EVALUATION OF NUTRIENT RETENTION AND SEDIMENT DEPOSITION IN TWO
URBAN STORMWATER RETENTION PONDS

by

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Abstract

EVALUATION OF NUTRIENT RETENTION AND SEDIMENT DEPOSITION IN TWO
URBAN STORMWATER RETENTION PONDS

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Stormwater ponds have been implemented in many municipalities to control urban runoff and retain pollutants, such as nutrients and suspended solids. Two stormwater ponds in Toronto, Ontario were evaluated for their ability to retain nutrients and suspended solids and were also used to investigate mechanisms by which stormwater ponds remove nutrient pollutants, including the importance of deposition and internal loading. Over the entire study period, Hydro Pond East (HEP) retained 1415 mg of total suspended solids (TSS) and MAT retained 1127 mg of TSS. Both Hydro East Pond (HEP) and Mattamy Rouge (MAT) were net exporters of phosphorus (P) over the entire season, with 6.35 mol or 0.20 kg and 53.9 mol or 1.67 kg exported, respectively. HEP had net retention of 2672 mol or 37.4 kg of nitrogen (N) but MAT exported 264 mol or 3.7 kg of nitrogen over the entire study. This study has demonstrated that stormwater ponds have the ability to provide retention of nutrients and TSS, but their function may be enhanced as they may become exporters. However, the amount of nutrients exported was extremely low and may have been driven by the anomalously dry 2016 year in Toronto. Further research should be done on these same ponds to observe how they may perform under an anomalously wet year (e.g. 2017). There is a need for a future model to synthesize the data from literature on stormwater ponds to better understand their function to better help local water managers determine if these ponds are needed and how they may need to enhance their function.

Contributions of Authors

The following list provides the names and responsibilities of the people who have contributed to the manuscript which is the basis of this thesis:

Ryan C. I. Cheung (Candidate): primary author of the manuscript and thesis, performed data collection and analyses

Dr. Vadim Bostan (Supervisor): provided the design and identification of the research undertaking, provided guidance on the method of analysis, reviewed and edited manuscipt

Dr. Andrew Laursen (Supervisor): provided the design and identification of the research undertaking, provided guidance on the method of analysis, reviewed and edited manuscipt

Aslam Hanief: assisted with data collection and analyses

Ramesh Lilwah: assisted with data collection

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Dedication

I would like to dedicate my thesis to my Mom, Dad, and Grandparents, who have always been

there for me with their love, endless support, and encouragement.

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List of Abbreviations

DO — Dissolved Oxygen

DRP — Dissolved Reactive Phosphorus

HEP — Hydro East Pond

MAT — Mattamy Rouge Pond

N — Nitrogen

NURP — National Urban Runoff Program

OMOE — Ontario Ministry of the Environment

OMOEE — Ontario Ministry of the Environment & Energy

P — Phosphorus

PAHs — Polycyclic Aromatic Hydrocarbons

PWQO — Provincial Water Quality Objectives

TIN — Total Inorganic Nitrogen

TN — Total Nitrogen

TP — Total Phosphorus

TRCA — Toronto and Region Conservation

TSS — Total Suspended Solids

USEPA — United States Environmental Protection Agency

USGS — United States Geological Survey

1. Introduction

1.1 Overview

As the population around the world continues to increase, there is a rapid trend toward urbanization. It has been estimated that 54% of the world population currently resides in urban areas and this is projected to increase to 66% by 2050 (United Nations 2014). Much of the land surface has been converted for human use resulting in a variety of environmental impacts related to food production, freshwater and forest resources, climate and air quality, and infectious diseases (Foley et al. 2005). One of the major consequences of urbanization is it changes hydrological pathways. Under natural ground cover conditions in rural areas, 70 to 90% of rainfall infiltrates into the ground or is evapotranspired (Arnold and Gibbons 1996; Paul and Meyer 2001). However, due to the conversion of natural land into hardened, impervious surfaces (such as rooftops and streets) during urbanization, it has been estimated that up to 80% of precipitation may end up as direct surface runoff in high density residential areas (Arnold and Gibbons 1996; Paul and Meyer 2001).

Stormwater ponds have been implemented in many municipalities since the 1980s (Debo and Reese 1995) as a method to mitigate the potential for flooding and to remove pollutants, such as suspended solids, particulate nutrients, heavy metals, and hydrocarbons, from runoff in urbanized areas (McCuen et al. 1983; Marsalek et al. 1992; Marsalek and Marsalek 1997). However, there has been a lack of studies in the literature on the nutrient removal performance of stormwater ponds. This presents a major problem as high nutrient levels in receiving waters will allow for an increase in primary production and may lead to a eutrophic aquatic system

(Wetzel 2001). It is imperative to have performance data of stormwater ponds to know whether they are performing as desired and if not, what can be done to improve it.

Despite the lack of studies, all studies showed some removal of nutrients and agreed that removal was due to the adsorption to particulate matter, which settled to the bottom of the pond, and by biological uptake (Wu et al.1996; Comings et al. 2000; Mallin et al. 2002; Winston et al. 2013). However, all of the studies reviewed have only analyzed nutrients in the water column and none have analyzed the process of sedimentation in removing nutrients from the water column. The role of sediments can have great influence on the phosphorus and nitrogen cycling (Wetzel 2001; Golterman 2004) in stormwater ponds and it is important to include it as part of all limnologic studies.

The purpose of this study was to evaluate the function and ecosystem services provided by two wet retention ponds in an urban area, constructing a near-annual budget of nutrient inputs, outputs, and sedimentation. The results from this study will allow for the comparison and addition to the relatively few data available on stormwater retention ponds to advance the understanding of how these systems function in nutrient and sediment removal, and how environmental conditions and design/application may affect their performance in delivering these services.

1.2 Hydrologic Effects of Urbanization

The hydrological cycle describes the cyclical movement of water between the atmosphere, land, and oceans. The three main processes of the cycle are precipitation, evaporation, and surface and groundwater runoff (Fig. 1.1).
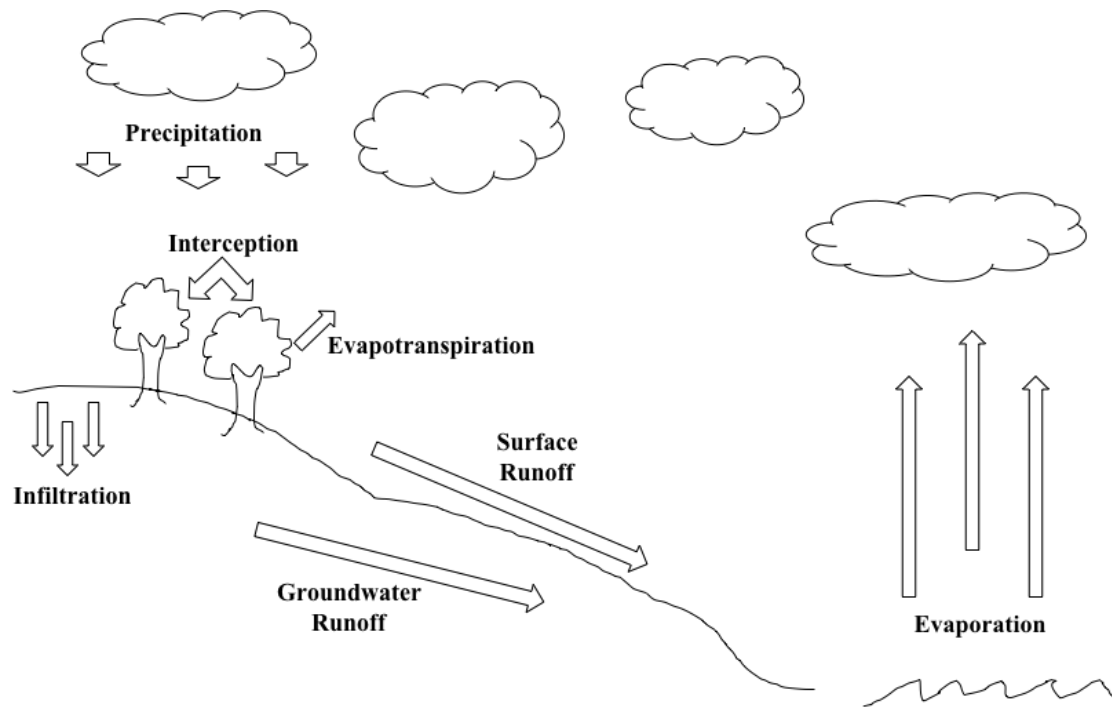
Fig. 1.1 The hydrologic cycle (Modified from Wetzel and Likens 1991).

Water from precipitation may be intercepted by plants, infiltrate into the ground or flow over and under the land surface. Under natural ground cover conditions, 70 to 90% of rainfall is infiltrated into the ground or evapotranspired (Davis and McCuen 2005). However, urbanization converts natural land into hardened, impervious surfaces (such as rooftops and streets) which result in major changes to the hydrological pathways. It has been estimated that up to 80% of precipitation may end up as direct surface runoff in high density residential areas (Davis and McCuen 2005). This causes higher and more rapid peak runoff flow rates (Fig. 1.2) and, as a result, increases the potential for flooding (McCuen et al. 1983; Lazaro 1990; Marsalek et al. 1992).
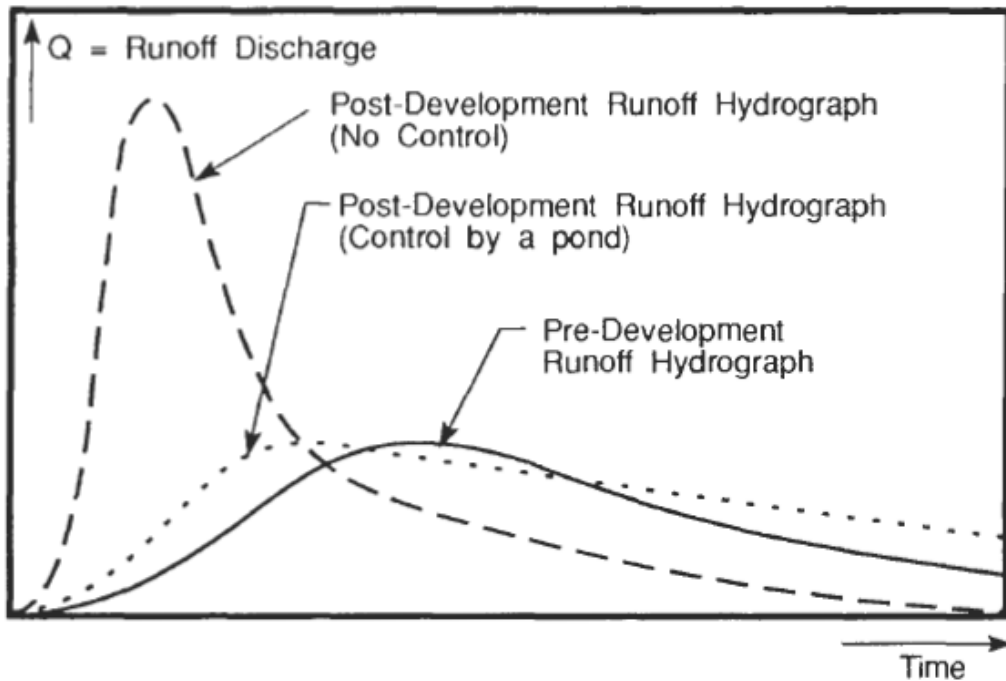
Fig. 1.2 Runoff hydrograph for pre- and post-development areas (Marsalek et al. 1992).

1.3 Historical Development of Stormwater Ponds

In response to the growing concern over localized flooding due to the development of urban areas, municipalities in the 1970s recognized the importance and need for on-site and regional stormwater detention and retention basins (Debo and Reese 1995). Initially, these detention and retention basins were viewed to be more economical and more efficient than traditional stormwater conveyance systems at managing stormwater quantity (McCuen et al. 1983; Debo and Reese 1995) (Fig. 1.3). Stormwater ponds can control the quantity of runoff by reducing and delaying peak flows and releasing runoff at rates close to predevelopment peak flow (Marsalek et al. 1992) (Fig. 1.2). Municipalities soon also recognized their ability to provide a community with improved aesthetics and recreational amenities (McCuen et al. 1983; OMOE 2003). During the 1980s the National Urban Runoff Program (NURP) and various other researchers reported that not only do the higher volumes of runoff increase the risk of

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flooding, but they also become a vehicle for various pollutants to be transported into nearby receiving waters (USEPA 1983; Novotny et al. 1985). These reports led to the development of regulations to reduce and control pollutants in urban stormwater runoff in the 1990s (Debo and Reese 1995; Burns et al. 2011).
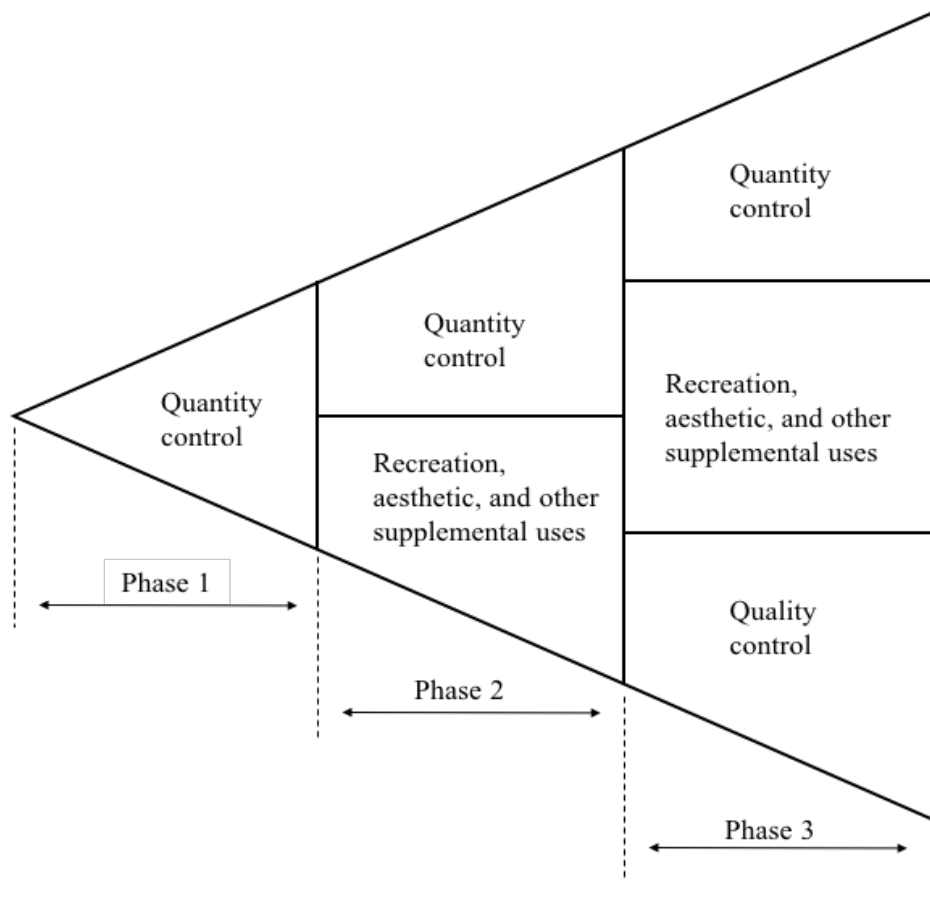
Fig. 1.3 Historical development of stormwater ponds (Reproduced from McCuen et al. 1983).

1.4 Stormwater Ponds: Detention vs. Retention Ponds

Retention ponds, also known as wet ponds, can be thought of as small, shallow man-made lakes which contain a permanent pool of water (Debo and Reese 1995). Detention ponds, also known as dry ponds, do not contain a permanent pool of water and are dry except for a period of time after a storm (Stanley 1996). Both retention and detention ponds collect runoff from

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storms as temporary storage facilities and slowly release it into receiving bodies of water

(McCuen et al. 1983). Retention ponds are the most common stormwater management facility

used in Ontario and have proven to be the most effective practice in Eastern United States as

well (Debo and Reese 1995; OMOE 2003). For the purposes of this study, "stormwater ponds"

refer to "retention ponds", or "wet ponds".

1.5 Water Quality Parameters

In 1994, the Ontario Ministry of Environment and Energy released the Provincial Water

Quality Objectives (PWQO) to ensure that the water quality in Ontario is acceptable for aquatic

life and recreation uses. The PWQO provides a long list of guidelines for various chemicals and

parameters (Table 1.1).

Table 1.1 Summary of selected water quality guidelines provided in Ontario's PWQO (MOEE 1994).

Parameter	Value	Parameter	Value
pH	5.0 – 9.0	*E. coli*	< 100/100 mL
Ammonia (un-ionized)	< 0.02 mg/L	Dissolved Oxygen	> 5.0 mg/L
Nitrate	< 10 mg/L	Total Phosphorus	< 0.01 mg/L

1.5.1 Basic Factors Essential for Aquatic Life

In order to maintain a healthy aquatic ecosystem, there are three main important

parameters: dissolved oxygen, pH, and temperature (Wetzel 2001; Davis and McCuen 2005).

1.5.1.1 Dissolved Oxygen (DO) and Temperature

Dissolved oxygen is the most vital factor in aquatic systems as it is required by all aerobic

aquatic organisms. However, there is a limit as to how much oxygen can be dissolved in water.

The solubility of oxygen is a function of temperature and increases with decreased temperature

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(Benson and Krause 1980; Mortimer 1981). Dependent on the temperature and salinity, it has been found that water can hold a maximum of 8 to 14 mg L^{-1} of oxygen (Benson and Krause 1980; Mortimer 1981). Studies have shown that fish become stressed when exposed to DO levels under 5 mg L^{-1} (Reynolds and Thompson 1974; Kramer 1987; Matthews and Berg 1997).

For oxygen to reach an equilibrium between the atmosphere and water, there must be circulation in the water column of a lake (Wetzel 2001). Wetzel (2001) illustrates the vertical distribution of oxygen and temperature of an oligotrophic (low nutrient inputs with low organic production) and eutrophic (high nutrient loading with high organic production) lake during the four main seasons (Fig. 1.4). During the spring and fall seasons, the lakes are completely saturated with oxygen as there is complete mixing within the lake resulting from no thermal stratification. During the summer season, a thermal stratification develops in both lakes, where the upper epilimnion layer has higher temperatures from exposure to the sun than the lower hypolimnion layer. However, contrasting vertical oxygen profiles are observed between oligotrophic and eutrophic lakes. The amount of deposition of organic matter from the epilimnion into the hypolimnion influences the intensity of oxidative processes within the lower layer (Wetzel 2001). As there is low productivity and organic production in oligotrophic lakes, the oxygen concentration distribution within the lake is dependent on temperature, where oxygen concentrations increase as temperature decreases with depth. In contrast, due to high organic production, and subsequently deposition, in eutrophic lakes, the hypolimnion is anoxic as oxygen is depleted rapidly from oxidation processes.
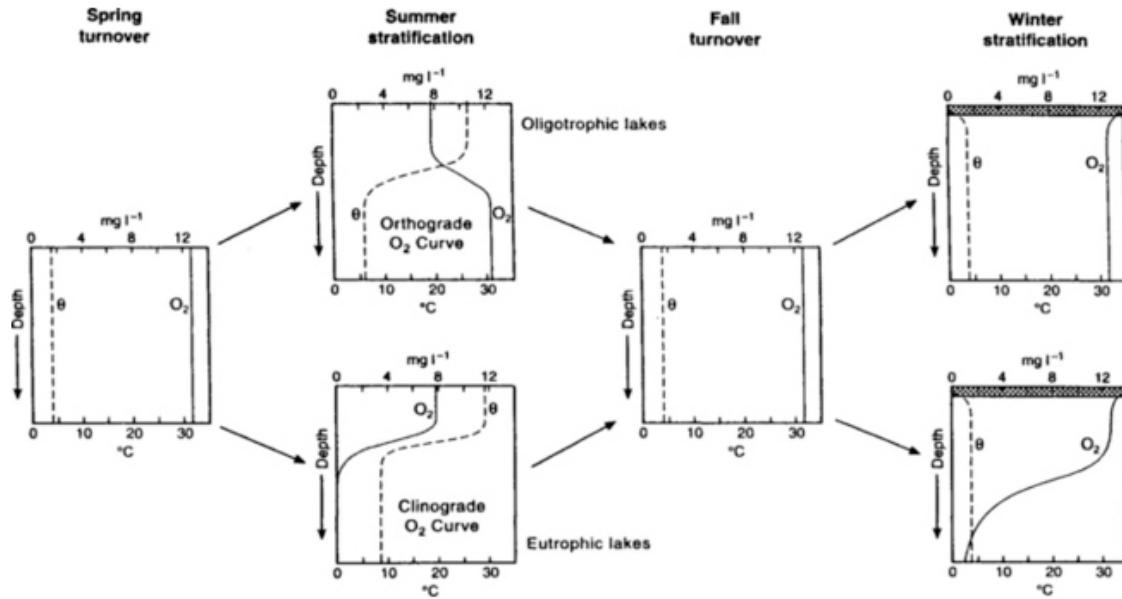
Fig. 1.4 Vertical distribution of oxygen concentrations and temperature (θ) of an oligotrophic and a eutrophic lake during the four main seasons (Reproduced from Wetzel 2001).

1.5.1.2 pH

The optimal pH for most aquatic organisms lies between 6 and 8. The pH of water can be influenced by various biological processes. Photosynthetic activity in the trophogenic zone, the upper portion of lake where enough light penetrates through for photosynthesis, consumes carbon dioxide (CO_2) and, as a result, increases pH (Wetzel 2001). Respiratory generation of CO_2, heterotrophic degradation of organic matter, microbial methane fermentation, nitrification of ammonia, and sulfide oxidation throughout the water column and sediments can decrease pH in a lake (Wetzel 2001).

1.5.2 Water Pollutants

Sources of pollution in stormwater runoff can result from wet and dry atmospheric deposition, litter and dirt from streets, vegetation and organic residues, overflow from sanitary sewers, lawn and agricultural fertilizers, animal droppings, and materials from other activities

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(Novotny et al. 1985; Whipple et al. 1987; Makepeace et al. 1995). Some of the major pollutants in stormwater runoff include: suspended solids, nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and pesticides (USEPA 1983; Makepeace et al. 1995; Mayer et al. 1996; Characklis and Wiesner 1997; Lee et al. 1997; Waschbusch et al. 1999; Davis et al. 2001; Weston et al. 2009).

