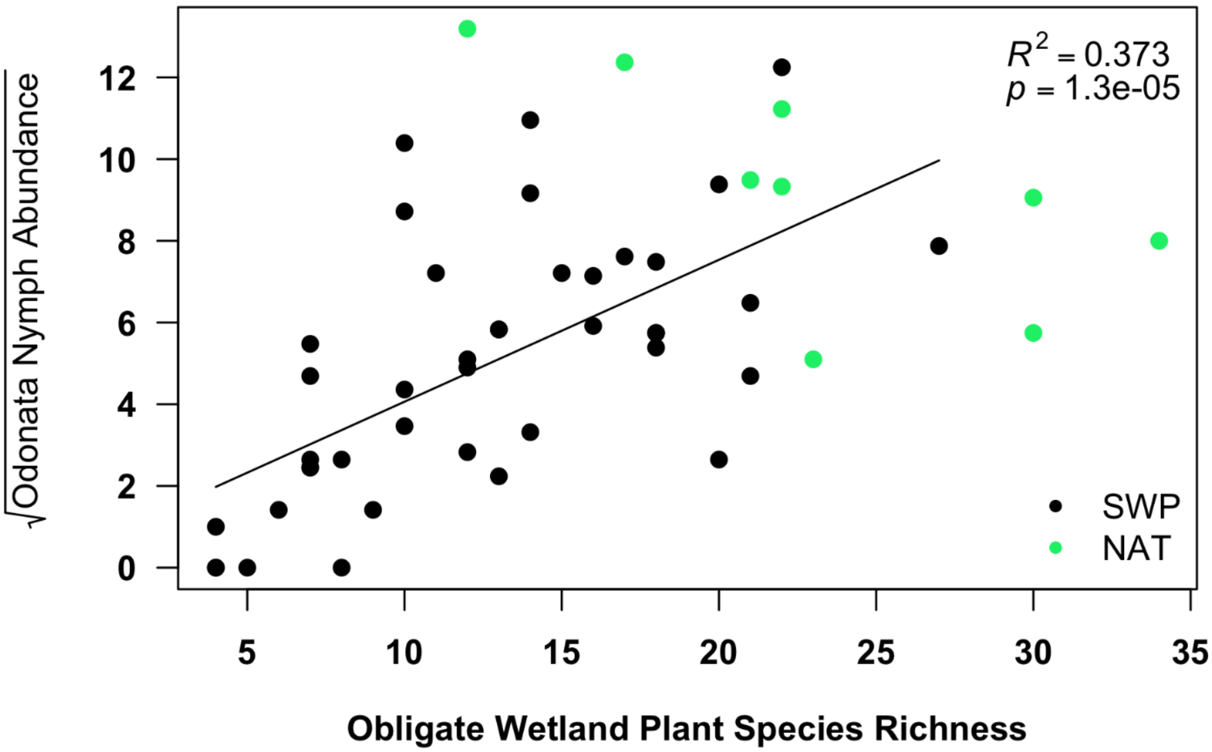


Figure S5.3 The relationship between total nymph abundance and the species richness of obligate wetland plants at stormwater ponds. The regression model is based on stormwater ponds exclusively (SWP, n=41, in black) with natural ponds (NAT, n=9, in green) indicated for reference only. Plants were assigned as obligate wetland plants based on Oldham et al. (1995).

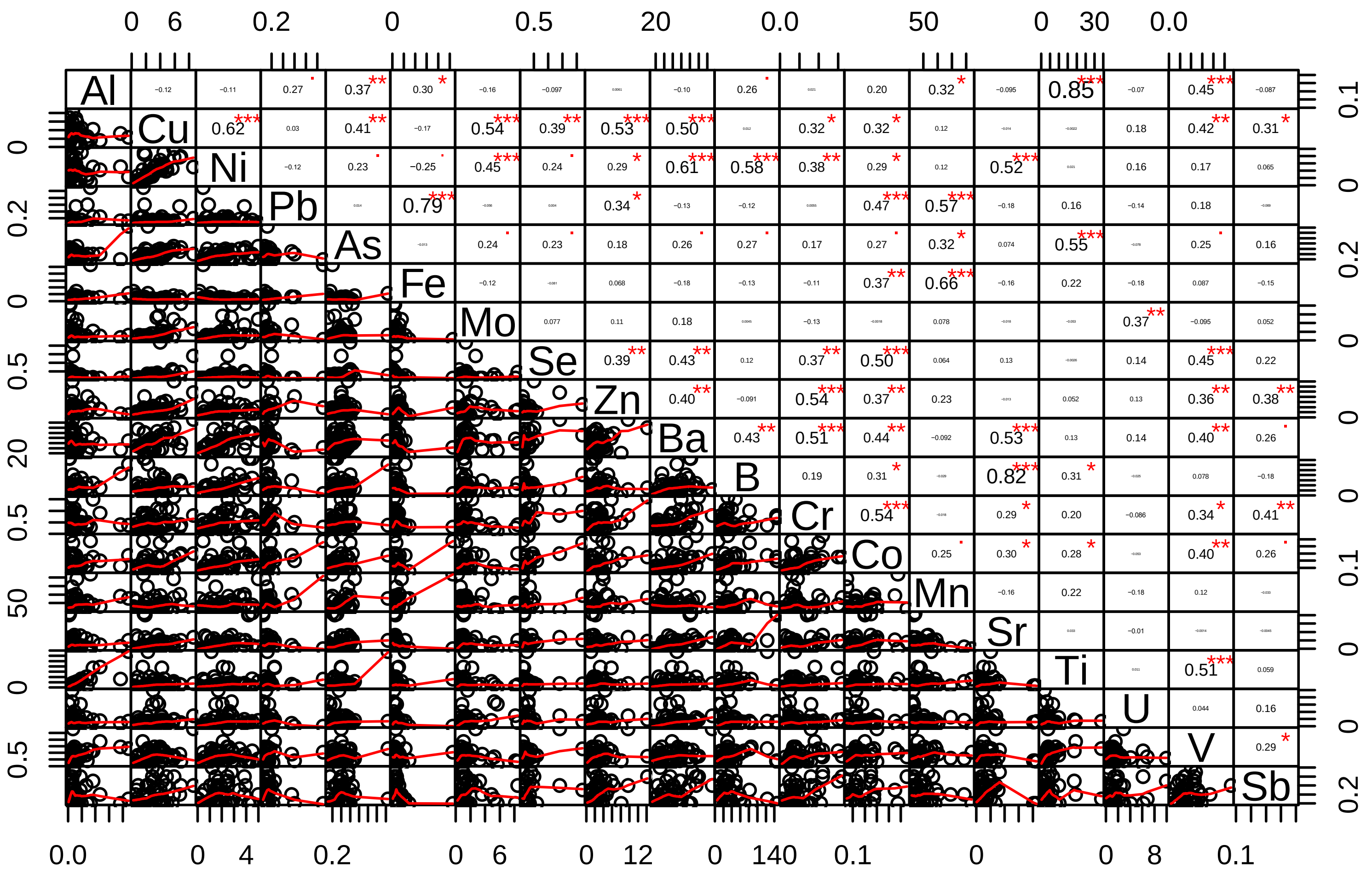


Figure S5.4 Pearson’s correlation panel of trace metals/metalloids in study ponds (41 stormwater ponds and 10 natural ponds).