

QUANTIFYING NUTRIENT CONCENTRATION, ALGAL BIOMASS, AND ALGAL
COMPOSITION AMONG URBAN STORMWATER AND BEAVER PONDS IN
MECKLENBURG COUNTY

by

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ABSTRACT

EMMA LACY . Quantifying Nutrient Concentration, Algal Biomass, and Algae Composition Between Urban Stormwater and Beaver Ponds in Mecklenburg County
(Under the direction of DR. SANDRA CLINTON)

Increasing impervious cover in urban areas due to population increases has caused increased runoff of excess nutrients and sediment into urban streams and ponds. These excess nutrient inputs can potentially lead to algal blooms, which can be detrimental to freshwater organisms and produce neurotoxins which can harm humans. While there are many studies of algal blooms in freshwater ecosystems, urban ponds, and especially urban beaver ponds, have been understudied. Our objective was to compare algal biomass, composition, photosynthetic active radiation (PAR), and nutrient concentrations (total and dissolved phosphorus) in three stormwater and three beaver ponds in the Charlotte-Mecklenburg, NC region. We hypothesized that algal biomass would be higher in stormwater ponds due to more sunlight, less vegetation to slow runoff, and longer retention times (stagnant waters) compared to beaver ponds. Four equidistant surface water samples were collected from around each pond, composited into 1 sample per pond visit and filtered for chlorophyll a and total suspended solids. A subsample was collected and preserved with Lugol's Iodine for algal composition (desmids, diatoms, green algae, and blue-green algae). One water sample was collected at the pond outlet for total (TP) and dissolved (phosphate) phosphorus analysis. Initial results indicate that average algal biomass, total phosphorus, and PAR was higher in stormwater ponds compared to beaver ponds. There were more desmids and blue-green algae in stormwater ponds compared to very low to no organisms at beaver ponds. Desmids and blue-green algae occur in freshwater that has very high nutrient levels such as those found in the stormwater ponds and can be components of harmful

algal blooms. My results suggest that, as natural retention ponds, urban beaver ponds could potentially be an alternative to stormwater ponds for improved water quality, while also providing additional ecosystem services in urban ecosystems.

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DEDICATION

I dedicate my dissertation work to my family, professors, and friends. I want to especially thank them for believing in me and showing me that I can achieve anything I set my mind to.

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LIST OF ABBREVIATIONS

BC	Briar Creek stormwater pond
BD	Beaverdam Creek pond
BSW	Beaverdam stormwater pond
CBP	Brocker stormwater pond
DO	dissolved oxygen
GI	green infrastructure
HABs	harmful algal blooms
MC5	MC5 beaver pond
P	phosphorus
PAR	photosynthetically active radiation
PAW	Paw beaver pond
SCM	stormwater control measures
TDP	total dissolved phosphorus
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids

4. INTRODUCTION

Charlotte, North Carolina (NC), one of the fastest-growing cities in Mecklenburg County and the U.S., is estimated to have over half a million people moving here over the next 30 years. With more people, there are more buildings and growth in the area, leading to an increase in impervious surfaces such as asphalt and concrete (Charlotte Future 2040 Comprehensive Plan; Davies and Bavor, 2000). The amount of impervious surface in a watershed can have a significant effect on water quality from contaminants that are washed off the surface by stormwater runoff and carried directly and indirectly into waterways (Arnold and Gibbons, 1996; Brabec et al., 2002). Wet detention ponds are one mitigation approach used for nonpoint source control in urbanized areas. A wet detention pond is a permanent pool of water that captures water runoff and removal of pollutants, usually by sedimentation processes, to protect the receiving waterways (Harrell and Ranjithan, 2003; Birch et al., 2006; Guo and Adams, 1999). These ponds are designed predominately for reducing suspended sediments and in North Carolina the only required criteria for pollutant removal is an 85% reduction in suspended solids (North Carolina Departments of Environment, Health, and Natural Resources, 1995). Within these stormwater ponds however, higher nutrient levels can lead to increased algal growth (Davis, 2022) and the presence of algae in ponds, such as blue-green algae, are indications of poor water quality. The decomposition of algal blooms deplete oxygen levels, which can be detrimental to the organisms living there (Fried et al., 2003).

As urban areas have proven to exacerbate various negative impacts, ecological restoration and landscape architecture have focused on restoring ecological processes in the urban environment to help increase habitat complexity and biodiversity. The reintroduction of the North American beaver, *Castor canadensis*, could be a way to re-establish these environments (Bailey et al., 2019). North American beavers are widely regarded as ecosystem engineers and

the dams they build are known to alter the hydrology of rivers with the creation of ponds and wetlands. Beavers provide many ecological benefits including the creation of natural wetlands that support diverse aquatic wildlife and abundant vegetation. Wetlands naturally help improve water quality and carbon sequestration (Mitsch et al., 2013) and beaver wetlands perform similar functions. Overall, beaver research has demonstrated that beavers enhance ecosystem resilience (Ronnquist and Westbrook, 2021).