1.5.2.1 Suspended Solids

Suspended solids are the most common pollutant found in urban stormwater runoff (USEPA, 1999; Davis and McCuen 2005). These solids are composed of fine particulate matter of clay, silt, vegetation, and bacteria (Davis and McCuen 2005) which are picked up during runoff flow and held in the water column of a water body by turbulence (Bilotta and Brazier 2008). Suspended solids can also be produced within the pond by growth of algae and bacteria, and may be a mechanism of nutrient (and other pollutant) removal from water through biological uptake. The accumulation of suspended solids can induce various physical, chemical, and biological changes in a water body. High levels of suspended solids can increase turbidity and subsequently decrease the amount of light penetration through the water column required by photosynthetic organisms, trigger temperature changes, and cause infilling of the reservoir which may result in a loss of habitat for fish and bottom-dwelling organisms (Davis and McCuen 2005; Bilotta and Brazier 2008). Suspended solids can also act as a medium for the transport, storage, and release of contaminants, such as heavy metals, PAHs, pesticides, and nutrients (Dawson and Macklin 1998; Russell et al. 1998; Kronvang et al. 2003; Golterman 2004). Suspended solids containing high organic matter may also deplete dissolved oxygen concentrations within the water column from *in situ* decomposition (Wetzel 2001; Bilotta and Brazier 2008).

1.5.2.2 Nutrients – Phosphorus

Phosphorus is the least abundant nutritional component in most fresh water systems, and is commonly the limiting nutrient for biological productivity (Schindler 1974). However, urbanization has allowed phosphorus compounds to enter receiving water bodies through runoff, creating eutrophic conditions. Some major sources of phosphorus in runoff include excess fertilizers, cleaning detergents, decay of vegetation, animal and wastes (Waschbusch *et al.* 1999; Wetzel 2001; Davis and McCuen 2005).

Orthophosphate (PO_4^{-3}) is the most basic inorganic form of phosphorus found in water. Over 90% of phosphorus in fresh water are organic phosphates and cellular compounds in organisms which are adsorbed to inorganic and dead material (Wetzel 2001). When analyzing total phosphorus content in water, it consists of phosphorus in two compartments: particulate and dissolved (Juday et al. 1927). Particulate phosphorus can be found in both inorganic and organic forms. Particulate inorganic phosphorus can be in forms of mineral phases adsorbed to abiotic or biotic particles and intercellular storage compounds as orthophosphate, pyrophosphate and polyphosphate (Yoshimura et al. 2007). Particulate organic phosphorus includes phosphorus found in living and detritus organic molecules. Dissolved phosphorus can be found in forms of orthophosphate, polyphosphates, organic colloids, and low-molecular-weight phosphate esters. It has been demonstrated by Vollenweider (1968) that lake productivity generally increases with increasing amounts of total phosphorus. Lakes are considered eutrophic when total phosphorus concentrations are between 30-100 µg L^{-1} (Vollenweider 1968).

A major component of the phosphorus cycle in natural waters is the exchange of phosphorus between sediments and the overlying water. The main mechanisms by which

phosphorus can be deposited into the sediment: settling of imported material, adsorption or precipitation with inorganic compounds, settling of allochtonous and autochthonous organic matter, uptake by algal or microbial communities and settling to sediment as detritus (Boström et al. 1988). Although there is commonly a net movement of phosphorus into sediments, several physical, chemical, and biological conditions dictate whether the sediments become a source or sink for phosphorus. It has been shown in past studies (Einsele 1936, 1938; Mortimer 1942) that under oxic condition, lake sediments retain phosphorus by precipitating iron (III) oxyhydroxides, which have the ability to adsorb phosphorus. Anoxic conditions will release phosphorus due to the reductive dissolution of iron (III) oxyhydroxides and subsequent dissolution of previously bound phosphorus. However, there has been discussion that the release of phosphorus from sediments is not only dependent on dissolved oxygen levels but a balance between the sedimentation of organic matter, phosphorus, iron, and sulfide production by diagenetic processes within in the sediment (Golterman 2001; Gächter and Müller 2003). For example, some microorganisms may catalyze the oxidation of iron (II) under oxic or anoxic conditions and also the reduction of iron (III) in anoxic environments (Kappler and Straub 2005). If microorganisms present in the sediment can catalyze the oxidation iron (II) to iron (III), this may allow for more precipitation of iron (III) oxyhydroxides to absorb phosphorus

1.5.2.3 Nutrients – Nitrogen

Nitrogen can be present in water in a number of different forms: dissolved molecular N_2, organic compounds from amino acids, amines, and proteins, recalcitrant humic compounds of low nitrogen content, ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-) (Wetzel 2001). Sources of nitrogen compounds in stormwater ponds include: atmospheric deposition, nitrogen fixation in the water and sediments, and from runoff containing nitrogen from fertilizers, animal wastes,

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and plant decay (Wetzel 2001; Davis and McCuen 2005). Similar to the trends found regarding

the positive relationship between phosphorus and lake productivity, Vollenweider (1968) also

showed a positive correlation between high productivity of algal populations and average

concentrations of inorganic and organic nitrogen. Lakes are considered eutrophic when

inorganic and organic nitrogen concentrations are between 0.5-1.5 mg L^{-1} and 0.7-1.2 mg L^{-1},

respectively (Vollenweider 1968). Although Schindler (1974) later showed that phosphorus is

the main driver of eutrophication, subsequent studies have shown that nitrogen can be limiting

in some systems (Goldman 1981; Howarth and Cole 1985; Wurtsbaugh 1988) and in some

cases, can also enhance the effect of any phosphorus addition (Elser and Kimmel 1985). A

study by Elser et al. (2007) has shown that there is an increasing prevalence nitrogen and

phosphorus limited systems and that the simultaneous addition of nitrogen and phosphorus can

create a positive synergistic response of higher production levels.

Ammonia can be generated by biological reduction of nitrate, and as a primary end-product

of the decomposition of organic matter by heterotrophic bacteria (Wetzel 2001). Ammonia

occurs primarily as ammonium (NH_4^+) in water. In aerobic waters, ammonium concentrations

are usually low as they can be readily assimilated by plants and commonly oxidized to nitrate

via a two-step process ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$), known as nitrification, by aerobic

chemoautotrophic bacteria (Sharma and Ahlert 1977; Wetzel 2001). However, nitrate is a major

pollutant in water bodies as excess nitrate can allow for additional growth of algae.

Subsequently, this will result in an increase in decaying algae and a decrease in DO from

oxygen utilization by decomposition processes (Carpenter et al. 1998). In eutrophic lakes,

bacterial nitrification ceases and the adsorptive capacity of NH_4^+ in sediments is reduced due to

anaerobic conditions (Wetzel 2001). This results in a release of NH_4^+ from sediments and

subsequent increase in NH_4^+ in the overlying waters. Additionally, anaerobic conditions allow for some facultative anaerobic bacteria to utilize nitrite and nitrate as terminal electron acceptors to convert nitrate into N_2 and N_2O, in a process known as denitrification (Austin 1988; Stumm and Morgan 1996; Wetzel, 2001).

1.5.2.4 Heavy Metals

Heavy metals commonly found in stormwater runoff include cooper, lead, zinc, arsenic, cadmium, and chromium (Makepeace et al. 1995; Mayer et al. 1996; Lee et al. 1997; Brown and Peake 2006). These metals are toxic to aquatic organisms and are persistent in the environment, as they cannot be chemically transformed or destroyed (Borchardt and Sperling 1997; Davis et al. 2001; Brown and Peake 2006; Søberg et al. 2016). Metals are often bound to particles in runoff when entering a stormwater pond (Davis et al. 2001; Karlsson et al. 2010) and are susceptible to being released into the dissolved phase in trace amounts, depending on the pH (Tai 1991) and dissolved organic carbon in the water column (Hamilton et al. 1984).

1.5.2.5 Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are compounds made up of two or more aromatic rings. They are formed during thermal decomposition of organic molecules (Haritash and Kaushik 2009). Common sources of PAHs in the environment include motor vehicle emissions, asphalt leaching, particles from tire abrasion, lubricating oils, and burning of fossil fuel, coal tar, wood, and garbage (Ngabe et al. 2000; Brown and Peake 2006; Haritash and Kaushik 2009). The greater molecular weight PAHs have (i.e. higher number of aromatic rings), the lower their solubilities in water and the slower their rates of biodegradation (Davis and McCuen 2005; Haritash and Kaushik 2009). Due to their low solubility in water, PAHs are commonly found adsorbed to sediment,

accumulating in stormwater ponds (Durand et al. 2004; El-Mufleh et al. 2014). Their

persistence in the environment is of great concern as they can bioaccumulate in organisms and

are also carcinogenic (Haritash and Kaushik 2009).

1.5.2.6 Pesticides

Pesticides, including insecticides, herbicides, and fungicides, have been detected in many

urban streams (Daniels et al. 2000; Paul and Meyer 2001; Amweg et al. 2006; Weston et al.

2009). It has been estimated that 70-97% of homes in the United States use a total of more than

136,000 kg of pesticides (LeVeen and Willey 1983; USGS 1999). Pesticides in urban runoff are

a major problem as pesticides applied before a rain event are easily washed away (Davis and

McCuen 2005). For example, various studies have used the amphipod *Hyalella azteca* as a test

organism for pesticide toxicity tests from urban runoff and have shown that residential runoff is

a source of pyrethriod insecticides containing high enough concentrations to impact aquatic

organisms (Amweg et al. 2006; Weston et al. 2009).

1.6 Stormwater Pond Performance for Suspended Solids and Nutrient Removal

Although many pollutants have been mentioned above, the scope of this study will focus

on the suspended solids and nutrient removal ability stormwater ponds have. While stormwater

ponds have been in place for decades (McCuen et al. 1983; Debo and Reese 1995), only a few

studies in the literature (e.g. Mayer et al. 1996; Wu et al.1996; Borden et al. 1998; Comings et

al. 2000; Mallin et al. 2002; Winston et al. 2013) have examined their performance for nutrient

removal. The results from these studies have shown very little consistency amongst each other.

For example, some studies have yielded a range of annual removal efficiencies, the percent

difference of pollutant mass entering and leaving pond, of total phosphorus from 19% to 57%

(Comings et al. 2000; Mallin et al. 2002; Winston et al. 2013). Winston et al. (2013) found that

the annual removal efficiency of total nitrogen varied between the two ponds that were studied,

with one pond having a removal efficiency of 36% and 59% in the other. Studies by Mayer et

al. (1996) and Mallin et al. (2002) have even observed a net export of accumulated TP and TN

from their stormwater retention ponds. The removal of total suspended solids by stormwater

ponds have also showed a range of results in previous studies (Wu et al. 1996; Winston et al.

2013) with one study showing 41% removal efficiency and 92% removal efficiency in another.

Despite the variation found in stormwater ponds reported by past research, most studies showed

that stormwater ponds were able to provide some level of nutrients and suspended solids

removal.

The inconsistencies shown in past research may be a result of various factors, including:

retention time, the physical characteristics of the ponds, catchment type, the biota within the

ponds, and weather conditions. The retention time of ponds is an important factor as a higher

retention time may allow for physical, chemical, and biological processes to provide treatment

of the water entering the ponds, through sedimentation and biological uptake, and may allow

for a lower mass of pollutants entering the receiving body of water (Davis and McCuen 2005).

Pond shape and depth can also influence the performance of stormwater ponds to retain

pollutants. Ponds with higher length-to-width ratios and storage capacities allow for long

retention times and thus, better retention (Sønderup et al. 2015). For example, when comparing

pond depths between the studies by Mayer et al. (1996) and Wu et al. (1996), the Tapscott Pond

in Mayer's study had an average depth of 0.8 m and Lakeside Pond in Wu's study had an

average depth of 2.4 m. In terms of performance, Tapscott Pond was found to be a net exporter

of phosphorus and nitrogen, whereas Lakeside Pond retained both phosphorus and nitrogen.

However, it is important to look at the catchment types as well when comparing ponds from different studies. Sønderup et al. (2015) showed that urban, rural, and developing catchments had lower pollutant concentrations compared to industrial and mixed catchment areas. When revisiting the example above, Tapscott Pond mainly drains an agricultural area and Lakeside Pond is located within a residential area. The difference in catchment area type may explain why Tapscott Pond performed poorly, but if designed properly to suit its conditions, one would expect it could perform well. As stormwater ponds are designed to retain runoff, rainfall and inflow of TSS, phosphorus, and nitrogen are positively related (Mallin et al. 2002; Sønderup et al. 2015).

Although studies in the past have looked at individual factors which may affect a pond's performance, as described above, none have examined the actual mechanisms that drive retention within the pond. It is proposed that stormwater ponds function to remove pollutants mainly by sedimentation and biological uptake. Many have studied whether there was retention of nutrients and TSS in the water column by examining the difference between inlet and outlet concentrations. However, no study in the literature has analyzed the process of sedimentation in removing nutrients from the water column in stormwater ponds.

1.7 Objectives of Study

The objectives of this study are to: 1) evaluate and compare the nutrient removal efficiency of two similar stormwater ponds, simultaneously, in the City of Toronto 2) examine the mechanisms by which stormwater ponds remove nutrient pollutants, including the importance of deposition and internal loading to help improve the understanding of why some ponds function well and others more poorly.

2. Evaluation of Nutrient Retention and Sediment Deposition in Two Urban Stormwater Retention Ponds

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2.1 Introduction

Municipalities in the 1970s began to recognize the need for localized management of stormwater to mitigate the effects of urbanization and increased impervious surfaces, and began integrating retention and detention ponds into stormwater management infrastructure (Debo and Reese 1995). Initially, these detention and retention basins were viewed to be more economical and more efficient than traditional stormwater conveyance systems at managing stormwater quantity (McCuen et al. 1983; Debo and Reese 1995), reducing and delaying peak flows by releasing runoff at rates close to predevelopment peak flow (Marsalek et al. 1992). Increased stormwater runoff associated with urbanization can lead to flooding, erosion, and deterioration to water quality in receiving bodies of water (Leopold 1968; Mattraw et al. 1978; Wanielista et al. 1982). Municipalities soon recognized that retention and detention ponds might, in addition to reducing peak flow volumes, also retain pollutants in stormwater runoff when designed properly. Further, they could also provide a community with improved aesthetics and recreational amenities (McCuen et al. 1983; Ferguson 1991). With climate change, particularly an increased frequency and intensity of storm events in some regions, storm water ponds may have growing importance in mitigating localized flooding in urban

areas (Trenberth 2011), as well as in protecting surface water quality. However, the value of ponds in providing this latter ecosystem service is difficult to assess, as there are relatively few data on the ability of ponds to retain nutrient and other pollutants. The effective use of these ponds in reducing the impact of urban runoff on water quality, both under current and future climate scenarios, depends on better understanding of their function and capacity for nutrient retention. In this study, we consider the function of retention ponds, those containing permanent pools of water, as opposed to detention ponds which are dry except for a period of time after a storm (Ferguson 1991; Stanley 1996).

Sources of pollution in stormwater runoff can result from wet and dry atmospheric deposition, litter and dirt from streets, vegetation and organic residues, overflow from sanitary sewers, lawn and agricultural fertilizers, animal droppings, and materials from other activities (Novotny et al. 1985; Whipple et al. 1987; Makepeace et al. 1995). Some of the major pollutants in stormwater runoff include suspended solids, nutrients, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and pesticides (USEPA 1983; Makepeace et al. 1995; Mayer et al. 1996; Characklis and Wiesner 1997; Lee et al. 1997; Waschbusch et al. 1999; Davis et al. 2001; Durand et al. 2004; Weston et al. 2009). Nutrients and suspended solids are a particular concern as they are major contributors to eutrophication (Carpenter et al. 1998). Phosphorus is generally the limiting nutrient in many freshwater systems and are the primary cause of eutrophication (Edmondson 1970; Maloney et al. 1972; Schindler 1974; Boyce et al. 1987). Urbanization has allowed nutrient compounds to enter receiving water bodies through runoff, creating eutrophic conditions. Suspended solids are composed of fine particulate matter of clay, silt, vegetation, and bacteria (Davis and McCuen 2005) which are picked up during runoff flow and held in the water column of a water body by turbulence (Bilotta and Brazier 2008).

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Suspended solids containing high organic matter may deplete dissolved oxygen concentrations within the water column during *in situ* decomposition (Wetzel 2001; Bilotta and Brazier 2008). To mitigate these negative effects, stormwater ponds have been built in urban areas to retain pollutants in runoff. This retention occurs by the adsorption of the pollutant to particulate matter, settling to the bottom of the pond, or by biological uptake of the pollutant, particularly nutrient pollutants (Wu et al.1996; Comings et al. 2000; Mallin et al. 2002; Winston et al. 2013). Pollutants that are taken up by algae, bacteria, and aquatic plants may also be deposited in sediments when the organisms senesce. If these materials become buried, retention of nutrients and other pollutants may be long-term, rather than merely seasonal. Mineralization of some organic nitrogen deposited by either mechanism may lead to coupled nitrification and denitrification, representing a more permanent removal of nitrogen by the retention ponds.

One of the major factors which affects the performance of stormwater ponds is the age of the pond (OMOE 2003; Drake and Guo 2008; Sønderup et al. 2015). As stormwater ponds are designed to retain solids from runoff, it is expected that sediment accumulation at the bottom of the pond will increase over time. However, this will result in a decrease in storage volume (Yousef et al. 1994; Graham and Lei 2000) and can greatly compromise the ability of stormwater ponds to perform their pollutant removal functions (Weiss et al. 2007; Egemose et al. 2015; Sønderup et al. 2015). Thus, it is important that stormwater ponds are properly maintained and sediment is periodically removed to ensure that they perform their function effectively. Various jurisdictions manage sediment removal and disposal from retention ponds as a part of infrastructure maintenance. For example, Ontario regulates sediment removal and disposal under the Water Resources Act and Environmental Protection Act (Graham and Lei 2000). The Stormwater Management Planning and Design Manual published by the Ontario

Ministry of Environment (2003) provides recommendations for frequency of dredging as a function of pond type (e.g. retention vs. detention), storage volume, and percent impervious.

Although stormwater ponds have been widely used since the 1980s, there have been relatively few studies in the primary literature on the performance of stormwater ponds in terms of their ability to retain nutrient pollutants (e.g. Wu et al.1996; Borden et al. 1998; Comings et al. 2000; Mallin et al. 2002; Winston et al. 2013). This ability likely depends on age of the pond and its maintenance, as nutrient retention is connected with deposition of particles. Of the studies present in the literature, many suggest limited value of stormwater ponds for nutrient retention. For example, several studies have shown annual average removal efficiencies of TP below 50% (Wu et al.1996; Borden et al. 1998; Comings et al. 2000; Winston et al. 2013), and two studies, by Mayer et al. (1996) and Mallin et al. (2002), observed a net export of accumulated TP and TN over the entire season from the stormwater retention ponds.

The purpose of this study was to evaluate the function and ecosystem services provided by two wet retention ponds in an urban area, constructing a near-annual budget of nutrient inputs, outputs, and sedimentation. The results from this study will allow for the comparison and addition to the relatively few data available on stormwater retention ponds to advance the understanding of how these systems function in nutrient and sediment removal, and how environmental conditions and design/application may affect their performance in delivering these services.

2.2 Materials and Methods

2.2.1 Site Descriptions

Hydro East Pond (HEP) and Mattamy Rouge (MAT) are stormwater ponds located in Scarborough, ON, designed for control of stormwater quantity and quality discharging into the Rouge River (Fig. 2.1). Located within residential areas, HEP was built in 2001 and MAT in 2004 (Table 2.1). HEP serves a catchment area of 63.7 ha and has a storage capacity of 5958 m^3 and a permanent storage volume of 2392 m^3. MAT serves a smaller catchment basin of 48.4 ha and has a larger storage capacity of 26000 m^3, with a permanent storage volume of 8000 m^3.
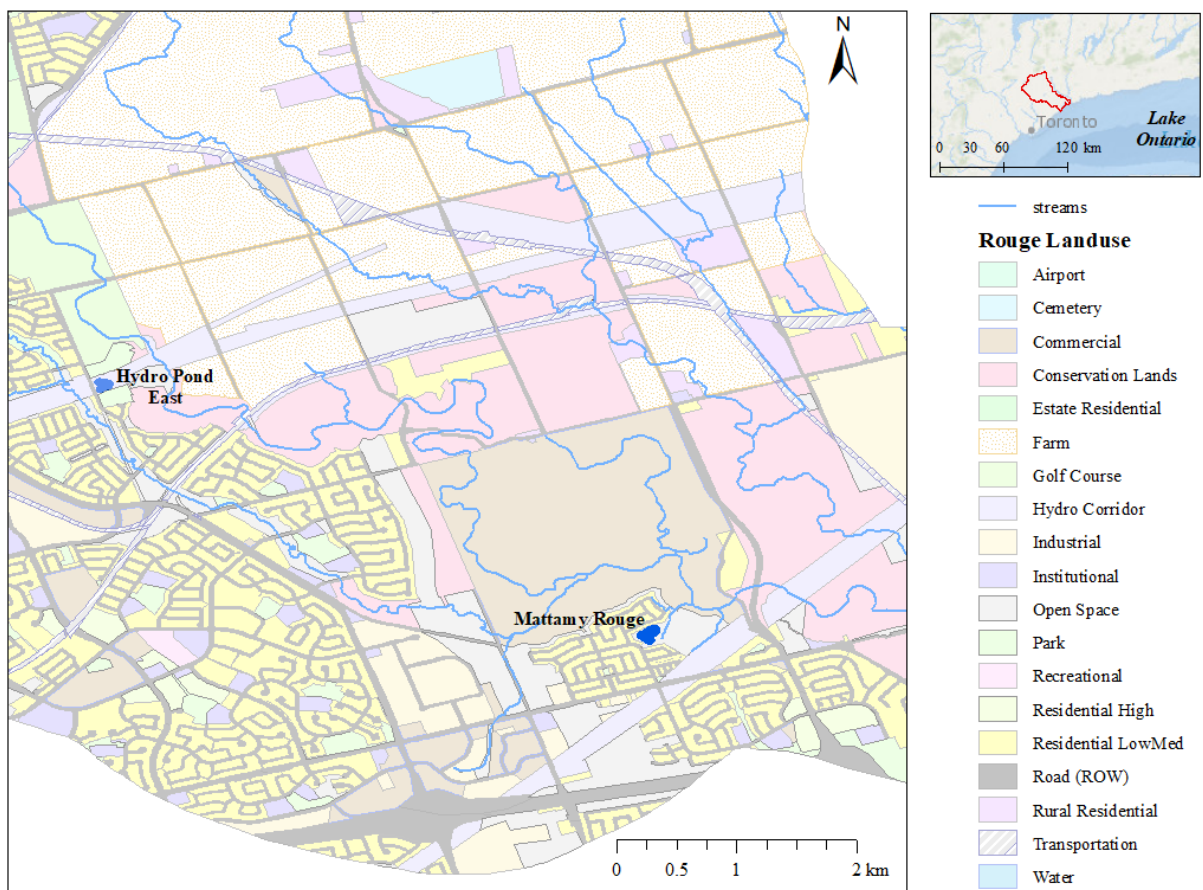
Fig. 2.1 Map displaying the locations and proximity of Hydro East Pond and Mattamy Rouge Pond in Toronto, Ontario, Canada. (ESRI base map, TRCA land use shapefile)

Table 2.1 Characteristics of Hydro East and Mattamy Rouge stormwater ponds.

Characteristics	Hydro East Pond	Mattamy Rouge Pond
Built (year)	2001	2004
Purpose	Quantity and quality	Quantity and quality
Land use	Residential	Residential
Catchment area (ha)	63.7	48.4
Storage capacity (m^3)	5958	26000
Permanent storage (m^3)	2392	8000
Permanent water level (cm)	160.25	110.44
Surface area (m^2)	5443.75	9644.75

2.2.2 Field Sampling Methods

2.2.2.1 Water and Sediment Sampling

Water samples (> 500 mL) were collected as grab samples at ~30 cm depth, near the inlet

and outlet of each pond (Fig. 2.2) to permit determination of retention within each pond.

Samples were collected at approximately 2-3 week intervals between April and June 2016, and

longer intervals (4-6 weeks) later in the season (Table 2.2).

Table 2.2 Field monitoring and sampling schedule at Hydro East and Mattamy Rouge ponds.

	Apr. 8	Apr. 20	May 5	May 12	May 31	Jun. 1	Jun. 7	Jun. 15	Jul. 8	Jul. 27	Aug. 19	Sept. 16	Nov. 5	Dec. 12
Nutrients (w & s)	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Sediment Traps									X	X	X	X	X	

A composite sample (1 L) was also collected, which consisted of a mixture of water of equal

volumes collected from the inlet, outlet, and three additional points (Fig. 2.2, points A, B, and

C) of the pond. Water samples were collected for the analysis of total phosphorus (TP),

dissolved reactive phosphorus (DRP), ammonium (NH_4^+), and nitrate (NO_3^-). Water clarity was

measured using a Secchi disk at three locations (Fig. 2.2 - A, B, and C) within each pond, on

each date.
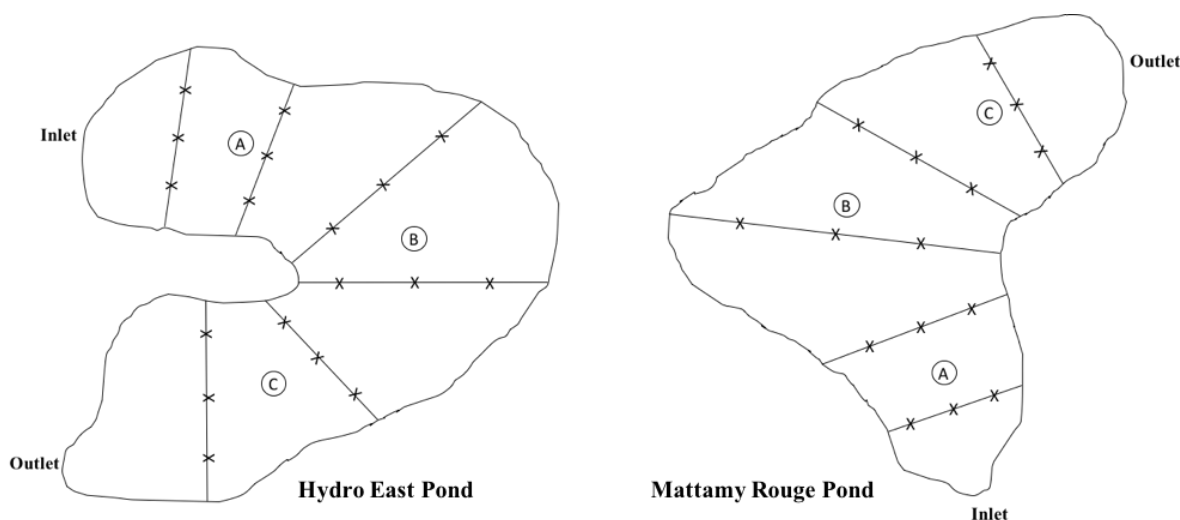
Fig. 2.2 Map of the sampling points at Hydro East Pond and Mattamy Rouge Pond.

A clear acrylic tube (3 cm x 2.16 m) fitted with a valve on the top was used to collect bottom sediment samples near the middle of the pond. The coring tube was lowered gently into the sediment with the valve open. The valve was then closed to maintain suction. The coring tube was removed and the valve slowly opened to evacuate all but the top 10 cm of sediment. This top fraction of the sediment core was collected and composited with two other such samples from each pond on each date. Sediment cores were collected to measure pore water and particulate concentrations of TP and TN.

2.2.2.2 Measurement of Sedimentation Rate

Sediment traps were used to study deposition of particulate matter. Following the recommendations of Bloesch and Burns (1980), sediment traps were constructed with funnels (30-cm diameter) and 50-mL test tubes attached to the bottom to collect sediment that was being deposited. A mesh screen (nylon, 1 cm x 1 cm) was attached to cover the openings of the funnels to exclude large debris. Three sediment traps were installed at points A, B, and C (Fig. 2.2) in each pond during mid to late summer (Table 2.2).

2.2.2.3 Measurement of Temperature and Dissolved Oxygen

Temperature and dissolved oxygen (DO) concentrations were measured at points A, B, and C in each pond using a handheld field meter (HI 9828, Hanna Instruments, Woonsocket, RI). Temperature and DO profiles were created by taking measurements in 10 cm depth intervals from the pond surface to the pond bottom.

2.2.2.4 Meteorological Data

Local precipitation and daily mean temperature data were obtained from a weather station located at University of Toronto, Scarborough.

2.2.3 Laboratory Methods

2.2.3.1 Sample Processing and Storage

Water samples were filtered through pre-ashed (550ºC for 4 hours) and pre-weighed Whatman GF/F filters (0.7 μm) and subsequently filtered through a 0.22-μm pore size filter (PolyPropylene Membrane Filter, Membrane Solutions). Unfiltered water samples were used to determine total phosphorus concentrations. Filtered water samples were used for the determination of dissolved reactive phosphorus, ammonium, nitrate, and total nitrogen concentrations. Filters from the inlet and outlet water samples were dried (105ºC for 12 hours), reweighed, and used to calculate total suspended solids (TSS; mg L^{-1}). Sediment samples (50 g) were centrifuged at 5000 rpm for 15 minutes and the supernatant was decanted to obtain a pore water sample. Processed water, pore water, and sediment samples were frozen at -20ºC until analysis.

2.2.3.2 Organic Matter in Sediment Samples

Organic matter in sediment samples was determined by the ignition method (Howard and Howard 1990). A sample (~0.5 g) of dried sediment (105°C for 12 hours) was sieved (2 mm mesh), and weighed into ceramic crucibles (pre-weighed, pre-ashed). The samples were then placed into a muffle furnace and were ignited at 550°C for 2 hours, cooled in a drying oven (105°C), and re-weighed. Percent organic matter was determined by difference between the pre-ignited and post-ignited mass.

2.2.3.4 Analysis of Nutrient Composition in Water and Sediment Samples

The nutrient concentrations in water samples were analyzed using colorimetric methods (American Public Health Association 2012), based upon modifications of the cadmium reduction technique for nitrate (Wood et al. 1967), the ascorbic acid method for phosphate (Murphy and Riley 1962), and the phenate method for ammonium (Solórzano 1969). Total phosphorus and inorganic phosphorus in sediment were extracted using 1M hydrochloric acid (Aspila et al. 1976). Organic phosphorus concentrations in sediment were determined from the difference between phosphorus extracted with 50 mL of 1 M hydrochloric acid in 0.5 g of dried, unignited (inorganic phosphorus fraction) and ignited (total phosphorus fraction, 550°C for 2 hours) sediment samples. Extractions were done at room temperature for 16 h, in centrifuge tubes, agitated using a bench top shaker. After extraction, aliquots of each sample were transferred into 15-mL centrifuge tubes and centrifuged at 5500 rpm for 15 minutes. The supernatant of each sample was used to determine total and inorganic phosphorus concentrations by the ascorbic acid method.

2.2.3.5 Nutrient Retention

Nutrient removal/retention efficiency can be defined as the amount of a pollutant retained to the amount of pollutant which entered the pond (Davis and McCuen 2005). As it is difficult to measure the amount of pollutant retained, the amount of pollutant in the outflow can be used through mass balance principles, where the percent removal/retention efficiency (RE) can be mathematically defined as:

$$RE = \left(1 - \frac{C_{out}}{C_{in}}\right) \times 100$$

where, C_{out} is the pollutant concentration found in the outflow and C_{in} is the amount of pollutant in the inflow (Davis and McCuen 2005). A positive value indicates the percentage of pollutant which has been retained within the stormwater pond and a negative value represents the percentage of excess pollutant which has been discharged (Davis and McCuen 2005).

2.2.3.6 Estimation of Flow and Nutrient Loading

The loading of phosphorus and nitrogen into ponds was calculated based on the concentrations of nutrients at the inlet to each pond (mmol m^{-3}), and an estimate of water volume entering the pond ($m^3 d^{-1}$). Water volume at the inlet was calculated using the Rational Method for estimation of storm water flow (Toronto Water, 2009), assuming that all run-off within a stormwater pond's catchment entered the pond during the interval between sample collections. Flow was estimated as:

$$Q = 2.78 \text{ x A x C x I}$$

where Q is flow (L s^{-1}), A is area of drainage (ha), C is a run-off coefficient for land use, and I is intensity of rainfall (mm h^{-1}). For single-family homes, the predominant land-use type within each storm water pond's catchment, the City of Toronto uses a runoff coefficient of 0.65, which

was applied here. Total rainfall was summed over a period of 15 days prior to each sampling date, and divided by 360 hours to estimate hourly precipitation over that interval. The volume of water leaving the pond was assumed equal to the volume entering the pond on each sampling date, and was multiplied by nutrient concentrations at the outflow to estimate export of nitrogen and phosphorus.

2.2.3.7 Estimation of Pond Surface Area, Volume, and Hydraulic Retention Time

The ruler tool in Google Earth Pro was used to measure the surface area of MAT and HEP ponds as polygons. The surface area was multiplied by depth on each date to calculate volume. For each date, minimum, maximum, and quartile depths were determined from among the sampling points (18 in HEP and 15 in MAT). Volume was calculated assuming 5% of the pond's surface was represented by the minimum depth value, 5% by the maximum depth value, and 30% by each of the quartile values. Volume and water inflow were used to calculate hydraulic retention time, and net daily average retention for each sampling interval.

2.2.4 Statistical Analyses

Water quality data were statistically analyzed to compare the difference between the two ponds based on composite concentrations, treating rainfall and temperature as continuous variables in ANCOVA models. Statistical analyses were performed on SAS 94.

2.3 Results and Discussion

2.3.1 Temperature and DO Concentrations

Temperature and DO concentration profile measurements were conducted at both HEP and MAT over the entire sampling season. Stratification was first observed in both ponds on June 15, 2016 (Fig. 2.3) and persisted throughout the summer season until late autumn.
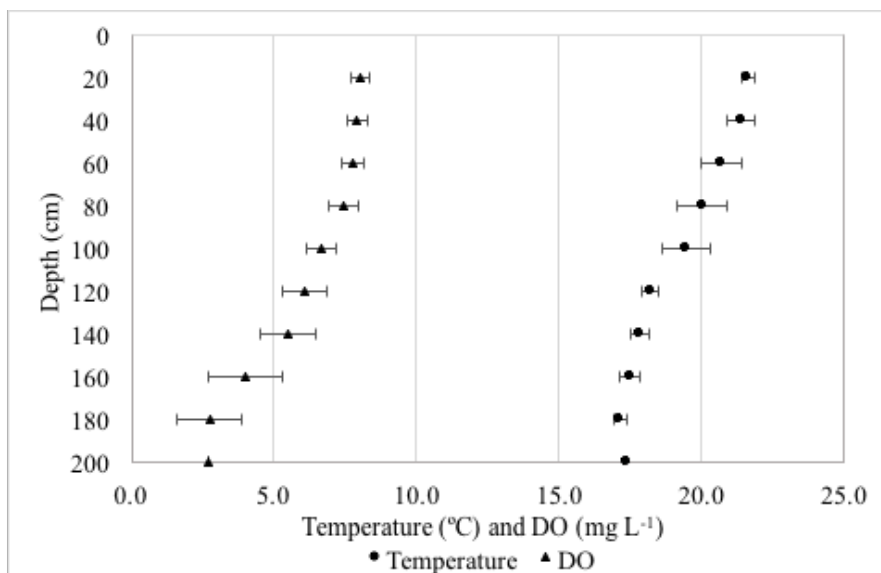
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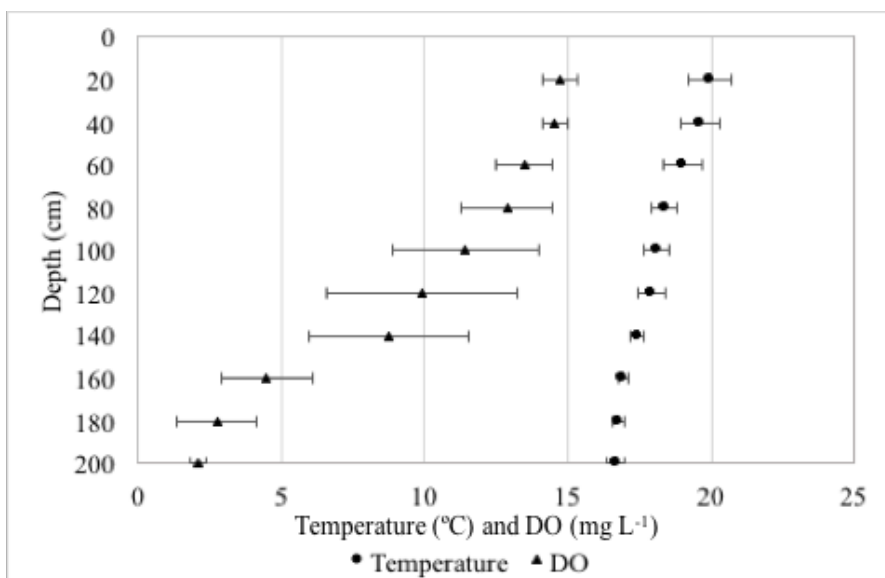
b)

Fig. 2.3 Temperature and Dissolved Oxygen (DO) concentrations measured at depths of 10 cm intervals from the pond surface to the pond bottom on June 15, 2016. a) HEP b) MAT.

2.3.2 Nutrient Concentrations

A total of twelve sampling days occurred between April and December of 2016 (Table 2.2). The average concentrations of DRP, TP, and NH_4^+ over the entire sampling period were similar between HEP and MAT. However, average concentrations of NO_3^- in HEP were significantly different between ponds, controlling for temperature and rainfall as covariates (ANCOVA, $p = 0.0105$; $p = 0.6400$, respectively). HEP is located directly beside a residential roadway which may explain why concentrations of NO_3^- are higher than in MAT. A previous study by Kojima et al. (2011) found that road dust accounted for more than half of the nitrate found in surface runoff. With the exception of nitrate, nutrient constituents measured were comparable with previous studies on stormwater retention ponds (Table 2.3). The 2016 season in Toronto was generally dry and the low frequency of flushing may have played a role in the higher nitrate concentrations. The values obtained from the study by Mayer et al. (1996) are of particular interest, as the study was also done within the Greater Toronto Area. Nitrate values reported by Mayer et al. (1996) were also higher than those reported in studies elsewhere, however they were much lower than in the current study. Further investigation should be done to determine the sources and concentrations of NO_3^- in stormwater runoff within the Greater Toronto Area.

Table 2.3 Summary of data comparison between study and previous studies on stormwater ponds. Values in parenthesis are concentration ranges observed.

Study	Ponds	Mean Concentrations Over the Sampling Season (µM)			
		DRP	TP	NH_4^+	NO_3
Current Study	HEP	1.18 (0.38 – 2.43)	3.58 (0.51 – 7.49)	6.65 (0.80 – 16.72)	99.9 (33.31 – 251.09)
	MAT	1.44 (0.22 – 4.08)	4.10 (1.07 – 9.88)	3.70 (1.19 – 11.87)	40.6 (10.27 – 197.50)
Mayer et al. (1996)[1]	Heritage	2.86	5.34	13.15	16.43
	S. Smith	1.87	4.16	9.38	18.66
	Tapscott	0.48	2.41	5.57	15.25
	Unionville	0.98	3.11	13.03	7.51
Wu et al. (1996)[2]	LS Pond	-	4.84	-	-
	WF Pond	-	4.84	-	-
	RB pond	-	5.81	-	-
Borden et al. (1998)[3]	Davis	5.20	9.27	5.38	4.40
	Piedmont	0.97	4.28	-	2.86
Comings et al. (2000)[4]	Pond C	0.84	2.81	-	-
	Pond A	0.48	2.49	-	-
Mallin et al. (2002)[5]	Ann McCrary	0.87	1.74	3.66	-
	Silver Stream	1.99	3.25	6.79	-
Winston et al. (2012)[6]	DOT	4.20	6.94	-	2.26
	Museum	3.23	5.97	-	1.45
Schwartz et al. (2017)[7]	Ashby Pond	1.29	6.13	4.16	4.35

[1] Ponds were located in the Greater Toronto Area; Heritage and Unionville ponds drained residential areas; Smith pond drained from industrial and commercial lands, and a major highway; Tapscott pond received runoff from agricultural lands; samples collected during February – November, 1993. [2] Stormwater ponds drained from residential areas; samples collected over a 13-month period (no year specified). [3] Davis pond drained from agricultural land; Piedmont pond drained from an industrial area; samples collected from December 1993 – November 1994. [4] Stormwater ponds drained from residential and commercial areas; samples collected from October 1996 – March 1997. [5] Stormwater ponds drained from residential areas, samples collected from October 1997 – February 2000. [6] DOT pond drained from a roadway; Museum pond drained from a parking lot, maintenance building, and picnic area; samples collected from December 2008 – February 2010. [7] Pond located in Northern Virginia; Stormwater pond drained from commercial and residential areas; samples collected from September 2012 – March 2013.

When comparing each individual nutrient constituent between HEP and MAT, similar seasonal trends were observed between HEP and MAT (Fig. 2.4). Both ponds experienced a peak in DRP and TP concentrations during mid-summer, with declines over late summer into autumn (Fig. 2.4 a & b). DRP concentrations were found to increase with increasing temperature and rainfall (ANCOVA, $p = 0.0007$; $p = 0.0023$, respectively). During the entire summer season, stratification was observed in the ponds and this likely caused a release of iron-bound phosphate from the sediment due to the anoxic conditions at the sediment-water interface. Studies of shallow lakes have also shown maximum concentrations of phosphorus during mid-summer due to internal loading (Welch & Cooke 1995; Ekholm et al. 1997; Jeppesen et al. 1997). It has also been demonstrated in previous studies that high phosphate export in runoff is associated with heavy rainfall events (Miguntanna et al. 2013; Hobbie et al. 2017). NH_4^+ concentrations in HEP and MAT were highest during late spring and early summer when the ponds were mixed (Fig. 2.4c). This was likely due to the external loading from the spring flush of nutrients into the ponds. During early to mid-summer, concentrations of NH_4^+ were low, likely due to a combination of biological uptake and nitrification. NH_4^+ increased again between mid to late summer and decreased at the start of autumn. This may have reflected internal loading from sediments during late summer. Stratification broke during early-autumn and oxic conditions were observed near the sediment and likely inhibited NH_4^+ release (Moore et al. 1992; Rysgaard et al. 1994; Beutel 2006) as sediment TN concentrations increased during the latter part of the year. As shown in Fig. 2.4d, the trends of NO_3^- concentrations in HEP and MAT are similar over the sampling period, but as mentioned above, the concentrations within each pond were different when controlling for temperature and rainfall as covariates (Table 2.4). Both ponds experienced a spring flush of NO_3^- during early

spring and concentrations were the highest during this season. This was likely due to precipitation and snowmelt in the spring season, as rain on snow events in southern Ontario have been found to export up to 24% of annual NO_3^- into streams (Crossman et al. 2016). NO_3^- concentrations decreased rapidly after the peak in concentrations in spring and remained below 100 μM during the summer season. This seasonal trend was similar to observations by Ledford et al. (2017) of a pulse of nitrate into an urban stream following a large rain event in the spring, and subsequently low nitrate concentrations in the summer due to autotrophic uptake. An increase in NO_3^- concentrations was observed during the early autumn season, with the increase greater in HEP than MAT. Nitrate was also found to have decreased with increased temperature (ANCOVA, $p = 0.0105$). It is known that increased temperatures and anoxic conditions result in less flux of nitrate from the sediment due to higher denitrification rates, where nitrate and nitrite are reduced to N_2O and N_2 (Christensen and Sorensen 1986, Liikanen et al. 2002).

Table 2.4 Analysis of covariance results for nutrient concentrations, comparing ponds with temperature and rainfall as covariates.

Constituent	$F_{(1,20)}$	p
DRP		
Pond	$1.24_{(1/0.458)}$	0.2787
Temperature	$15.80_{(1/0.458)}$	0.0007
Rainfall	$12.25_{(1/0.458)}$	0.0023
TP		
Pond	$0.20_{(1/6.601)}$	0.6563
Temperature	$5.04_{(1/6.601)}$	0.0363
Rainfall	$0.34_{(1/6.601)}$	0.5663
NH_4^+		
Pond	$2.45_{(1/17.919)}$	0.1334
Temperature	$0.03_{(1/17.919)}$	0.8537
Rainfall	$1.34_{(1/17.919)}$	0.2606
NO_3^-		
Pond	$6.67_{(1/3073.7)}$	0.0178
Temperature	$7.97_{(1/3073.7)}$	0.0105
Rainfall	$0.23_{(1/3073.7)}$	0.6400
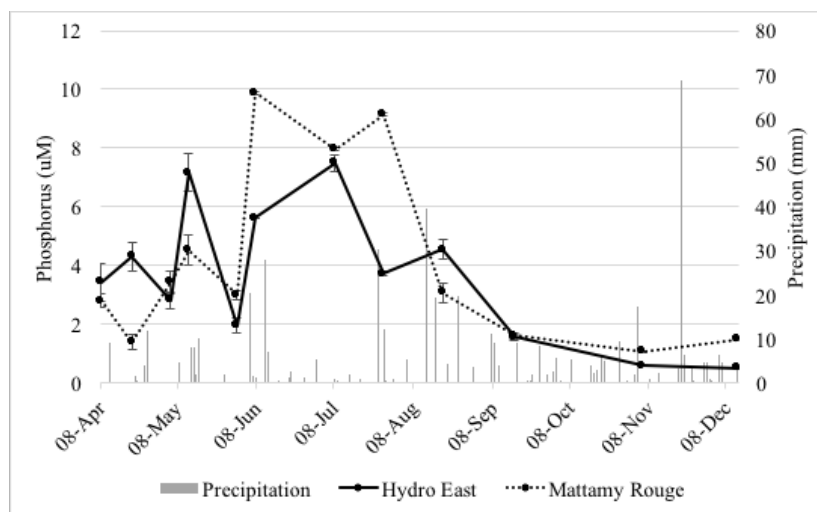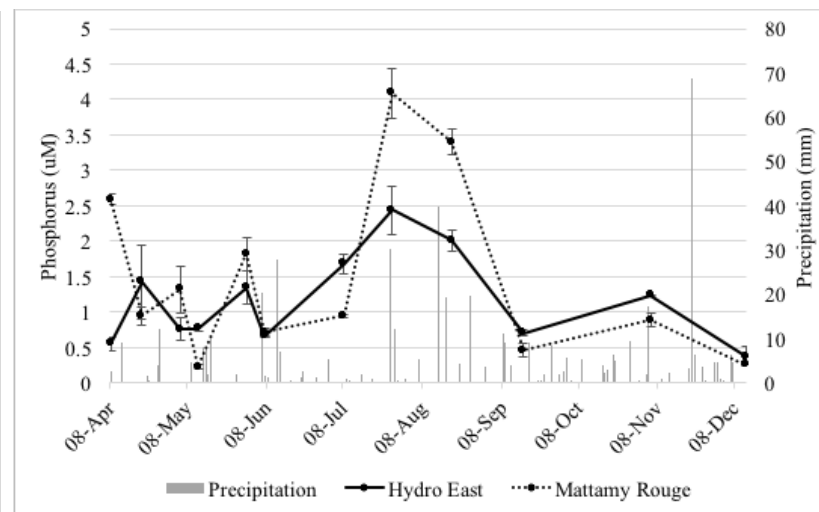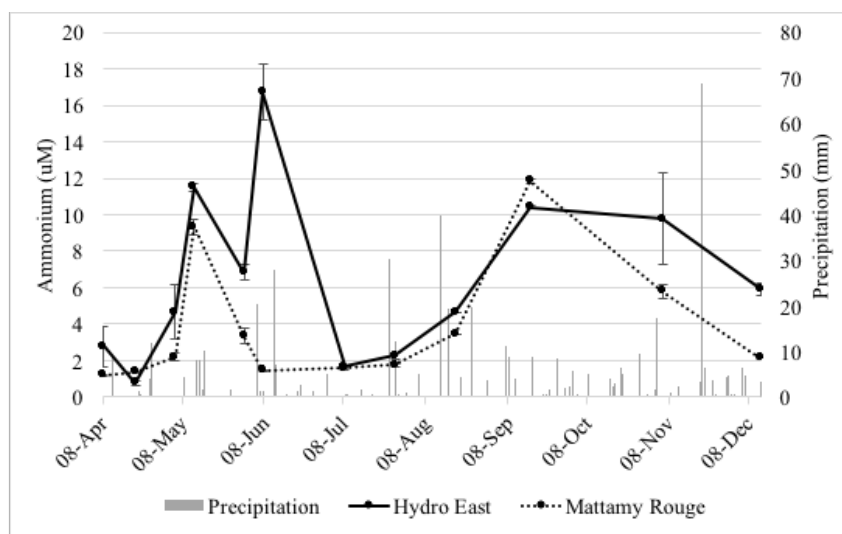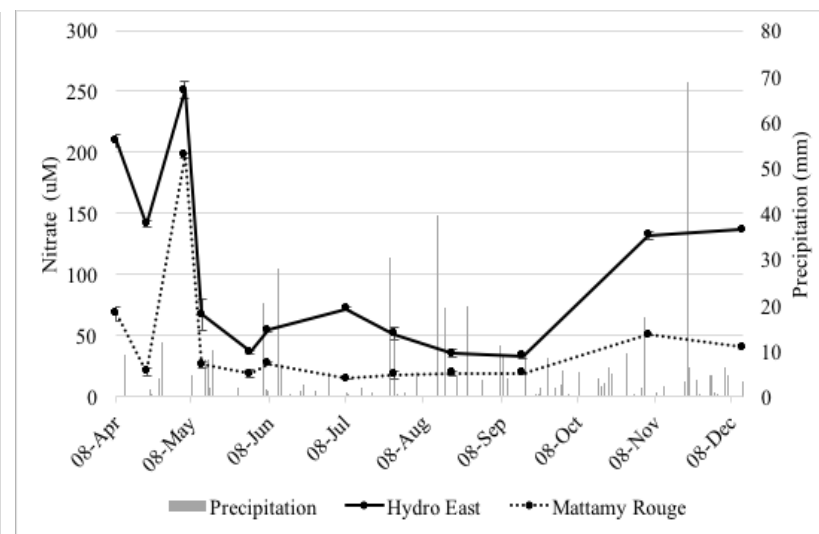
Fig. 2.4 Concentrations of nutrient constituents from composite samples in HEP and MAT and total precipitation during the two weeks prior to sampling date: a) total phosphorus, b) dissolved reactive phosphorus, c) ammonium, d) nitrate.

2.3.2 Percent Retention of Nutrients & Total Suspended Solids

One of the main purposes of stormwater ponds is to retain pollutants from runoff, mitigating export into receiving waters. Fig. 2.5 illustrates the percent retention of each nutrient constituent on individual sampling days over the entire sampling period. Both HEP and MAT experienced a high percent of TP export during late spring. Compared to previous studies on urban stormwater ponds, HEP and MAT performed poorly in regards to retention of TP as most other ponds studied were able to retain TP to some degree (Mayer et al. 1996; Wu et al. 1996; Borden et al. 1998; Comings et al. 2000; Mallin et al. 2002; Winston et al. 2013; Schwartz et al. 2017). Percent retention of DRP was highest during mid-summer, suggesting that DRP may have been retained by biological uptake in the two ponds (Fig. 2.5b). Retention of DRP began to decline shortly after mid-summer and interestingly, rebounded in MAT but continued to decrease to negative values (net export) in HEP during the later summer to early winter. It is also notable that during the summer season, both ponds were exporting TP, but retaining DRP, suggesting biological uptake and export of P from the ponds as particulate matter (algae and bacteria). Both ponds experienced fluctuations in the retention/export of NH_4^+. Generally, retention of NH_4^+ occurred during the summer months where it was likely controlled by biological uptake. NO_3^- was the only constituent which was retained in both ponds. The retention of NO_3^- was likely driven by the process of denitrification, where NO_3 is lost as it becomes reduced to N_2. High export of TSS was observed at the beginning of the study in both ponds, likely due to the flush of particulate matter from snowmelt. Retention of TSS occurred two weeks following the initial sampling date in early April and no export of TSS was observed in either ponds until mid-August. No retention or export was observed in HEP during September to November, whereas retention occurred in MAT during this time.

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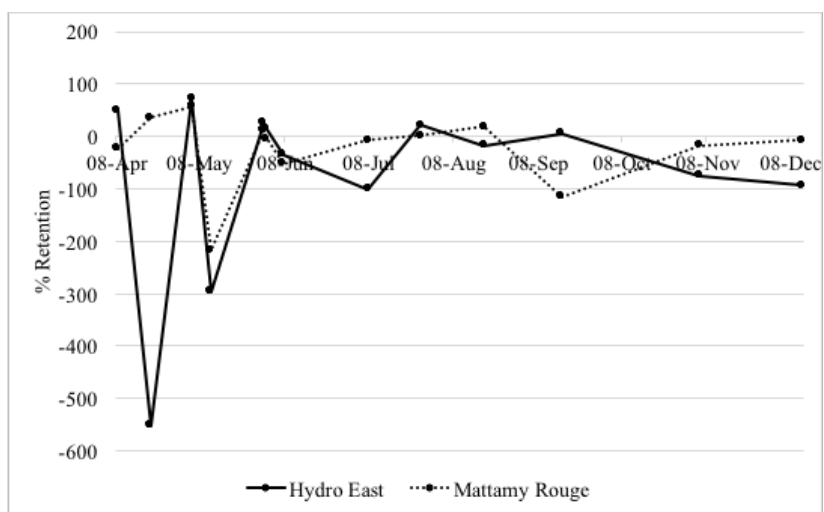
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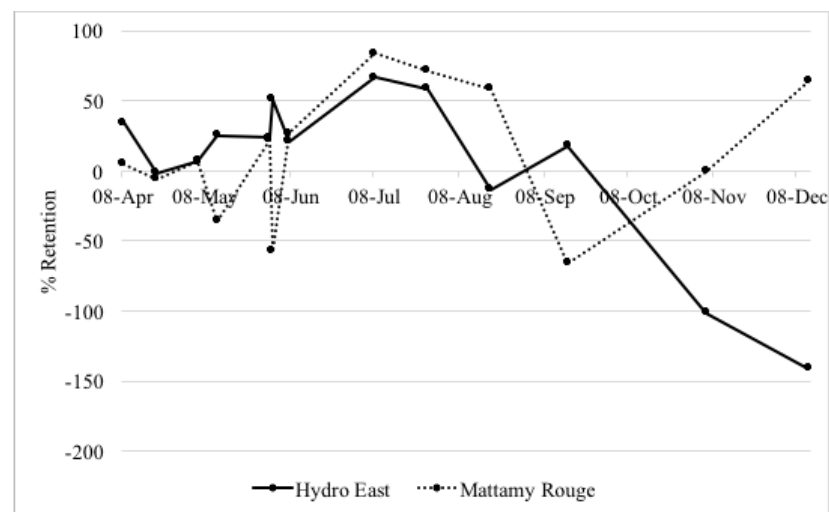
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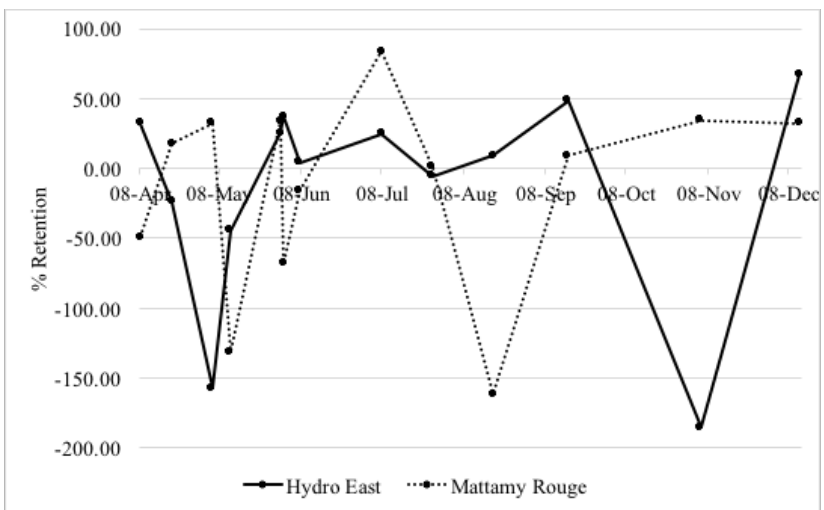
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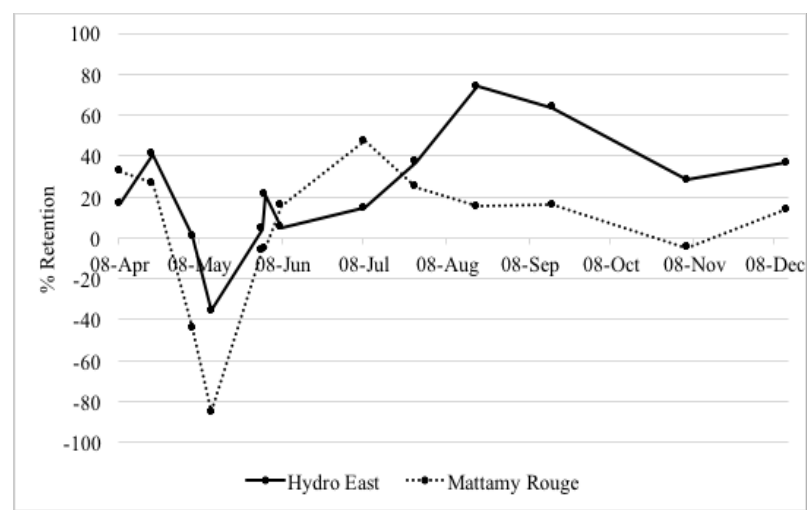
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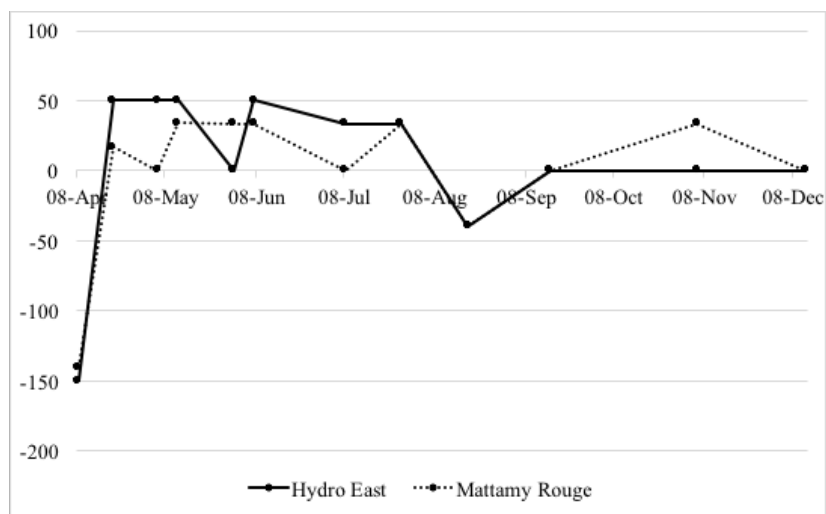
e)

Fig. 2.5 Percent retention of nutrient constituents and TSS in HEP and MAT: a) total phosphorus, b) dissolved reactive phosphorus, c) ammonium, d) nitrate, e) total suspended solids.

The term 'retention' has been commonly expressed in literature as a percentage change over time. However, the original usage of 'retention' by Vollenweider (1975) was defined as the difference between what was imported into the lake and what was exported. For this study, we used the Vollenweider definition of retention, where the retention of different nutrient constituents over time was determined by weighting concentrations by the volume of water flowing into the pond on each sampling date.

HEP had a slightly larger catchment area, and smaller volume than MAT. Consequently, hydraulic retention time in MAT was, on average, slightly more than double in MAT (31.1 d) relative to HEP (13.9 d). Phosphorus and nitrogen loading were temporally variable, with highest loading during early April. Retention of nutrients also varied temporally, both in magnitude and in direction. In HEP, Total P retention was most commonly negative, indicating net export of P. Over the entire study, 6.35 mol of P, or 0.20 kg P were exported from the pond. In contrast to P, HEP had net retention of N (as $NO_3^- + NH_4^+$). A total of 2672 mol N, or 37.4 kg were retained by the pond. Placing this in context, HEP exported 3.09 g P ha^{-1}, and trapped 587 g N ha^{-1} of catchment area. MAT was a net exporter of both phosphorus and nitrogen. Total P export over the duration of the study totaled 54.0 mol P (or 1.67 kg) and 264 mol N (or 3.7 kg). Placed in context, this amounted to a net loss of 34.6 g P ha^{-1} and 76.3 g N ha^{-1} of catchment area.

Sediment traps were installed in each pond for four of the study's sampling intervals in late summer to autumn. The material captured in sediment traps was quantified, and digested to determine the amount of TP and N deposited in particulate material. These quantities were used to calculate the average flux of P and N to sediments (mmol m^{-2} d^{-1}), and from these values, the flux of N and P to sediments for the entire pond (mol d^{-1}). Material collected in sediment traps

was highly enriched in N during the first three intervals (Jul. 27 – Sept. 16) for both ponds, with N:P ranging from 20 to 103. In each pond, the material tended to be relatively rich in P during the final interval (Sept. 16 – Nov. 5) with N:P of 4.2 in MAT and 8.6 in HPE.

The differences between flux of P and N (from the water column to sediments as particulate matter) and overall retention were calculated to determine internal loading of nutrients, most likely loading from sediments (Table 2.5). Where retention and flux were equivalent, all retention would be explained by flux of particulate N or P to sediments. Where flux exceeds retention, the difference is attributed to internal loading. Where flux is less than retention (negative values for loading), a mechanism other than deposition contributes to net retention (e.g., denitrification in the case of N retention). Internal loading of P was generally positive for both ponds, and of similar magnitude to P flux to sediments, suggesting that most of the P deposited to sediments is remineralized and released into the water column, with an average of 22% of TP buried in HEP, and 26% buried in MAT sediments during the period of July 14 – Nov 5. Internal nitrogen loading was negative for three of four intervals in HEP. The magnitude of this loss suggests approximately 59% of nitrogen deposited to sediments as particular matter is subsequently lost, most likely via denitrification. In contrast, internal loading of N was always positive in MAT, and of the same magnitude as flux of particulate N to sediments, suggesting that 97% of nitrogen reaching sediments in particulate form was remineralized and released to the water column as ammonium and nitrate (or nitrite).

TSS loading in both ponds was low and consistent during the majority of the study period (Table 2.5). HEP and MAT experienced a pulse of TSS into the ponds during the mid-summer months (Jul. 27 – Aug. 19). Over the entire study, a total of 1416 mg of TSS was retained in HEP and 1127 mg in MAT. When placing this into the context of catchment areas, HEP

retained 22.23 mg TSS ha^{-1} and MAT retained 23.29 mg TSS ha^{-1}. Although both ponds retained TSS over the entire season, it was interesting that they were net exporters of TSS on a daily basis. The daily average export of TSS was higher in MAT, with 101.58 mg TSS ha^{-1} d^{-1} exported, compared to 66.18 mg TSS ha^{-1} d^{-1} exported in HEP. This finding is not surprising as particles take time to settle and due to the shallow depth of stormwater ponds, generally less than 2 m deep, bottom sediment can be easily disturbed and resuspended due to strong winds and high inflow, resulting in low or negative retention (He & Marsalek 2014). Interestingly, there was no significant relationship found between retention of TSS and rainfall entering the ponds (ANCOVA, f = 3.91, p = 0.0794) and this was likely due to the low number of rainfall events during our period of study.

Table 2.5 Loading, export, and retention of TP, TN, and TSS in HEP and MAT.

	mol (P or N) d^{-1}; mg (TSS) d^{-1}						Hydraulic Retention time (d)	Retention (P or N) mol d^{-1}; mg (TSS) d^{-1}						
	Loading			Export				Net retention			Flux to sediments		Internal loading	
Hydro East Pond – Total P	P	N	TSS	P	N	TSS		P	N	TSS	P	N	P	N
April 08	10.9	498	47	5.50	412	117	3.8	5.42	86.0	-70				
April 20	0.08	49.4	49	0.51	29.9	25	16.6	-0.43	19.4	25				
May 5	0.81	57.1	50	0.23	59.1	25	16.7	-0.59	-2.04	25				
May 12	0.25	31.5	31	0.99	43.4	16	13.1	-0.74	-11.9	16				
May 31	0.55	15.6	17	0.41	14.4	17	20.5	0.14	1.14	0				
June 7	2.17	62.9	66	2.91	59.7	33	11.3	-0.74	3.14	33				
July 8	0.44	17.8	27	0.89	15.2	18	42.1	-0.44	2.64	9				
July 27	5.57	64.6	136	4.36	41.6	90	8.5	1.21	22.9	45	0.31	6.28	-0.90	-16.6
August 19	3.27	179	296	3.85	50.5	413	4.1	-0.58	128	-117	0.60	61.0	1.18	-67.0
September 16	0.89	56.4	33	0.84	21.0	33	10.4	0.05	35.4	0	0.64	65.8	0.59	30.4
November 05	0.29	144	47	0.51	111	47	7.6	-0.22	32.2	0	0.55	4.73	0.77	-27.5
December 12	0.37	125	30	0.71	77.4	30	11.8	-0.34	47.3	0				

Whole study Total P retention (mol) = **-6.35**   Whole study Total N retention (NH$_4^+$ + NO$_3^-$) (mol) = **2672**
Whole study Total TSS retention (mg) = **1416**

	Loading			Export			Hydraulic Retention time (d)	Net retention			Flux to sediments		Internal loading	
Mattamy Pond – Total P	P	N	TSS	P	N	TSS		P	N	TSS	P	N	P	N
April 08	6.49	142	59	7.99	99.5	142	6.6	-1.50	42.1	-83				
April 20	0.21	11.6	30	0.14	8.65	25	34.2	0.07	2.94	5				
May 5	1.40	71.2	25	0.59	99.8	25	33.4	0.81	-28.6	0				
May 12	0.48	11.6	24	1.53	23.0	16	27.7	-1.05	-11.4	8				
May 31	0.86	4.64	39	0.76	4.35	26	49.5	0.10	0.29	13				
June 7	2.89	10.4	50	4.38	9.55	33	27.5	-1.49	0.87	17				
July 8	1.07	8.95	20	1.15	4.38	20	94.9	-0.08	4.57	0				
July 27	4.72	13.7	103	4.68	10.7	69	19.4	0.05	2.96	34	0.51	45.6	0.46	42.6
August 19	7.06	26.1	225	5.79	26.3	314	8.9	1.27	-0.13	-89	1.09	89.0	-0.19	89.1
September 16	0.30	15.4	25	0.65	13.3	25	26.0	-0.35	2.12	0	0.98	64.1	1.33	62.0
November 05	0.45	44.7	54	0.54	44.6	36	17.6	-0.08	0.11	18	0.75	3.14	0.83	3.03
December 12	0.60	23.2	23	0.64	19.6	23	27.3	-0.04	3.60	0				

Whole study Total P retention (mol) = **-53.9**   Whole study N retention (NH$_4^+$ + NO$_3^-$) (mol) = **-264**
Whole study Total TSS retention (mg) = **1127**

2.3.3 Sediment Traps

The sedimentation rates were similar between ponds over most of the study, although higher rates were seen in MAT between July 14 and July 27 (Fig. 2.6). The annual average sedimentation rate (mm y^{-1}) in HEP was 51.1 ± 6.0 and 65.7 ± 12.3 in MAT. Although there have not been any studies on sediment deposition rates in stormwater ponds, studies by Marsalek & Marsalek (1997) and Yousef et al. (1994) measured sediment accumulation rates in stormwater ponds which are comparable to deposition rates (Szmytkiewicz & Zalewska 2014). Marsalek & Marsalek (1997) estimated the rate of accumulation in a stormwater pond in Kingston, Ontario to be 20 mm y^{-1} and Yousef et al. (1994) measured sediment accumulation rates in nine different ponds in Florida and the rates ranged from 10.3 to 42.0 mm y^{-1}.
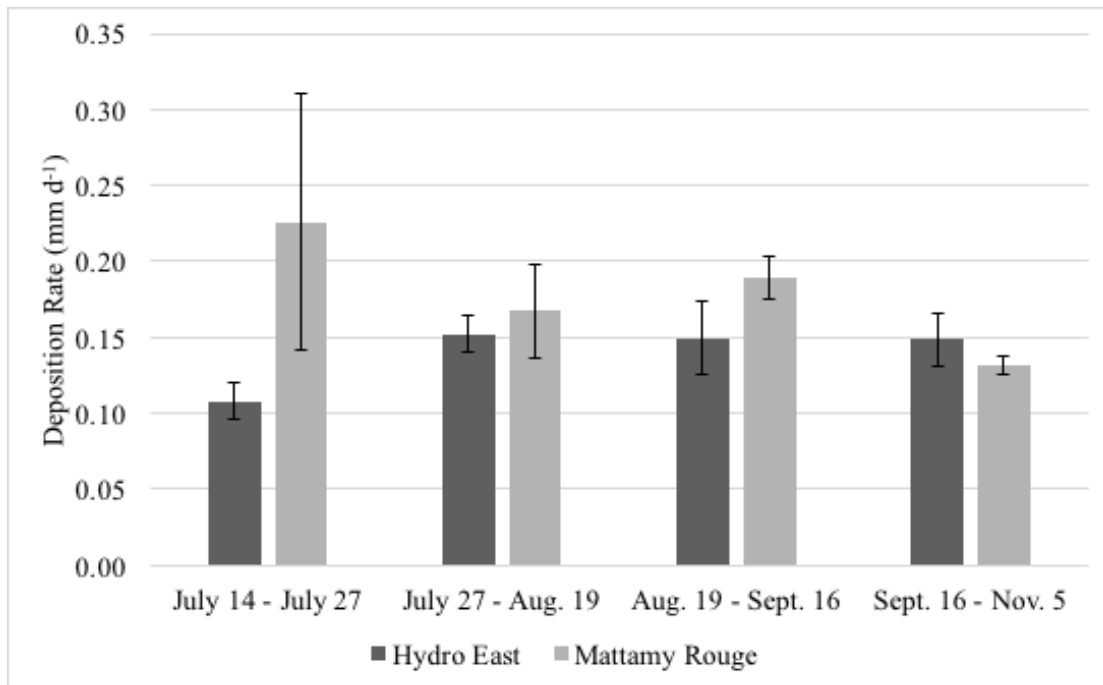
Fig. 2.6 Sediment deposition rates (mm day^{-1}) from sediment traps in HEP and MAT.

As for the material composition, the majority (> 80%) of the material being deposited in HEP and MAT was inorganic. This was reflective of the material composition of bottom

sediment in both ponds, as the bottom sediment was 92% and 93% inorganic in HEP and

MAT, respectively. Overall, a higher percentage of organic phosphorus was being deposited in

MAT than in HEP (Fig. 2.7). An increase in deposition of organic phosphorus was observed

beginning late summer into autumn, which likely reflects the settling of dead biomass. A recent

study by Song et al. (2017) observed that the high rate of accumulation of organic phosphorus

in sediment from primary production due to external phosphorus loading could lead to internal

P release through decomposition or other biological processes in urban stormwater ponds.
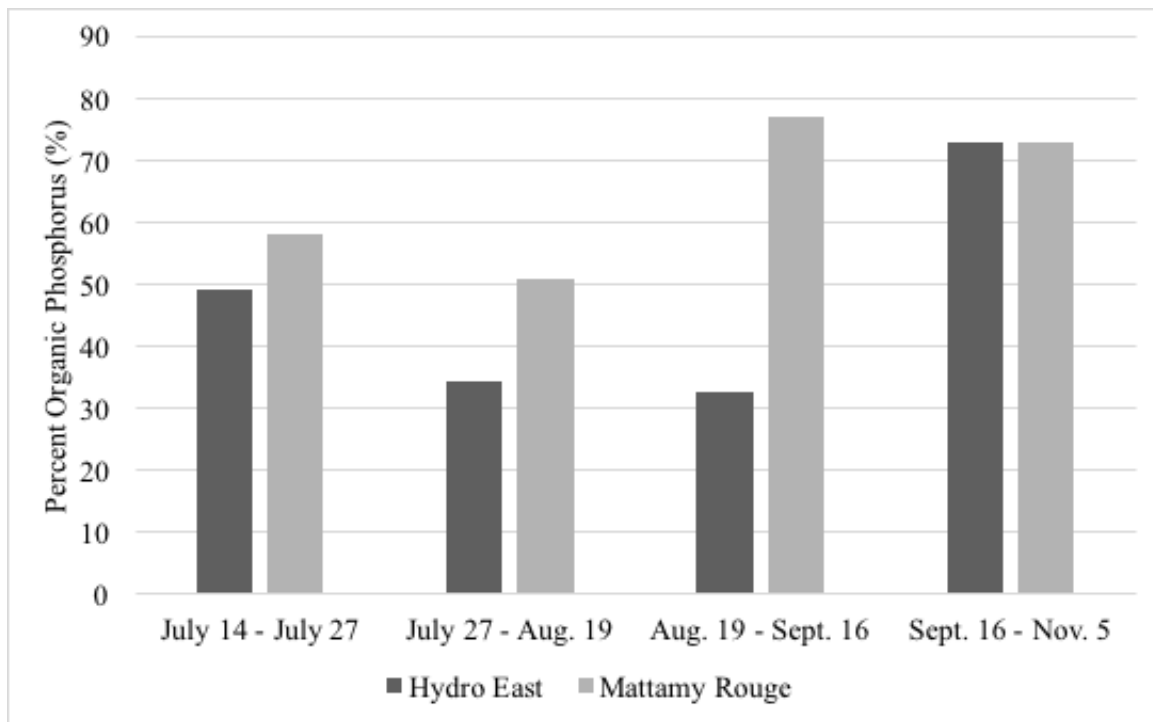
Fig. 2.7 Percent organic phosphorus in sediment collected from sediment traps in HEP and
MAT.

2.3.4 Nutrient Budget Model

Higher phosphorus loading was observed in MAT compared to HEP and the reverse was

seen for nitrogen loading (Fig. 2.8). Internal loading of TP was observed in both ponds due to

the remineralization of P deposited in sediment and release into the water column. Although

there was a higher loading of inorganic nitrogen in HEP compared to MAT, HEP retained

higher amounts of inorganic nitrogen and exported less than MAT over the sampling season. This retention was likely due to loss of inorganic nitrogen via denitrification. In contrast, there was internal loading of inorganic nitrogen in MAT from remineralization and release to the water column from sediment.

a) Nutrient budget for HEP.

b) Nutrient budget for MAT.
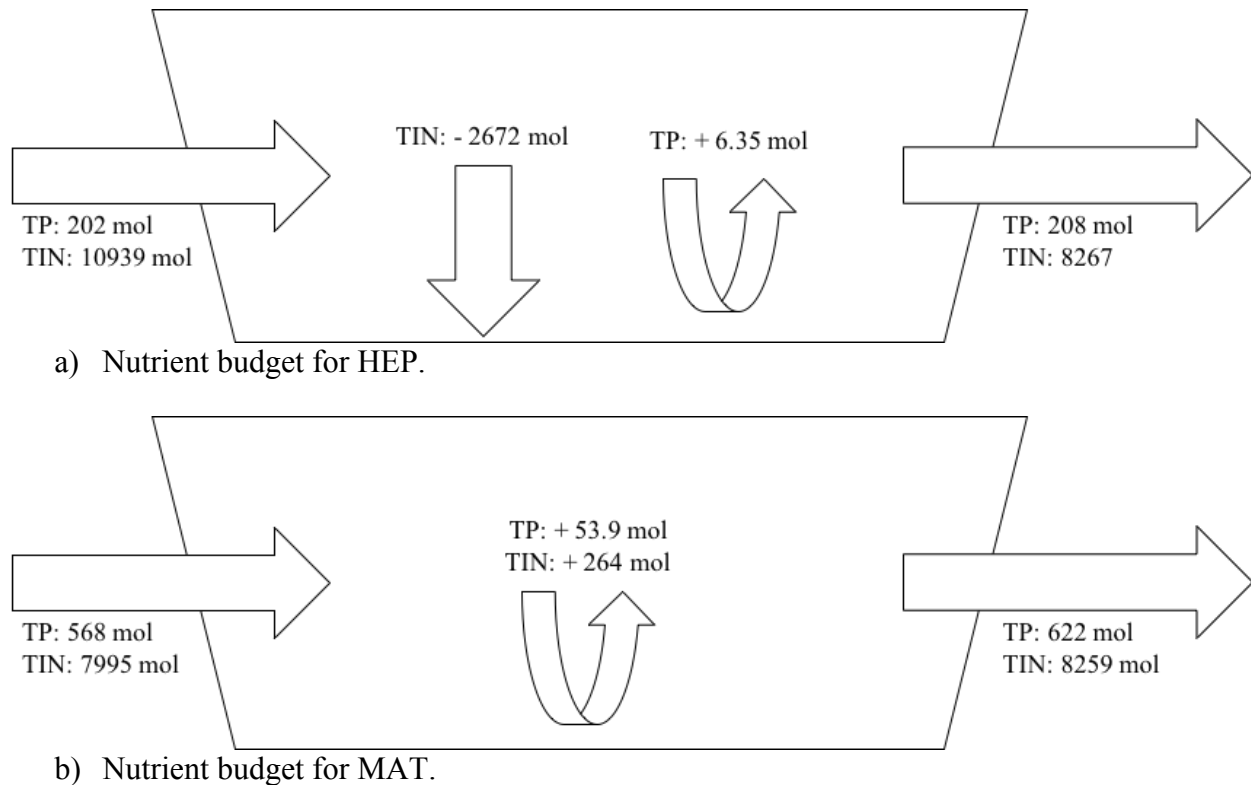
Fig. 2.8 Nutrient budgets for HEP and MAT over the entire sampling season in 2016. The total amount loading and washout of TP and TIN was used to calculate retention/internal loading. Arrows pointing down with negative values represent retention and curved up arrows with positive values represent internal loading of each nutrient constituent.

Stormwater ponds have been widely constructed in North American cities to reduce and delay peak flows from urban runoff and have also been recognized for their potential ability to retain pollutants, such as nutrients and TSS. The results from this study have demonstrated that these retention ponds are able to provide retention of TSS but can be exporters of phosphorus and nitrogen. This is in contrast to previous studies in the literature, which have reported retention efficiencies of phosphorus between 12% and 57% and retention efficiencies of

nitrogen between 6% and 84% (Mayer et al. 1996; Wu et al. 1996; Borden et al. 1998; Comings et al. 2000; Mallin et al. 2002; Winston et al. 2013). However, it important to highlight that 2016 in Toronto, Ontario, was an abnormally dry and hot year and stratification was observed in HEP and MAT in early summer. Due to the dry year, concentrations of phosphorus and nitrogen loading were generally found to be low in HEP and MAT. When looking into percent retention, low concentrations can give the illusion that ponds perform poorly. For example, if there is a loading of 0.1 mol of phosphorus, a 10% retention of 0.01 mol may appear low. But when putting it into context, the initial loading was already low and further reduction may be difficult due to recalcitrant material. A common misconception is that stormwater ponds do not experience thermal stratification as they are well mixed due to their shallow depth and short residence time (Persson 2000; Zoppou 2001). But stratification was observed in HEP and MAT, consistent with findings from other ponds studied in Ontario, Canada (McEnroe et al. 2013; Song et al. 2013) and when stratification does occur, it may lead to a release of iron-bound phosphate and ammonium from the sediment. Much more work is needed to investigate how biogeochemical cycles function and may be altered in stormwater ponds.

Overall, this study and previous studies have shown that stormwater ponds have the ability to provide retention of pollutants from urban runoff. However, during particularly dry years, these ponds may become net exporters of nutrients. The results from this study have shown that the function of these ponds should be enhanced to provide further treatment before the water flows into receiving bodies of water. One potential solution may be to increase the depth of these ponds. But as discussed above, these ponds already experience thermal stratification with their shallow depth and an increase in depth may further add to this problem. However, instead

of building ponds with greater depths, sediment in ponds should be periodically removed to maintain their effective depth and also to prevent potential internal loading from the release of phosphorus from sediment into the water column.

3. Conclusion

Two stormwater ponds in Toronto, Ontario, Canada were evaluated for their nutrient and TSS retention ability over a period of eight months. The following conclusions were drawn from this study:

1) Nutrient concentrations between the studied ponds were found to be similar, with the exception of NO_3^-, as concentrations of NO_3^- were higher in HEP than in MAT. Despite the difference, NO_3^- concentrations in both ponds were higher than those reported in other studies in the literature. The dry year and low flushing may have played a role in high NO_3^- concentrations.

2) Over the entire sampling period, the seasonal trends for TP, DRP, NH_4^+, and NO_3^- were similar between HEP and MAT. TP and DRP concentrations were highest during mid-summer and may have been caused by the release of iron-bound phosphate from the sediment due to anoxic conditions resulting from stratification. Concentrations of NH_4^+ were highest during late spring, likely due to external loading from the spring flush, and were lowest during early to mid-summer, likely due to a combination of biological uptake and nitrification. Similar to NH_4^+, concentrations of NO_3^- were highest during early spring, likely due to the spring flush. However, concentrations of NO_3^- decreased rapidly as it was probable that higher denitrification rates occurred with increased temperatures.

3) Retention of nutrients varied temporally, both in magnitude and in direction. Both HEP and MAT were net exporters of phosphorus over the entire season, with -6.35 mol and -53.9 mol exported, respectively. However, HEP had net retention of 2672 mol of nitrogen, while MAT exported 264 mol of nitrogen over the entire study.

4) Internal loading of phosphorus was generally positive for both ponds, suggesting that most of the phosphorus deposited to sediments was remineralized and released into the water column. In HEP, 56% of the nitrogen was deposited to sediments as particulate matter and lost, most likely through denitrification. In contrast, 97% of nitrogen deposited to sediment in MAT was remineralized and released to the water column as ammonium and nitrate (and nitrite).

5) A total of 1416 mg and 1127 mg of TSS was retained in HEP and MAT, respectively.

6) The annual average sedimentation rate (mm y^{-1}) in HEP was 51.1 ± 6.0 and 65.7 ± 12.3 in MAT.

7) The majority of material being deposited in HEP and MAT, was inorganic in nature.

This study has demonstrated that stormwater ponds have the ability to provide retention of nutrients and TSS, but their function may be enhanced. Pond depth may be one factor in improving pond function. However, as shown in this study, stratification already occurs in these shallow ponds and increasing the depth physically may not be the real solution. Instead, sediment in ponds should be periodically removed to maintain their effective depth and also to prevent potential internal loading from the release of phosphorus from sediment into the water column. More studies should focus on the relationship between sediment accumulation and effective pond volume on nutrient retention. The results from this study also showed that during an anomalously dry year, these ponds may become net exporters of nutrients. Further research should be done to examine and compare how these ponds would function during an anomalously wet year (e.g. 2017) to determine how much of the results found from this study was driven by the lack of rainfall. As stormwater ponds have been widely built in many municipalities as water management infrastructures, there is a need for a model synthesizing

the data from literature on stormwater ponds to better understand their function. For example, a model could be created to predict retention as a function of local climate, catchment characteristics, and pond hydrologic/morphologic characteristics. As the building of stormwater ponds comes at a cost of alternative land uses, such a model could help local water managers determine if these ponds are worth building and if any special designs or features are needed to ensure that the ponds will function as expected

Appendices

Appendix A: Map of Location and Proximity of Hydro East and Mattamy Rouge Ponds

Appendix B: Site Drawing of Hydro East Pond

Appendix C: Site Drawing of Mattamy Rouge Pond

51
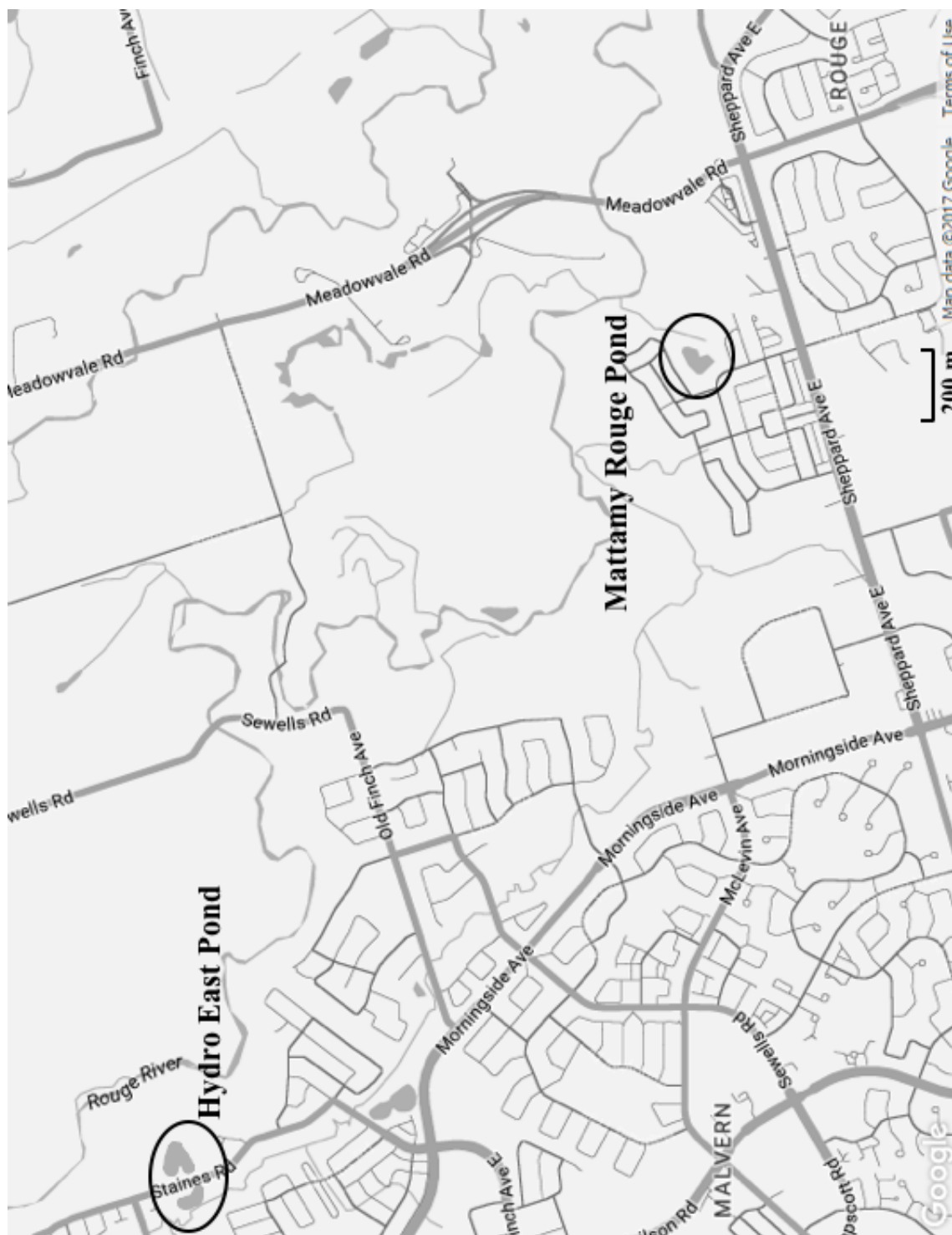
Appendix D: Extended Methods

Secchi Depth

A Secchi disk was used to measure the water clarity of the pond. A Secchi disk is a flat, weighted disk with alternating black and white quadrants. The following technique used was developed by Angelo Secchi in 1866 (Preisendorfer 1986).

1. The Secchi disk was lowered slowly into the water column until all four quadrants were no longer visible. This depth was recorded.

2. The disk was then slowly raised until all quadrants just become visible again. This depth was also recorded and averaged with the first recorded depth to obtain the Secchi depth.

3. Secchi depth measurements were made at three locations (A, B, and C) in each pond (Fig. 2.2).

Sediment Mapping

First Approach

1. Depths of the water column to sediment were measured at various points along transects depicted in Fig. 2.2.

2. A measuring tape attached to a weighted disk was lowered to the bottom of the pond. With the disk lying flat on the sediment surface, the depth of the water column was measured at each point (18 points total in HEP, 16 points total in MAT).

3. The distance was measured from a fixed point on shore (above the water line) to the water surface on each date, and this value was added to the depth of the water column to determine depth to the sediments at each location relative to a fixed point on shore (Fig. 2.2). This

measurement allowed for observations regarding any loss or gain of sediment throughout the pond over the sampling period.

4. Linear regression was used to determine rate of sediment accumulation for each sampling location over the duration of the study, and the average rate of accumulation throughout the pond was determined based on mean of all site-specific regression coefficients.

Second Approach

1. Sediment accumulation was also measured by inserting a pole vertically into the sediment until it was no longer possible to push, and reading the total depth.

2. The thickness of sediment was then determined by taking the difference between this observed value and the water column depth at each location.

1. Distance from Fixed Point to Sediment Surface = Fixed Point to Water Surface + Depth of Water Column

2. Sediment Thickness = Surface to Bottom of Sediment - Depth of Water Column

Fixed Point to Water Surface

Surface to Bottom of Sediment

Depth of Water Column
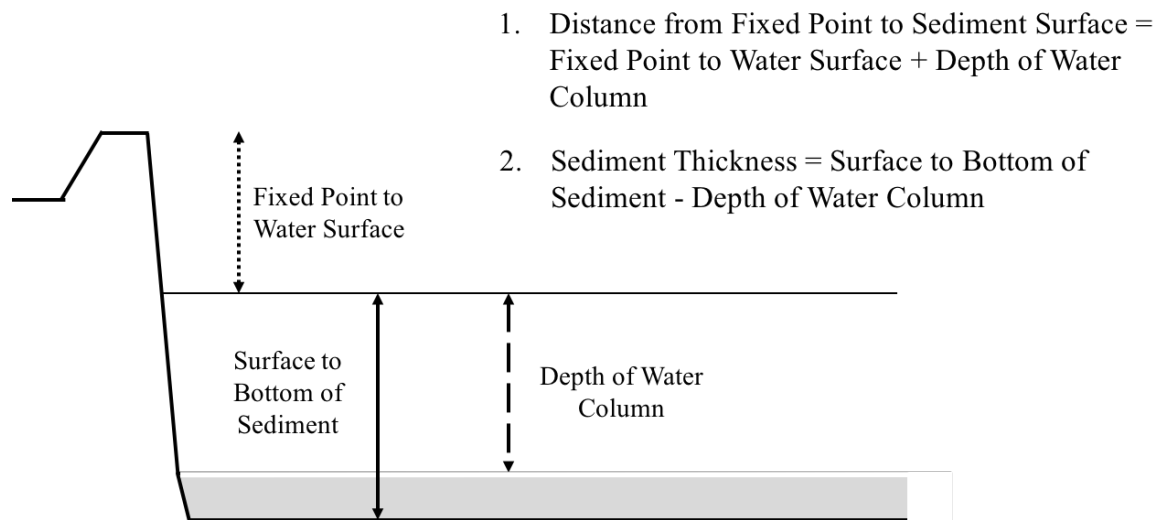
Figure D1 Measurement of water depth and sediment thickness.

Analysis of Organic Matter in Sediment Samples

1. Organic matter in sediment samples was determined by the ignition method (Howard and Howard 1990).

2. A sample (~0.5 g) of dried sediment (105°C for 12 hours) was sieved (2 mm mesh), and weighed into ceramic crucibles (pre-weighed, pre-ashed).

3. The samples were then placed into a muffle furnace and were ignited at 550°C for 2 hours, cooled, and re-weighed.

4. The percent organic matter in the sediment was calculated using the following equation:

$$\% \, Organic \, Matter = \frac{(Pre - ignition \, mass) - (Post - ignition \, mass)}{(Pre - ignition \, weight)} \times 100$$

Analysis of Total Suspended Solids (TSS)

1. The weight of pre-ashed (550°C for 4 hours) Whatman GF/F filters (0.7 μm) was measured before each was used for the filtering of water samples, to obtain the original filter paper weights.

2. The filter papers were placed into a filtration apparatus and were first wet with milliQ water.

3. Aliquots of water were filtered through a filtration apparatus.

4. The filters were then dried in an oven for 12-hrs at 105°C.

5. The dried filter papers were cooled and weighed. The concentration of TSS was calculated using the following equation:

$$mg \, Suspended \, Solids \, L^{-1} = \frac{(mass \, of \, filter \, with \, dried \, residue - mass \, of \, filter) \times 100}{mL \, Sample}$$

Nutrient Analyses of Water Samples

Dissolved Reactive Phosphorus (DRP) - Ascorbic Acid Method

1. DRP concentrations were measured in filtered water samples using the Ascorbic Acid Method (Murphy and Riley 1962).

2. Aliquots of 5-mL of sample water were transferred into a clean, dry test tubes.

3. 1 drop of phenolphthalein indicator solution was added into each test tube.

4. If a red colour developed, 2.5 M H_2SO_4 solution was added dropwise to discharged the colour.

5. 0.8-mL of combined reagent (Murphy and Riley 1962) was added into each test tube and were mixed thoroughly.

6. All test tubes containing the mixed sample and reagent were left at room temperature for at least 10 minutes for colour to develop.

7. The absorbance of each sample at 880-nm was then measured on a UV/VIS spectrophotometer (Perkin Elmer Lambda 20).

Total Reactive Phosphorus

1. Total reactive phosphorus concentrations were measured in unfiltered water samples using the Ascorbic Acid Method (Murphy and Riley 1962), as described above.

Total Phosphorus (TP)

1. The water samples were first digested using the Persulfate Digestion Method to oxidize organic material and release phosphorus as orthophosphate (American Public Health Association 2012).

2. Aliquots of 25-mL of sample water were transferred into borosilicate glass bottles.

3. 1 drop of phenolphthalein indicator solution was added into each bottle.

4. If a red colour developed, H_2SO_4 solution (American Public Health Association 2012) was added dropwise to discharge the colour.

5. Then 0.5-mL of H_2SO_4 solution and 0.25-g of $K_2S_2O_8$ were added into each bottle.

6. The samples were then heated in an autoclave at 98 to 137 kPa for 30 minutes.

7. Once cool, 1 drop of phenolphthalein indicator solution was added into each bottle and neutralized to a faint pink colour with 6 M NaOH.

8. The phosphorus concentrations were then determined by the Ascorbic Acid Method (Murphy and Riley 1962), as described above. A separate calibration curve was constructed with standards which had undergone the persulfate digestion procedure.

Ammonium

1. Ammonium concentrations were measured using a modification of the Phenate Method (Solórzano 1967). During the presence of hypochlorite, ammonia found in the samples reacts with phenate and produces a blue colour. Sodium nitroferricyanide was used as a catalyst for this reaction.

2. Aliquots of 5-mL of sample water were transferred into clean, dry test tubes.

3. The following reagents were added to each test tube in sequence and mixed: 0.2-mL of phenol solution, 0.2-mL of sodium nitroferricyanide, and 0.5-mL of oxidizing solution (Solórzano 1967).

4. Samples with reagents were then capped and allowed to stand for one hour in the dark.

5. The absorbance of each sample at 640-nm was then measured on a UV/VIS spectrophotometer (Perkin Elmer Lambda 20).

Nitrate

1. Nitrate concentrations were determined using the Cadmium Reduction Method (Wood et al. 1967).

2. Aliquots of 2.5-mL of sample was transferred into clean, dry test tubes and 7.5-mL of ammonium chloride-EDTA solution (Wood et al. 1967) was added into each test tube and mixed.

3. Samples were then passed through a reduction column, packed with copper-cadmium granules, using a peristaltic pump.

4. As the samples were passed through the reduction column, the first 5-mL of each sample were discarded and the next 2-mL was collected into a clean, dry test tube.

5. 0.1-mL of colour reagent was then added into each test tube and mixed.

6. Samples were left at room temperature for at least 15 minutes to allow for colour development.

7. The absorbance of each sample at 543-nm was then measured on a UV/VIS spectrophotometer (Perkin Elmer Lambda 20).

Extraction of Pore Water from Sediment Samples and Nutrient Analyses

1. To obtain the pore water from sediment, sediment samples were centrifuged at 5000 rpm for 15 minutes and the supernatant was decanted to obtain the pore water sample.

2. Pore water samples were analyzed for DRP, ammonium, and nitrate using the methods described above for analyses of water sample.

Nutrient Analyses of Sediment Samples

Total Phosphorus (TP)

1. Total phosphorus concentrations in sediment were determined by ignition and extraction with 1 M hydrochloric acid (Aspila *et al.* 1976).

2. 0.5-g of oven-dried, sieved sediment samples were weighed and transferred into ceramic crucibles.

3. The samples were then placed into a muffle furnace and were ignited at 550ºC for 2 hours.

4. Once samples cooled, they were transferred into 200-mL flasks.

5. 50-mL of 1 M hydrochloric acid was added into each flask.

6. The solutions were shaken for 16 hours on a benchtop shaker at room temperature.

7. Aliquots of each mixture sample were transferred into 15-mL centrifuge tubes and centrifuged at 5500 rpm for 15 minutes.

8. The supernatant of each sample was used to determine total phosphorus concentrations by the Ascorbic Acid Method (Murphy and Riley 1962), as described above.

Organic Phosphorus (OP)

1. Organic phosphorus concentrations in sediment were determined from the difference between phosphorus extracted with 1 M hydrochloric acid in unignited (inorganic phosphorus fraction) and ignited (total phosphorus) sediment samples.

2. The procedure to determine the inorganic phosphorus concentrations in sediment was the same as the one for TP, except dried sediment samples were not ignited at 500ºC.

Bioavailable Phosphorus (BAP)

1. Bioavailable phosphorus concentrations in sediment were determined by a NaOH extraction scheme (Burrus *et al.* 1990).

2. 0.2-g of oven-dried, sieved sediment samples were weighed and transferred into 50-mL centrifuge tubes.

3. 20-mL of 1 M sodium hydroxide was added into each tube and the mixtures were shaken for 16 hours on a benchtop shaker at room temperature.

4. The samples were then centrifuged at 5000 rpm for 15 minutes.

5. 10-mL of the supernatant from each sample was transferred into 15-mL centrifuge tubes and 4-mL of 3.5 M hydrochloric acid was added into each tube.

6. The solutions were then allowed to stand for 16 hours at room temperature to settle organic particles.

7. After 16 hours, samples were centrifuged at 5500 rpm for 15 minutes.

8. The supernatant of each sample was used to determine bioavailable phosphorus concentrations by the Ascorbic Acid Method (Murphy and Riley 1962), as described above.

Total Nitrogen (TN)

1. The supernatant extracted for TP analysis of sediment was also used for analysis of TN.

2. Aliquots of 4-mL of sample water were transferred into a clean, dry test 50-mL centrifuge tubes.

3. TN concentrations were measured on a Teledyne Tekmar Apollo 9000 Combustion TOC/TN Analyzer.

Calculation for Concentrations of Nutrient Constituents in Sediment Samples

The amount of each phosphorus and nitrogen constituent measured in sediment samples was calculated using the following equation:

$$Concentration\ of\ P\ /\ N\ (mg\ kg^{-1}) = \frac{Conc.\ of\ P\ /\ N\ (mg\ L^{-1}) \times Volume\ of\ Extractant\ (L)}{Mass\ of\ Soil\ (kg)}$$

Calculation for Conversion of Sediment Concentrations from mg kg^{-1} to mol L^{-1}

1. Average sediment thickness of each pond was determined by taking the difference between the average depth to bottom of sediment and the average depth to the top of sediment from all points sampled in the entire season.

2. Total volume of bottom sediment in each pond was determined by multiplying the surface area of the pond by the average sediment thickness of the season.

3. Given the total volume of the pond, the mass of sediment in each pond was determined by the following equation, assuming bulk density of the sediment to be 1.3 g mL^{-1}:

$$\rho_b = \frac{M}{V}$$

   where, ρ_b is the bulk density, M is the mass of sediment, and V is the total volume of sediment.

4. Given the mass and volume of sediment, concentrations from mg P kg^{-1} sediment was converted into mol P L^{-1} sediment.

Appendix E: Secchi Depth Measurements

All values expressed as centimeter.

Hydro East Pond

Location	08-Apr	20-Apr	05-May	12-May	01-Jun	07-Jun	15-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov
A	62	48.5	45	29	45	29	39	-	36	40	30	29
B	63	44	45	29	44	32	30	-	39	40	30	34
C	64	39.5	41	29	42	28	30	-	37	39	26	35
Mean	63	44	43.7	29	43.7	29.7	33	-	37.3	39.7	28.7	32.7
Std. Err.	0.33	1.50	0.77	0.00	0.51	0.69	1.73	-	0.51	0.19	0.77	1.07

Mattamy Rouge Pond

Location	08-Apr	20-Apr	05-May	12-May	01-Jun	07-Jun	15-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov
A	58	76.5	94.5	83	51.5	39	60	28.5	44.5	31.5	39	52
B	58	70.5	97.5	79.5	48.5	45	59	28.5	43.4	36	52	53
C	58	62.5	90	71.5	49.5	42	60	29.5	46	36	58	53
Mean	58	69.8	94	78	49.8	42	59.7	28.8	44.6	34.5	49.7	52.7
Std. Err.	0.00	2.34	1.26	1.96	0.51	1.00	0.19	0.19	0.44	0.87	3.24	0.19

Appendix F: Depth of Water Column and Depth from Surface to Bottom of Sediment Layer

Depth of Water Column

Values expressed in metres.

Hydro East Pond

Sample Point	08-Apr	20-Apr	05-May	12-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov
E1	1.7	1.43	1.65	1.27	1.46	1.53	1.45	1.58	1.49	1.52	1.52
E2	1.74	1.53	1.78	1.75	1.57	1.62	1.6	1.65	1.49	1.54	1.58
E3	0.95	1.37	1.45	1.45	1.35	1.21	1.22	1.31	1.11	1.19	1.32
E4	1.9	1.79	1.9	1.66	1.36	1.61	1.32	1.57	1.61	1.6	1.54
E5	1.99	2.10	1.87	1.81	1.6	1.65	1.57	1.65	1.66	1.56	1.6
E6	1.3	1.85	1.66	1.8	1.4	1.49	1.38	1.52	1.36	1.36	1.54
E7	2.02	1.92	1.87	1.85	1.57	1.66	1.56	1.65	1.54	1.57	1.63
E8	2.02	1.95	1.9	1.83	1.61	1.66	1.58	1.67	1.59	1.63	1.64
E9	1.5	1.57	1.91	1.82	1.6	1.69	1.65	1.68	1.64	1.59	1.6
E10	-	1.49	1.91	1.83	1.59	1.7	1.58	1.64	1.64	1.61	1.62
E11	1.9	2.01	1.93	1.84	1.63	1.69	1.62	1.69	1.64	1.61	1.62
E12	-	1.30	1.55	1.69	1.35	1.57	1.29	1.58	1.51	1.45	1.4
E13	-	1.12	1.13	1.11	0.6	0.72	0.51	0.93	1.02	0.59	0.62
E14	1.2	1.12	1.15	1.15	0.99	0.99	0.79	1.35	0.91	0.84	0.89
E15	-	0.63	0.84	0.89	1.08	1.01	0.81	1.16	0.94	0.85	0.98
E16	-	1.22	1.19	1.13	0.88	0.99	0.74	0.99	1.03	0.82	0.98
E17	1.54	1.48	1.38	1.34	0.96	1.14	1.09	1.17	0.94	1.02	1.1
E18	-	1.29	1.17	1.08	0.83	0.86	0.84	0.95	0.83	0.92	0.97
Fixed-Point	1.24	1.35	1.45	1.49	1.7	1.61	1.69	1.6	1.68	1.7	-

Mattamy Rouge Pond

Sample Point	08-Apr	20-Apr	05-May	12-May	31-May	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov
M1	1.3	0.49	1.45	1.85	1.55	1.55	1.64	1.3	0.44	1.8	1.44
M2	2.06	2.18	2.13	1.93	2.16	2.02	1.9	2.1	2.4	2.06	2.03
M3	0.97	2.04	1.34	1.98	1.22	1.83	1.79	1.83	1.45	1.65	1.95
M4	0.71	1.22	0.73	0.7	1.45	1.86	0.9	1.49	0.72	1.3	0.92
M5	1.67	1.06	1.1	1.64	1.98	2	1.84	1.82	1.1	1.82	1.82
M6	0.45	1.43	2	1.95	1.69	2.05	1.85	1.85	1.55	1.85	1.94
M7	1.81	1.95	1.83	1.82	1.81	1.85	1.82	1.71	1.66	1.76	1.59
M8	1.99	2.06	2.12	1.57	1.69	1.72	1.67	1.45	1.32	1.72	1.6
M9	0.66	0.61	0.69	0.6	0.5	0.57	0.48	0.45	0.58	0.57	0.48
M10	0.45	0.51	0.35	0.5	0.36	0.48	0.39	0.52	0.42	0.42	0.37
M11	2.28	1.75	2.18	1.95	2.05	2.16	2.1	2.12	2.12	2.03	1.93
M12	2.24	2.23	2.25	2.24	2.15	2.14	2.07	2.6	2.5	1.98	1.94
M13	1.71	2.08	1.76	1.46	1.63	1.73	1.51	1.68	1.75	1.64	1.69
M14	2.47	2.08	2.36	2.03	2.01	2.07	1.93	2.26	2.46	2.02	1.82
M15	2.09	2.33	1.97	2.04	1.95	2.11	1.89	2.1	2.9	1.8	1.87
M16	1.95	1.93	1.78	1.77	1.62	1.63	1.85	1.77	1.78	1.81	1.47
Fixed-Point	1.28	1.35	1.38	1.39	1.45	1.39	1.42	1.34	1.45	1.45	1.38

Depth from Surface to Bottom of Sediment Layer

All values expressed in metres.

Hydro East Pond

Sample Point	19-Aug	05-Nov
E1	2.06	1.91
E2	1.66	1.83
E3	1.40	1.68
E4	1.87	1.97
E5	1.82	1.87
E6	1.83	1.85
E7	1.79	1.84
E8	1.82	1.89
E9	1.91	1.91
E10	1.87	1.88
E11	1.84	1.91
E12	1.89	1.60
E13	1.26	0.76
E14	0.94	0.94
E15	1.02	1.17
E16	1.45	1.42
E17	1.41	1.52
E18	1.19	1.24

Mattamy Rouge Pond

Sample Point	19-Aug	16-Sep	05-Nov
M1	1.88	2.11	1.98
M2	2.08	2.11	2.21
M3	1.93	1.91	2.21
M4	0.81	1.88	1.57
M5	1.12	2.11	2.24
M6	1.93	2.21	2.24
M7	2.72	2.13	2.13
M8	1.42	2.24	2.08
M9	0.58	0.51	0.69
M10	0.48	0.56	0.46
M11	2.41	2.34	2.41
M12	2.62	2.31	2.26
M13	2.11	1.85	2.13
M14	2.16	2.16	2.29
M15	2.31	2.16	2.24
M16	2.41	2.11	1.91

Appendix G: Temperature and Dissolved Oxygen (DO) Concentrations

Temperature and DO profiles on June 15, 2016.

Hydro East Pond

Depth	Sample Point A		Sample Point B		Sample Point C	
	Temperature (ºC)	DO (mg L^{-1})	Temperature (ºC)	DO (mg L^{-1})	Temperature (ºC)	DO (mg L^{-1})
20	22.04	8.68	21.51	7.66	21.33	7.79
40	22.04	8.6	21.73	7.7	20.43	7.41
60	22.06	8.53	20.47	7.42	19.55	7.37
80	21.79	8.47	19.37	6.92	18.98	6.92
100	21.15	7.64	18.79	5.84	18.41	6.46
120	18.69	7.56	18.24	5.54	17.72	5.12
140	18.45	7.25	17.76	5.22	17.36	3.98
160	18.15	6.56	17.29	3.26	17.03	2.23
180	17.58	5.02	16.99	1.47	16.87	1.71
200	17.4	2.72	-	-	-	-

Mattamy Rouge Pond

Depth	Sample Point A		Sample Point B		Sample Point C	
	Temperature (ºC)	DO (mg L^{-1})	Temperature (ºC)	DO (mg L^{-1})	Temperature (ºC)	DO (mg L^{-1})
20	21.33	13.56	18.78	15.61	19.67	15
40	20.73	13.9	18.32	14.33	19.8	15.4
60	19.8	13.45	17.67	11.81	19.5	15.22
80	18.86	13.64	17.52	9.84	18.71	15.08
100	18.55	13.19	17.23	6.42	18.55	14.65
120	18.09	12.93	17.06	3.31	18.59	13.48
140	17.72	12.04	17.02	3.2	17.47	10.98
160	16.58	4.86	16.93	1.53	17.24	7.09
180	16.36	2.13	16.83	0.74	17.11	5.39
200	16.38	1.85	-	-	16.95	2.36

Appendix H: Volume of Sediment Collected from Sediment Traps

All values expressed in milliliters.

Hydro East Pond

Trap Location	July 14 - July 27	July 27 - Aug. 19	Aug. 19 - Sept. 16	Sept. 16 - Nov. 5
A	125	265	225	580
B	92	305	400	650
C	90	230	325	430

Mattamy Rouge Pond

Trap Location	July 14 - July 27	July 27 - Aug. 19	Aug. 19 - Sept. 16	Sept. 16 - Nov. 5
A	363.5	400	450	520
B	190	250	400	500
C	89	230	350	450

Appendix I: Percent Organic Matter in Bottom Sediment

Sample Date & Location	Crucible Weight (g)	Pre-ignition Weight (g)	Post-ignition Weight (g)	Post-ignition minus Crucible Weight (g)	% OM	Mean % OM	Std. Err.
Apr. 8 - HEP	18.9915	1.0081	19.9478	0.9563	5.14		
	17.5979	1.001	18.5482	0.9503	5.06	5.05	0.03
	18.5818	1.0013	19.5336	0.9518	4.94		
Apr. 8 - MAT	17.8435	1.0031	18.7144	0.8709	13.18		
	18.5636	1.0037	19.4239	0.8603	14.29	13.96	0.23
	17.2956	1.0058	18.1565	0.8609	14.41		
May 31 - HEP	17.1897	1.0041	18.1533	0.9636	4.03		
	17.5012	1.0019	18.4625	0.9613	4.05	4.06	0.01
	15.764	1.0006	16.7236	0.9596	4.10		
May 31 - MAT	17.9019	1.0035	18.869	0.9671	3.63		
	19.3541	1.0032	20.3191	0.965	3.81	3.86	0.09
	17.4607	1.0014	18.4205	0.9598	4.15		
July 14 - HEP	18.8992	0.5336	19.3733	0.4741	11.15		
	17.5174	0.514	17.9789	0.4615	10.21	10.80	0.17
	18.492	0.5046	18.9409	0.4489	11.04		
July 14 - MAT	17.7656	0.4974	18.2401	0.4745	4.60		
	18.4752	0.4908	18.9438	0.4686	4.52	4.81	0.14
	17.1119	0.5038	17.589	0.4771	5.30		
Sept. 16 - HEP	17.4117	0.4995	17.8744	0.4627	7.37		
	15.6975	0.5055	16.1448	0.4473	11.51	9.30	0.70
	17.8231	0.0587	17.8765	0.0534	9.03		
Sept. 16 - MAT	19.2583	0.5034	19.7443	0.486	3.46		
	17.3758	0.4931	17.8504	0.4746	3.75	3.56	0.06
	18.0874	0.5021	18.5721	0.4847	3.47		
Nov. 5 - HEP	19.3512	0.5029	19.8128	0.4616	8.21		
	18.5791	0.5027	19.0392	0.4601	8.47	8.38	0.05
	17.4578	0.5067	17.9216	0.4638	8.47		
Nov. 5 - MAT	17.8994	0.5019	18.3692	0.4698	6.40		
	18.1777	0.5019	18.6458	0.4681	6.73	6.52	0.06
	17.5953	0.5055	18.0683	0.473	6.43		

Appendix J: Percent Organic Matter in Sediment Collected from Sediment Traps

Sample Date & Location	Crucible Weight (g)	Pre-ignition Weight (g)	Post-ignition Weight (g)	Post-ignition minus Crucible Weight (g)	% OM	Mean % OM	Std. Err.
July 27 - MAT Trap A	17.4981	0.5022	17.9395	0.4414	12.11	12.34	0.11
	18.9887	0.5097	19.4335	0.4448	12.73		
	19.3512	0.5001	19.7904	0.4392	12.18		
July 27 - MAT Trap B	17.5951	0.4925	17.9785	0.3834	22.15	22.31	0.09
	17.8993	0.4958	18.2852	0.3859	22.17		
	17.1871	0.5073	17.5797	0.3926	22.61		
July 27 - MAT Trap C	18.5609	0.4959	18.9504	0.3895	21.46	21.77	0.23
	17.8405	0.516	18.2425	0.402	22.09		
July 27 - HPE Trap A	18.579	0.5014	19.0216	0.4426	11.73	11.92	0.06
	18.1776	0.496	18.6137	0.4361	12.08		
	15.7613	0.4984	16.2001	0.4388	11.96		
July 27 - HPE Trap B	18.9618	0.5162	19.4089	0.4471	13.39	13.53	0.05
	17.9032	0.5081	18.3426	0.4394	13.52		
	18.2416	0.5091	18.6811	0.4395	13.67		
July 27 - HPE Trap C	16.259	0.504	16.6894	0.4304	14.60	14.81	0.09
	19.2811	0.4969	19.7048	0.4237	14.73		
	15.9437	0.4968	16.3655	0.4218	15.10		
Aug 19 - MAT Trap A	17.8933	0.5043	18.3113	0.418	17.11	17.31	0.06
	16.6368	0.5014	17.0509	0.4141	17.41		
	17.4579	0.5082	17.8776	0.4197	17.41		
Aug 19 - MAT Trap B	18.171	0.509	18.549	0.378	25.74	25.54	0.06
	18.243	0.5023	18.6176	0.3746	25.42		
	16.1628	0.5018	16.5369	0.3741	25.45		

Sample Date & Location	Crucible Weight (g)	Pre-ignition Weight (g)	Post-ignition Weight (g)	Post-ignition minus Crucible Weight (g)	% OM	Mean % OM	Std. Err.
Aug 19 - MAT Trap C	18.6416	0.5059	19.0149	0.3733	26.21	26.30	0.11
	18.9142	0.501	19.2848	0.3706	26.03		
	18.0889	0.5005	18.4559	0.367	26.67		
Aug 19 - HPE Trap A	18.3263	0.5018	18.7543	0.428	14.71	14.62	0.03
	16.8597	0.4949	17.2825	0.4228	14.57		
	18.8593	0.5051	19.2908	0.4315	14.57		
Aug 19 - HPE Trap B	19.444	0.5191	19.8816	0.4376	15.70	15.43	0.10
	20.6796	0.5023	21.1042	0.4246	15.47		
	24.0587	0.5037	24.4862	0.4275	15.13		
Aug 19 - HPE Trap C	27.6154	0.4998	28.0605	0.4451	10.94	10.80	0.05
	20.7001	0.499	21.146	0.4459	10.64		
	18.0845	0.51	18.5393	0.4548	10.82		
Sept. 16 - MAT Trap A	17.4981	0.5025	17.8953	0.3972	20.96	21.20	0.08
	18.9887	0.5054	19.3868	0.3981	21.23		
	19.3512	0.4915	19.7374	0.3862	21.42		
Sept. 16 - MAT Trap B	17.5951	0.5044	17.9922	0.3971	21.27	21.48	0.08
	17.8993	0.5003	18.2908	0.3915	21.75		
	17.1871	0.5026	17.582	0.3949	21.43		
Sept. 16 - MAT Trap C	18.5609	0.5054	18.9532	0.3923	22.38	22.57	0.08
	17.8405	0.5	18.228	0.3875	22.50		
	17.8933	0.503	18.2815	0.3882	22.82		
Sept. 16 - HPE Trap A	18.579	0.5032	19.0141	0.4351	13.53	13.57	0.02
	18.1776	0.5088	18.6171	0.4395	13.62		
	15.7613	0.5106	16.2027	0.4414	13.55		

Sample Date & Location	Crucible Weight (g)	Pre-ignition Weight (g)	Post-ignition Weight (g)	Post-ignition minus Crucible Weight (g)	% OM	Mean % OM	Std. Err.
Sept. 16 - HPE Trap B	18.9618	0.5115	19.4027	0.4409	13.80	13.92	0.04
	17.9032	0.5061	18.339	0.4358	13.89		
	18.2416	0.5015	18.6726	0.431	14.06		
Sept. 16 - HPE Trap C	16.259	0.5041	16.6922	0.4332	14.06	14.03	0.02
	19.2811	0.5105	19.7197	0.4386	14.08		
	15.9437	0.5048	16.3781	0.4344	13.95		
Nov. 5 - MAT Trap A	8.6175	0.4999	9.0129	0.3954	20.90	20.80	0.04
	16.6369	0.5049	17.0366	0.3997	20.84		
	17.4584	0.5074	17.861	0.4026	20.65		
Nov. 5 - MAT Trap B	18.1706	0.5038	18.5632	0.3926	22.07	21.91	0.22
	18.2432	0.5056	18.6417	0.3985	21.18		
	16.1632	0.4986	16.5498	0.3866	22.46		
Nov. 5 - MAT Trap C	18.6421	0.5028	19.0223	0.3802	24.38	24.43	0.04
	18.9146	0.4946	19.2881	0.3735	24.48		
Nov. 5 - HPE Trap A	18.089	0.5057	18.5288	0.4398	13.03	13.03	0.00
	18.3275	0.5002	18.7625	0.435	13.03		
Nov. 5 - HPE Trap B	16.8598	0.5018	17.2913	0.4315	14.01	14.17	0.11
	18.86	0.5039	19.2917	0.4317	14.33		
Nov. 5 - HPE Trap C	19.4448	0.5059	19.8747	0.4299	15.02	15.00	0.01
	18.0864	0.5005	18.5119	0.4255	14.99		

Appendix K: Concentrations of TSS in Water Samples

All values expressed in mg L^{-1}.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	20	100	100	50	50	100	150	150	167	50	50	50
Outlet	50	50	50	25	50	50	100	100	233	50	50	50

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	33.3	80	66.7	50	150	100	150	150	167	50	75	50
Outlet	80	66.7	66.7	33	100	66.7	150	100	233	50	50	50

Appendix L: Mean Concentrations of TP in Water Samples

All values expressed in $\mu mol\ L^{-1}$.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	4.68	0.16	1.63	0.40	1.64	1.62	3.31	2.46	6.16	1.84	1.33	0.31	0.60
Std. Err.	0.33	0.05	0.43	0.17	0.01	0.21	0.10	0.06	0.66	0.14	0.23	0.01	0.06
Outlet	2.36	1.04	0.45	1.60	1.22	1.39	4.44	4.93	4.82	2.17	1.26	0.53	1.17
Std. Err.	0.27	0.17	0.08	0.41	0.32	0.02	0.04	0.32	0.54	0.33	0.11	0.00	0.08
Composite	3.44	4.30	2.81	7.17	1.95	2.87	5.61	7.49	3.72	4.54	1.55	0.58	0.51
Std. Err.	0.63	0.50	0.30	0.66	0.24	0.02	0.00	0.29	0.07	0.33	0.11	0.01	0.03

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	3.66	0.56	3.70	1.02	3.36	3.75	5.79	7.83	6.87	5.23	0.60	0.63	1.30
Std. Err.	0.39	0.09	0.63	0.10	0.12	0.02	0.38	0.15	0.66	0.14	0.23	0.01	0.06
Outlet	4.50	0.36	1.56	3.23	2.96	3.92	8.78	8.39	6.80	4.29	1.28	0.74	1.39
Std. Err.	0.25	0.17	0.19	0.42	0.14	0.27	0.39	0.12	0.54	0.33	0.11	0.00	0.08
Composite	2.80	1.37	3.43	4.52	3.00	3.94	9.88	7.96	9.15	3.08	1.62	1.07	1.48
Std. Err.	0.23	0.26	0.38	0.52	0.14	0.06	0.06	0.04	0.07	0.33	0.11	0.01	0.03

Appendix M: Mean Concentrations of DRP in Water Samples

All values expressed in μmol L^{-1}.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	0.88	0.55	0.74	0.76	0.86	1.01	0.87	3.01	2.79	2.13	0.76	0.21	0.18
Std. Err.	-	-	-	-	-	-	-	0.07	0.05	0.05	0.02	0.01	0.05
Outlet	0.57	0.56	0.69	0.57	0.65	0.49	0.68	1.01	1.15	2.42	0.63	0.42	0.44
Std. Err.	-	-	-	-	-	-	-	0.07	0.13	0.05	0.07	0.04	0.16
Composite	0.55	1.42	0.76	0.76	1.34	1.38	0.65	1.68	2.43	2.01	0.70	1.23	0.38
Std. Err.	0.10	0.52	0.16	0.04	0.23	0.27	0.02	0.14	0.34	0.15	0.04	0.00	0.13

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	0.43	0.68	0.46	0.39	0.69	0.54	0.91	4.17	1.44	1.59	0.46	1.26	0.84
Std. Err.	-	-	-	-	-	-	-	0.12	0.32	0.10	0.07	0.00	0.04
Outlet	0.41	0.72	0.43	0.53	0.54	0.86	0.66	0.69	0.41	0.66	0.76	1.27	0.30
Std. Err.	-	-	-	-	-	-	-	0.13	0.09	0.10	0.01	0.12	0.07
Composite	2.59	0.95	1.32	0.22	1.82	1.16	0.71	0.94	4.08	3.40	0.45	0.88	0.25
Std. Err.	0.08	0.13	0.33	0.03	0.23	0.19	0.06	0.02	0.35	0.18	0.10	0.10	0.00

Appendix N: Mean Concentrations of Ammonium in Water Samples

All values expressed in µmol L^{-1}.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	6.32	2.38	3.20	11.94	6.50	14.79	13.38	4.23	2.35	3.28	5.01	4.10	9.23
Std. Err.	-	-	-	-	1.43	-	-	0.05	0.04	0.01	0.37	0.30	1.32
Outlet	4.27	2.95	8.25	17.24	4.87	9.27	12.80	3.20	2.48	2.98	2.58	11.71	3.07
Std. Err.	-	-	-	-	0.37	-	-	1.09	0.03	0.09	0.11	3.25	0.19
Composite	2.77	0.80	4.68	11.51	6.84	8.40	16.72	1.66	2.26	4.66	10.41	9.78	5.93
Std. Err.	1.09	0.13	1.47	0.20	0.41	0.14	1.56	0.11	0.14	0.01	0.08	2.50	0.31

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	2.64	4.51	9.93	6.64	5.62	4.60	4.92	6.96	2.65	1.72	9.83	7.87	5.14
Std. Err.	-	-	-	-	0.56	-	-	0.32	0.07	0.12	0.35	0.16	0.24
Outlet	3.95	3.70	6.74	15.38	3.73	7.75	5.70	1.13	2.64	4.50	8.95	5.15	3.49
Std. Err.	-	-	-	-	0.21	-	-	0.04	0.12	0.02	0.06	0.27	1.25
Composite	1.19	1.36	2.20	9.33	3.35	2.54	1.47	1.60	1.75	3.46	11.87	5.80	2.17
Std. Err.	0.01	0.04	0.21	0.44	0.42	0.06	0.04	0.08	0.10	0.02	0.13	0.39	0.12

Appendix O: Mean Concentrations of Nitrate in Water Samples

All values expressed in μmol L^{-1}.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	206.76	98.31	111.64	38.68	39.55	81.19	82.46	95.15	69.02	97.35	79.19	147.73	196.03
Std. Err.	2.39	8.36	2.60	2.73	3.10	1.19	5.42	0.96	2.14	0.52	4.84	3.66	10.41
Outlet	171.96	58.11	110.70	52.56	37.81	64.06	78.25	81.48	43.56	25.50	28.76	106.03	124.38
Std. Err.	3.11	3.82	6.46	0.10	3.76	1.40	1.30	6.73	1.81	0.44	1.77	3.26	5.80
Composite	209.46	140.88	251.09	66.94	36.58	79.35	54.14	71.96	51.19	35.10	33.31	131.92	136.64
Std. Err.	5.26	2.63	7.29	13.33	1.29	2.67	1.62	1.15	5.17	3.43	1.72	2.75	0.90

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	77.11	26.62	178.44	17.98	12.44	18.06	15.98	58.65	17.27	17.67	20.41	54.26	45.20
Std. Err.	0.34	0.48	6.08	1.53	0.02	1.81	2.22	0.87	2.22	0.29	4.51	1.47	0.72
Outlet	52.09	19.53	257.34	33.29	13.19	19.04	13.46	31.00	12.98	14.98	17.12	56.82	39.05
Std. Err.	2.49	0.24	6.30	0.80	0.29	0.62	0.71	0.12	0.60	0.37	1.12	1.93	1.21
Composite	67.64	20.07	197.50	25.92	18.72	10.27	26.93	14.65	17.79	19.04	18.85	50.36	40.18
Std. Err.	5.97	3.30	1.77	2.56	3.47	0.31	0.95	0.13	3.36	1.62	1.16	0.04	1.52

Appendix P: Mean Concentrations of TIN in Water Samples

$$TIN = NH_4^+ + NO_3$$

All values expressed in µmol L^{-1}.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	213.07	100.70	114.84	50.62	46.05	95.97	95.84	99.38	71.37	100.63	84.21	151.83	205.26
Outlet	176.23	61.06	118.95	69.80	42.68	73.33	91.05	84.68	46.04	28.48	31.34	117.74	127.45
Composite	212.22	141.68	255.77	78.45	43.41	87.76	70.86	73.62	53.44	39.76	43.72	141.71	142.56

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
Inlet	79.75	31.13	188.37	24.62	18.06	22.67	20.90	65.61	19.93	19.39	30.24	62.12	50.34
Outlet	56.04	23.23	264.08	48.67	16.92	26.80	19.16	32.13	15.62	19.48	26.07	61.97	42.54
Composite	68.83	21.43	199.70	35.25	22.07	12.81	28.40	16.25	19.54	22.50	30.72	56.16	42.35

Appendix Q: Retention of TSS and Nutrient Constituents in HEP and MAT

Percent Retention Approach

All values expressed as percentages.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
TSS	-150	50	50	50	0	-	50	33.33	33.33	-39.52	0	0	0
TP	49.61	-551.61	72.32	-295.52	25.51	14.24	-34.19	-100.46	21.66	-17.63	5.61	-74.47	-94.05
DRP	34.48	-1.82	6.76	25.00	23.53	51.00	20.93	66.62	58.65	-13.44	17.74	-101.52	-141.38
NH_4^+	32.39	-23.88	-157.50	-44.47	25.13	37.33	4.32	24.39	-5.35	9.16	48.61	-185.53	66.73
NO_3	16.83	40.89	0.84	-35.88	4.39	21.09	5.10	14.36	36.88	73.81	63.68	28.23	36.55
TIN	17.29	39.36	-3.58	-37.90	7.31	23.60	4.99	14.79	35.49	71.70	62.78	22.45	37.91

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
TSS	-140.24	16.63	0	34	33.33	-	33.30	0	33.33	-39.52	0	33.33	0
TP	-23.02	35.19	57.82	-217.16	12.00	-4.48	-51.71	-7.23	0.97	18.00	-115.30	-18.04	-7.00
DRP	4.65	-5.88	6.52	-35.90	21.74	-57.41	26.67	83.51	71.31	58.61	-66.07	-0.76	63.88
NH_4^+	-49.33	17.87	32.12	-131.77	33.70	-68.41	-15.91	83.71	0.66	-161.89	8.91	34.49	32.04
NO_3	32.44	26.65	-44.22	-85.09	-6.03	-5.42	15.78	47.14	24.85	15.21	16.14	-4.72	13.61
TIN	29.73	25.38	-40.20	-97.67	6.34	-18.21	8.32	51.02	21.63	-0.49	13.79	0.25	15.49

In – Out Approach

All values expressed in μmol L^{-1}, except for TSS which are expressed as mg L^{-1}.

Hydro East Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
TSS	-30	50	50	25	0	-	50	50	50	-66	0	0	0
TP	2.32	-0.88	1.18	-1.19	0.42	0.23	-1.13	-2.47	1.33	-0.33	0.07	-0.23	-0.57
DRP	0.30	-0.01	0.05	0.19	0.20	0.51	0.18	2.01	1.64	-0.29	0.13	-0.21	-0.26
NH_4^+	2.05	-0.57	-5.04	-5.31	1.63	5.52	0.58	1.03	-0.13	0.30	2.44	-7.61	6.16
NO_3	34.80	40.20	0.94	-13.88	1.73	17.13	4.21	13.67	25.46	71.85	50.43	41.70	71.65
TIN	36.84	39.63	-4.11	-19.19	3.37	22.65	4.79	14.70	25.33	72.15	52.86	34.09	77.81

Mattamy Rouge Pond

	08-Apr	20-Apr	05-May	12-May	31-May	01-Jun	07-Jun	08-Jul	27-Jul	19-Aug	16-Sep	05-Nov	12-Dec
TSS	-46.7	13.3	0	17	50	-	33.3	0	50	-66	0	25	0
TP	-0.84	0.20	2.14	-2.21	0.40	-0.17	-2.99	-0.57	0.07	0.94	-0.69	-0.11	-0.09
DRP	0.02	-0.04	0.03	-0.14	0.15	-0.31	0.24	3.48	1.03	0.93	-0.30	-0.01	0.53
NH_4^+	-1.30	0.81	3.19	-8.75	1.90	-3.15	-0.78	5.83	0.02	-2.78	0.88	2.71	1.65
NO_3	25.01	7.09	-78.91	-15.30	-0.75	-0.98	2.52	27.65	4.29	2.69	3.29	-2.56	6.15
TIN	23.71	7.90	-75.72	-24.05	1.15	-4.13	1.74	33.47	4.31	-0.10	4.17	0.15	7.80

Appendix R: Mean Concentrations of TP from Bottom Sediment and Sediment Collected from Sediment Traps

Bottom Sediment

Hydro East Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration (mg P kg^{-1})	884.36	780.44	1100.56	1026.93	974.70
Std. Err.	36.20	4.42	4.23	9.81	5.57
Concentration (mol L^{-1})	0.037	0.033	0.046	0.043	0.041
Std. Err.	0.0015	0.0002	0.0002	0.0004	0.0002

Mattamy Rouge Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration (mg P kg^{-1})	1154.89	669.44	817.34	659.32	794.48
Std. Err.	24.63	7.10	12.00	6.69	3.89
Concentration (mol L^{-1})	0.048	0.028	0.034	0.028	0.033
Std. Err.	0.0010	0.0003	0.0005	0.0003	0.0002

Sediment Collected from Sediment Traps

All values expressed in mg P kg^{-1} sediment.

Hydro East Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration	1343.66	1489.51	4112.62	3253.72
A	Std. Err.	59.97	7.36	81.15	242.71
B	Concentration	2301.44	2671.88	2562.03	2397.98
B	Std. Err.	17.21	83.57	64.86	53.69
C	Concentration	3935.36	5804.56	4118.39	3838.18
C	Std. Err.	101.56	104.79	40.72	92.28

Mattamy Rouge Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration	973.86	1305.91	3155.12	3017.51
A	Std. Err.	9.36	76.15	33.56	40.41
B	Concentration	1536.30	1663.60	3696.61	3604.87
B	Std. Err.	10.66	22.57	81.81	50.24
C	Concentration	1774.20	1810.58	3599.07	4590.32
C	Std. Err.	19.28	65.00	146.01	195.74

Appendix S: Percentage of IP and OP in Bottom Sediment

Mean Concentrations of IP and OP Fractions

All values expressed in mg P kg^{-1} sediment.

Concentrations of OP fraction were determined by difference between IP and TP (Appendix J).

Hydro East Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration of IP	462.23	480.48	561.42	595.14	541.18
Std. Err.	4.77	24.41	38.44	24.69	5.61
Concentration of OP	422.13	299.96	539.14	431.79	433.51

Mattamy Rouge Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration of IP	793.13	411.84	565.39	413.03	495.16
Std. Err.	5.89	1.68	8.14	5.33	7.29
Concentration of OP	361.76	257.60	251.95	246.29	299.32

Percent IP and OP

All values expressed as percentages.

Hydro East Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
% IP	52.27	61.56	51.01	57.95	55.52
% OP	47.73	38.44	48.99	42.05	44.48

Mattamy Rouge Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
% IP	68.68	61.52	69.17	62.64	62.32
% OP	31.32	38.48	30.83	37.36	37.68

Appendix T: Percentage of IP and OP in Sediment Collected from Sediment Traps

Mean Concentrations of IP and OP Fractions

All values expressed in mg P kg^{-1} sediment.

Concentrations of OP fraction were determined by difference between IP and TP (Appendix J).

Hydro East Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration of IP	643.55	796.70	1174.81	966.12
	Std. Err.	14.59	56.11	16.55	43.49
	Concentration of OP	700.11	692.81	2937.81	2287.60
B	Concentration	1085.94	1701.32	2453.98	336.45
	Std. Err.	15.99	67.33	63.12	25.25
	Concentration of OP	1215.50	970.56	108.05	2061.52
C	Concentration	2132.60	4046.58	3668.47	1281.94
	Std. Err.	165.81	76.59	49.94	54.15
	Concentration of OP	1802.76	1757.98	449.93	2556.24

Mattamy Rouge Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration of IP	582.84	734.41	877.24	891.13
	Std. Err.	27.77	39.56	49.66	6.17
	Concentration of OP	391.02	571.50	2277.88	2126.38
B	Concentration	575.70	805.03	799.08	1081.57
	Std. Err.	8.70	26.65	72.94	11.22
	Concentration of OP	960.60	858.57	2897.54	2523.30
C	Concentration	637.20	819.31	753.06	1079.99
	Std. Err.	11.78	33.39	44.33	33.67
	Concentration of OP	1137.00	991.27	2846.02	3510.33

Percent IP and OP

All values expressed as percentages.

Hydro East Pond

	27-Jul	19-Aug	16-Sep	05-Nov
% IP	50.95	65.67	67.61	27.23
% OP	49.05	34.33	32.39	72.77

Mattamy Rouge Pond

	27-Jul	19-Aug	16-Sep	05-Nov
% IP	41.91	49.35	23.25	27.23
% OP	58.09	50.65	76.75	72.77

Appendix U: Mean Concentrations and Percentage of BAP in Bottom Sediment and in Sediment Collected from Sediment Traps

Bottom Sediment

Hydro East Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration (mg P kg^{-1})	96.90	31.77	2.68	0.28	0.00
Std. Err.	0.62	0.28	0.52	0.16	0.00
Concentration (mol L^{-1})	4.07	1.33	0.11	0.01	0.00
Std. Err.	0.03	0.01	0.02	0.01	0.00
% BAP	10.96	4.07	0.24	0.03	0.00

Mattamy Rouge Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration (mg P kg^{-1})	127.23	32.05	0.00	0.00	0.00
Std. Err.	3.21	1.33	0.00	0.00	0.00
Concentration (mol L^{-1})	5.34	1.35	0.00	0.00	0.00
Std. Err.	0.13	0.06	0.00	0.00	0.00
% BAP	11.02	4.79	0.00	0.00	0.00

Sediment Collected from Sediment Traps

All concentrations expressed as mg P kg^{-1} sediment.

Hydro East Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration	0	53.09	0	0
	Std. Err.	0	3.05	0	0
B	Concentration	4.06	69.46	14.02	0.00
	Std. Err.	0.68	4.45	1.89	0.00
C	Concentration	20.22	0.00	0.00	0.00
	Std. Err.	0.73	0.00	0.00	0.00
Mean	% BAP	0.32	1.23	0.13	0.00

Mattamy Rouge Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration	17.61	7.01	85.17	88.87
	Std. Err.	9.93	2.08	7.55	2.32
B	Concentration	38.99	150.37	63.35	101.97
	Std. Err.	1.81	5.84	2.28	4.30
C	Concentration	84.45	80.68	54.89	121.81
	Std. Err.	2.23	9.63	3.61	4.21
Mean	% BAP	3.29	4.98	1.95	2.79

Appendix V: Mean Concentrations of TN in Bottom Sediment and in Sediment Collected from Sediment Traps

Bottom Sediment

Hydro East Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration (mg N kg^{-1})	344.00	352.50	215.00	107.50	167.25
Std. Err.	0.55	0.40	9.91	0.12	0.59
Concentration (mol L^{-1})	31.93	32.72	19.95	9.98	15.52
Std. Err.	0.051	0.038	0.920	0.011	0.055

Mattamy Rouge Pond

	08-Apr	31-May	14-Jul	16-Sep	05-Nov
Concentration (mg N kg^{-1})	86.00	78.00	144.00	140.00	266.00
Std. Err.	0.55	0.10	0.44	1.19	0.10
Concentration (mol L^{-1})	7.98	7.24	13.37	12.99	24.69
Std. Err.	0.051	0.010	0.041	0.110	0.009

Sediment Collected from Sediment Traps

All values expressed in mg N kg^{-1} sediment.

Hydro East Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration	203	103.75	1881	28
A	Std. Err.	2.74	0.10	4.19	0.65
B	Concentration	50.75	1807.25	130.25	48.5
B	Std. Err.	0.25	4.65	1.75	1.12
C	Concentration	67.75	183.25	1045.5	132.25
C	Std. Err.	0.27	2.66	1.71	3.05

Mattamy Rouge Pond

Trap Location		27-Jul	19-Aug	16-Sep	05-Nov
A	Concentration	270.5	565	604	57.75
A	Std. Err.	0.25	0.70	1.49	1.33
B	Concentration	399	1470	323	26.25
B	Std. Err.	0.92	2.45	0.28	0.61
C	Concentration	111.5	182.75	446.5	12.5
C	Std. Err.	0.14	1.29	0.76	0.29

Appendix W: Nutrient Loading and Retention Calculations in HEP and MAT

$Q = 2.78 \times 0.65 \times I \times SA$

Loading and Retention of TP

Hydro East Pond

	Inlet (mmol m-3)	Outlet (mmol m-3)	mm rain (previous 15 d)	I (mm/h)	Q (L/s)	Inflow (m3 d-1)	Loading (mmol d-1)	Export (mmol d-1)	Pond Volume (m3)	Retention Time (d)	Net Retention (mmol)	Net Retention (d-1)	Net Flux to Sediment (mmol P d-1)	Burial (mmol P d-1)
08-Apr	4.68	2.36	84.55	0.23	27.03	2335	10919	5502	8845	3.79	20521	5417	-	-
20-Apr	0.16	1.04	17.75	0.05	5.67	490	79	512	8121	16.57	-7176	-433	-	-
05-May	1.63	0.45	18.00	0.05	5.75	497	812	225	8316	16.73	9829	588	-	-
12-May	0.40	1.60	22.50	0.06	7.19	621	251	993	8152	13.12	-9733	-742	-	-
31-May	1.64	1.22	12.25	0.03	3.92	338	554	413	6917	20.45	2889	141	-	-
01-Jun	1.62	1.39	12.25	0.03	3.92	338	547	469	6917	20.45	1594	78	-	-
07-Jun	3.31	4.44	23.75	0.07	7.59	656	2170	2913	7383	11.26	-8362	-743	-	-
08-Jul	2.46	4.93	6.50	0.02	2.08	180	442	886	7552	42.07	-18675	-444	-	-
27-Jul	6.16	4.82	32.75	0.09	10.47	904	5569	4363	7720	8.54	10295	1206	306.85	899
19-Aug	1.84	2.17	64.25	0.18	20.54	1774	3272	3850	7230	4.07	-2354	-578	601.39	-1179
16-Sep	1.33	1.26	24.25	0.07	7.75	670	893	843	6954	10.38	520	50	638.42	-588
05-Nov	0.31	0.53	34.25	0.10	10.95	946	289	505	7181	7.59	-1635	-215	554.03	-769
12-Dec	0.60	1.17	22.00	0.06	7.03	608	366	709	7181	11.82	-4064	-344	-	-

Total retention (season) (mmol)	-6351.60	Total retention (season) (kg)	-0.20
Total retention (season) per ha of catchment (mmol ha-1)	-99.74	Total retention (season) per ha of catchment (g ha-1)	-3.09
Daily avg retention (mmol ha-1 d-1)	7471.67	Daily avg retention (g ha-1 d-1)	231.62

Mattamy Rouge Pond

	Inlet (mmol m-3)	Outlet (mmol m-3)	mm rain (previous 15 d)	I (mm/h)	Q (l/s)	Inflow (m3 d-1)	Loading (mmol d-1)	Export (mmol d-1)	Pond Volume (m3)	Retention Time (d)	Net Retention (mmol)	Net Retention (d-1)	Net Flux to Sediment (mmol P d-1)	Burial (mmol P d-1)
08-Apr	3.66	4.50	84.55	0.23	20.54	1775	6493	7987	11622.19	6.55	-9789	-1495	-	-
20-Apr	0.56	0.36	17.75	0.05	4.31	373	208	135	12728.43	34.16	2499	73	-	-
05-May	3.70	1.56	18.00	0.05	4.37	378	1399	590	12624.07	33.41	27024	809	-	-
12-May	1.02	3.23	22.50	0.06	5.47	472	481	1526	13096.55	27.73	-28983	-1045	-	-
31-May	3.36	2.96	12.25	0.03	2.98	257	864	761	12722.74	49.48	5131	104	-	-
01-Jun	3.75	3.92	12.25	0.03	2.98	257	964	1007	12722.74	49.48	-2138	-43	-	-
07-Jun	5.79	8.78	23.75	0.07	5.77	499	2886	4378	13690.46	27.46	-40977	-1492	-	-
08-Jul	7.83	8.39	6.50	0.02	1.58	136	1068	1145	12944.75	94.88	-7324	-77	-	-
27-Jul	6.87	6.80	32.75	0.09	7.96	687	4721	4675	13350.81	19.42	886	46	505.53	-460
19-Aug	5.23	4.29	64.25	0.18	15.61	1349	7060	5789	12075.69	8.95	11377	1271	1085.53	185
16-Sep	0.60	1.28	24.25	0.07	5.89	509	303	652	13214.19	25.96	-9069	-349	980.16	-1329
05-Nov	0.63	0.74	34.25	0.10	8.32	719	454	535	12614.58	17.55	-1436	-82	745.33	-827
12-Dec	1.30	1.39	22.00	0.06	5.34	462	601	643	12614.58	27.32	-1149	-42	-	-

Total retention (season) (mmol)	-53948.00	Total retention (season) (kg)	-1.67
Total retention (season) per ha of catchment (mmol ha-1)	-1114.63	Total retention (season) per ha of catchment (g ha-1)	-34.55
Daily avg retention (mmol ha-1 d-1)	-3061.72	Daily avg retention (g ha-1 d-1)	-94.91

Loading and Retention of TN

Hydro East Pond

	Inlet (mmol m-3)	Outlet (mmol m-3)	mm rain (previous 15 d)	I (mm/h)	Q (l/s)	Inflow (m3 d-1)	Loading (mmol d-1)	Export (mmol d-1)	Pond Volume (m3)	Retention Time (d)	Net Retention (mmol)	Net Retention (d-1)	Net Flux to Sediment (mmol P d-1)	Burial (mmol P d-1)
08-Apr	213	176	84.55	0.23	27.03	2335	497526	411496	8845	3.79	325875	86030	-	-
20-Apr	101	61	17.75	0.05	5.67	490	49361	29932	8121	16.57	321878	19428	-	-
05-May	115	119	18.00	0.05	5.75	497	57089	59131	8316	16.73	-34154	-2042	-	-
12-May	51	70	22.50	0.06	7.19	621	31452	43374	8152	13.12	-156404	-11922	-	-
31-May	46	43	12.25	0.03	3.92	338	15578	14439	6917	20.45	23296	1139	-	-
01-Jun	96	73	12.25	0.03	3.92	338	32469	24807	6917	20.45	156640	7661	-	-
07-Jun	96	91	23.75	0.07	7.59	656	62861	59721	7383	11.26	35341	3140	-	-
08-Jul	99	85	6.50	0.02	2.08	180	17840	15201	7552	42.07	111010	2639	-	-
27-Jul	71	46	32.75	0.09	10.47	904	64553	41642	7720	8.54	195576	22912	6284.32	16628
19-Aug	101	28	64.25	0.18	20.54	1774	178560	50531	7230	4.07	521686	128029	61017.73	67011
16-Sep	84	31	24.25	0.07	7.75	670	56393	20990	6954	10.38	367635	35403	65804.40	-30401
05-Nov	152	118	34.25	0.10	10.95	946	143611	111368	7181	7.59	244776	32242	4730.34	27512
12-Dec	205	127	22.00	0.06	7.03	608	124708	77434	7181	11.82	558735	47274	-	-

Total retention (season) (mmol)	2671889.10	Total retention (season) (kg)	37.41
Total retention (season) per ha of catchment (mmol ha-1)	41958.06	Total retention (season) per ha of catchment (g ha-1)	587.41
Daily avg retention (mmol ha-1 d-1)	697944.13	Daily avg retention (g ha-1 d-1)	9771.22

Mattamy Rouge Pond

	Inlet (mmol m-3)	Outlet (mmol m-3)	mm rain (previous 15 d)	I (mm/h)	Q (l/s)	Inflow (m3 d-1)	Loading (mmol d-1)	Export (mmol d-1)	Pond Volume (m3)	Retention Time (d)	Net Retention (mmol)	Net Retention (d-1)	Net Flux to Sediment (mmol P d-1)	Burial (mmol P d-1)
08-Apr	213	176	84.55	0.23	27.03	2335	497526	411496	8845	3.79	325875	86030	-	-
20-Apr	101	61	17.75	0.05	5.67	490	49361	29932	8121	16.57	321878	19428	-	-
05-May	115	119	18.00	0.05	5.75	497	57089	59131	8316	16.73	-34154	-2042	-	-
12-May	51	70	22.50	0.06	7.19	621	31452	43374	8152	13.12	-156404	-11922	-	-
31-May	46	43	12.25	0.03	3.92	338	15578	14439	6917	20.45	23296	1139	-	-
01-Jun	96	73	12.25	0.03	3.92	338	32469	24807	6917	20.45	156640	7661	-	-
07-Jun	96	91	23.75	0.07	7.59	656	62861	59721	7383	11.26	35341	3140	-	-
08-Jul	99	85	6.50	0.02	2.08	180	17840	15201	7552	42.07	111010	2639	-	-
27-Jul	71	46	32.75	0.09	10.47	904	64553	41642	7720	8.54	195576	22912	6284.32	16628
19-Aug	101	28	64.25	0.18	20.54	1774	178560	50531	7230	4.07	521686	128029	61017.73	67011
16-Sep	84	31	24.25	0.07	7.75	670	56393	20990	6954	10.38	367635	35403	65804.40	-30401
05-Nov	152	118	34.25	0.10	10.95	946	143611	111368	7181	7.59	244776	32242	4730.34	27512
12-Dec	205	127	22.00	0.06	7.03	608	124708	77434	7181	11.82	558735	47274	-	-

Total retention (season) (mmol)	-263787.11	Total retention (season) (kg)	-3.69
Total retention (season) per ha of catchment (mmol ha-1)	-5450.15	Total retention (season) per ha of catchment (g ha-1)	-76.30
Daily avg retention (mmol ha-1 d-1)	24229.50	Daily avg retention (g ha-1 d-1)	993.41

Appendix X: Sediment Deposition Rates

Hydro East Pond

Trap Location	July 14 - July 27	July 27 - Aug. 19	Aug. 19 - Sept. 16	Sept. 16 - Nov. 5
A (cm d^{-1})	0.013	0.015	0.011	0.016
B (cm d^{-1})	0.01	0.017	0.019	0.017
C (cm d^{-1})	0.009	0.013	0.015	0.012
Mean (cm d^{-1})	0.011	0.015	0.015	0.015
Std. Err.	0.0012	0.0012	0.0024	0.0017
Mean (cm yr^{-1})	3.94	5.56	5.46	5.43
Std. Err.	0.44	0.45	0.87	0.64

Mattamy Rouge Pond

Trap Location	July 14 - July 27	July 27 - Aug. 19	Aug. 19 - Sept. 16	Sept. 16 - Nov. 5
A (cm d^{-1})	0.038	0.023	0.021	0.014
B (cm d^{-1})	0.02	0.014	0.019	0.013
C (cm d^{-1})	0.009	0.013	0.017	0.012
Mean (cm d^{-1})	0.023	0.017	0.019	0.013
Std. Err.	0.0085	0.0031	0.0014	0.0006
Mean (cm yr^{-1})	8.24	6.11	6.90	4.81
Std. Err.	3.08	1.12	0.50	0.20

Appendix Y: Weather Data (Daily Total Precipitation and Average Temperature)

Date	Total Precip. (mm)	Avg. Temp. (°C)	Date	Total Precip. (mm)	Avg. Temp. (°C)
25-Mar	3	-0.86	06-May	0	15.32
26-Mar	7.75	0.463	07-May	0	12.7
27-Mar	0	5.73	08-May	4.5	8.52
28-Mar	17	5.963	09-May	0	9.07
29-Mar	0	2.47	10-May	0	11.06
30-Mar	0	4.638	11-May	0	13.28
31-Mar	25.75	10.67	12-May	0	15.24
01-Apr	0	9.15	13-May	8	17.19
02-Apr	0	2.432	14-May	8	10.27
03-Apr	12.5	-4.347	15-May	1.75	4.202
04-Apr	0	-4.279	16-May	10.25	8.68
05-Apr	2	-3.094	17-May	0.25	11.07
06-Apr	4	0.7	18-May	0	11.59
07-Apr	2.75	4.668	19-May	0	15.43
08-Apr	0	-0.952	20-May	0	17.27
09-Apr	0	-3.38	21-May	0	17.22
10-Apr	0	-2.713	22-May	0	17.81
11-Apr	9	5.872	23-May	0	19.68
12-Apr	0	2.985	24-May	0	22.19
13-Apr	0	2.532	25-May	0	22.99
14-Apr	0	5.019	26-May	1.75	17.92
15-Apr	0	7.932	27-May	0	22.26
16-Apr	0	10.52	28-May	0	22.86
17-Apr	0	14.92	29-May	0	25.08
18-Apr	0	17.86	30-May	0	23.31
19-Apr	0	10.99	31-May	0	20.96
20-Apr	0	9.49	01-Jun	0	15.95
21-Apr	1.5	9.98	02-Jun	0	20.65
22-Apr	0.5	12.7	03-Jun	0	20.73
23-Apr	0	7.628	04-Jun	0	20.64
24-Apr	0	6.412	05-Jun	20.5	18.87
25-Apr	4	5.917	06-Jun	1.5	18.94
26-Apr	12	4.057	07-Jun	1.25	15.99
27-Apr	0	6.044	08-Jun	0.25	11.41
05-May	0	12.71	09-Jun	0	13.8

Date	Total Precip. (mm)	Avg. Temp. (°C)	Date	Total Precip. (mm)	Avg. Temp. (°C)
10-Jun	0	16.31	18-Jul	0.75	25.41
11-Jun	28	20.77	19-Jul	0	20.86
12-Jun	7	16.86	20-Jul	0	21.02
13-Jun	0	14.63	21-Jul	0	25.29
14-Jun	0	15.89	22-Jul	0	28.56
15-Jun	0	18.27	23-Jul	0	27.35
16-Jun	0.5	20.35	24-Jul	0	22.23
17-Jun	0	23.81	25-Jul	30.25	24.75
18-Jun	0	24.03	26-Jul	0	23.6
19-Jun	0	25.08	27-Jul	12.25	24.12
20-Jun	1.25	25.82	28-Jul	0.5	24.69
21-Jun	2.75	20.85	29-Jul	0.25	22.98
22-Jun	0	19.6	30-Jul	0	21.77
23-Jun	0	19.16	31-Jul	1	21.5
24-Jun	0	20.71	01-Aug	0	23.21
25-Jun	0	21.78	02-Aug	0	23.56
26-Jun	1.25	23.94	03-Aug	0	23.73
27-Jun	0	25.86	04-Aug	0	25.19
28-Jun	0	19.53	05-Aug	5.25	26.27
29-Jun	0	20.3	06-Aug	0	23.7
30-Jun	0	21.12	07-Aug	0	22.39
01-Jul	5.25	17.63	08-Aug	0	22.86
02-Jul	0	19.38	09-Aug	0	23.36
03-Jul	0	22.15	10-Aug	0	27.37
04-Jul	0	22.03	11-Aug	0	27.15
05-Jul	0	25.01	12-Aug	0	28.41
06-Jul	0	25.5	13-Aug	39.75	23.76
07-Jul	0	26.53	14-Aug	0	23.52
08-Jul	0.75	22.61	15-Aug	0	21.63
09-Jul	0.5	22.01	16-Aug	19.25	22.11
10-Jul	0	22.09	17-Aug	0	20.56
11-Jul	0	21.09	18-Aug	0	22.87
12-Jul	0	22.78	19-Aug	0	23.16
13-Jul	0	26.47	20-Aug	0.25	24.73
14-Jul	1.75	23.74	21-Aug	4.25	22.98
15-Jul	0	22.33	22-Aug	0	18.92
16-Jul	0	17.95	23-Aug	0	21.67
17-Jul	0	20.18	24-Aug	0	23.38

Date	Total Precip. (mm)	Avg. Temp. (°C)	Date	Total Precip. (mm)	Avg. Temp. (°C)
25-Aug	19.75	24.4	02-Oct	5.75	16.4
26-Aug	0	24.01	03-Oct	0	15.91
27-Aug	0	21.99	04-Oct	0.5	16.89
28-Aug	0	24.77	05-Oct	0	17.06
29-Aug	0	22.08	06-Oct	0	18.31
30-Aug	0	23.12	07-Oct	0	17.78
31-Aug	3.75	23	08-Oct	5.25	15.01
01-Sep	0	18.18	09-Oct	0	9.48
02-Sep	0	17.92	10-Oct	0	7.501
03-Sep	0	18.2	13-Oct	0	12.37
04-Sep	0	18.95	14-Oct	0	10.1
05-Sep	0	21.02	15-Oct	0	14.5
06-Sep	0	23.6	16-Oct	4	18.63
07-Sep	11.25	25.43	17-Oct	2.25	15.96
08-Sep	9	24.94	18-Oct	3	19.9
09-Sep	0	23.54	19-Oct	0	15.51
10-Sep	4	22.41	20-Oct	6.5	12.75
11-Sep	0	18.57	21-Oct	5	8.7
12-Sep	0	18.24	22-Oct	0.25	5.83
13-Sep	0	21.46	23-Oct	0	9.07
14-Sep	0	18.94	24-Oct	0	7.043
15-Sep	0	14.83	25-Oct	0	5.017
16-Sep	0	16.94	26-Oct	0	3.597
17-Sep	9	19.93	27-Oct	9.5	2.849
18-Sep	0	21.06	28-Oct	0	5.328
19-Sep	0	21.23	29-Oct	0	14.26
20-Sep	0	22.64	30-Oct	0.5	7.956
21-Sep	0.5	21.14	31-Oct	0	4.578
22-Sep	0.5	21.57	01-Nov	0	10.58
23-Sep	1.75	17.12	02-Nov	1.75	15
24-Sep	0	13.68	03-Nov	17.25	10.79
25-Sep	0	13	04-Nov	0	7.458
26-Sep	8.5	15.33	05-Nov	0	11.45
27-Sep	0.25	16.54	06-Nov	0	9.22
28-Sep	0	17.81	07-Nov	0	9.21
29-Sep	2	15.36	08-Nov	1	10.21
30-Sep	0.25	16.17	09-Nov	0	6.854
01-Oct	2.5	14.51	10-Nov	0	9.04

Date	Total Precip. (mm)	Avg. Temp. (°C)	Date	Total Precip. (mm)	Avg. Temp. (°C)
11-Nov	2.25	6.355	19-Dec	0	-8.18
12-Nov	0	4.616	20-Dec	1	-2.717
13-Nov	0	8.14	21-Dec	0	-1.25
14-Nov	0	9.46			
15-Nov	0	7.58			
16-Nov	0	8.41			
17-Nov	0	7.967			
18-Nov	0	9.68			
19-Nov	3.25	7.963			
20-Nov	68.75	0.123			
21-Nov	6.5	-1.816			
22-Nov	0	-0.776			
23-Nov	0	-1.469			
24-Nov	3.75	2.33			
25-Nov	0.5	4.656			
26-Nov	0	4.702			
27-Nov	0	4.822			
28-Nov	0	5.243			
29-Nov	4.5	9.66			
30-Nov	4.75	8.81			
01-Dec	0.75	6.031			
02-Dec	0.5	4.224			
03-Dec	0	2.606			
04-Dec	0	0.969			
05-Dec	6.5	3.449			
06-Dec	4.75	3.456			
07-Dec	0.25	2.728			
08-Dec	0	-0.224			
09-Dec	0	-4.119			
10-Dec	0	-5.149			
11-Dec	0	-3.109			
12-Dec	3.25	0.585			
13-Dec	0	-1.206			
14-Dec	0.25	-6.336			
15-Dec	0.75	-9.42			
16-Dec	0	-8.04			
17-Dec	0	-2.377			
18-Dec	3.5	-5.347			

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