Beavers populations are increasing across the United States and there is little research on their role in urban ecosystems. While the nutrient and suspended solid retention of stormwater ponds is well studied, there have not been direct comparisons of these wet detention ponds and beaver ponds in urban areas. Furthermore, while there are many studies of algal blooms in freshwater ecosystems, urban ponds, and especially urban beaver ponds, have been also understudied. I will address this research gap by quantifying nutrient concentrations, algal biomass, and algal composition in urban stormwater and beaver ponds in the Charlotte-Mecklenburg (NC) region.

2. LITERATURE REVIEW

2.1 Urban Stormwater Ponds

The impacts of urban stormwater runoff depends on the type, size, and hydrology of the receiving water body (U.S. Environmental Protection Agency, 1982). Green infrastructure (GI) is a commonly used tool to mitigate runoff. While there are several types of GI, stormwater control measures (SCMs) are a frequent choice in urban areas. The main purpose of a SCM is to manage and treat surface water runoff and prevent flooding, erosion, water pollution, and preserve aquatic life. The design of stormwater ponds is based on results that have been developed with years of data collected by engineers and water resources professionals. In NC these guidelines are summarized in the stormwater design manual. While SCMs are known to be effective at retaining sediment and some nutrients (NC DEQ, 2020; Yazdi et al., 2021), there is less known about the overall ecological function of these systems. A major concern with this management practice is the lack of specific rules in ecological risk assessment (ERA). There are concerns about the public health implications and ecological impacts of these stormwater ponds and a need for standardized methodologies for monitoring, assessing ecological quality and management (Behera and Teegavarapu, 2015). Stormwater ponds in housing developments are often marketed to residents as aesthetic or recreational features, however, these ponds lack water quality monitoring and pollution mitigation efforts (Grogan et al., 2023). While SCMs provide ecosystem benefits to people (Moore and Hunt, 2012), having people around these polluted water bodies may be potentially dangerous, such as the deaths of three dogs in Wilmington, NC, after coming into contact with stormwater pond water containing potent cyanobacteria toxins (WWAY News, 2019).

Stormwater ponds are designed to retain phosphorus (P) by burial in pond sediment. Over time, these ponds may begin to experience internal (P) loading to pond surface waters as they begin to age and accumulate additional phosphorus (Taguchi et al., 2020). A component that is understudied about SCMs, is how well they reduce nutrients over a longer time span (Janke et al., 2022). Younger stormwater ponds have higher retention rates of particulate fractions of phosphorus than older ones. A study done by Sønderup et al. (2016) found that stormwater ponds lose almost all of their nutrient reduction capabilities after 5-10 years. The nutrient capture function can decrease over time due to high amounts of sediment from urban runoff causing a reduction in water storage volume, which decreases retention time (Shukla et al., 2017). This reduced nutrient retention capacity can be reversed with regularly scheduled maintenance, including dredging.

The ability for a stormwater pond to have effective retention is also dependent on the size and design. The greater the distance between the pond inlet and outlet, the higher the retention of suspended solids, organic matter, nitrate, particulate P, and total dissolved phosphorus (TDP). It was found that the optimal distance between the inlet and outlet should be at least 50 m. The ratio between pond volume and impermeable area within a watershed correlated positively with the retention of suspended solids, particulate P, and TDP. Thus, the larger the pond, the greater the retention (Sønderup et al., 2016).

2.2 Urban Beaver ponds

Beavers have returned to highly populated areas like New York City where the first beaver in over 200 years was seen in 2007 (O'Connor, 2007). The increasing expansion of beaver populations has led to scientists looking at beavers as a natural and cost-effective tool for ecosystem restoration (Törnblom et al., 2011; Grudzinski et al., 2022).

Beavers are ecosystem engineers that alter riparian landscapes and expand wetland habitats (Wright et al., 2002; Remillard et al., 1987). When beavers build dams, they create natural stormwater infrastructure (Johnston and Naiman, 1990). When beaver dams raise water levels and spread water on the surface, it helps support the growth of wetland plant communities. Beavers help create wetlands, which help capture sediment rich in organics that can increase plant richness in riparian zones by 25% (Polvi and Wohl, 2012; Wright et al., 2002). The change in water availability creates conditions for the growth of wetland vegetation (Wright et al., 2002). Beaver ponds retain water, which increases both sediment deposition and the lateral connectivity between surface and subsurface water sources (Johnston and Naiman, 1990). Beaver ponds impact surface water hydrology by decreasing the size of storm event peaks (Poor, 2018). An analysis of storm events at four sites proved that after the construction of beaver dam complexes, there was an overall trend of reduced peak flows, reduced total stormflow, and increased lag times (Puttock et al., 2021). The decrease of the size of storm event peaks can reduce the concentrations of suspended solids, TP, and TN (Maret et al., 1987). When beavers build their dam structures they alter the stream geomorphology, which slows and widens streams by creating step-pool sequences that reduce erosion and help with sediment collection (Pollock et al., 2014).

The economic and ecological significance of beaver habitation is usually not considered. Rather, they are considered a nuisance species by land managers and property owners. Beavers have been threatened in the past, such as during the American fur trade, which killed off millions of beavers (Backhouse, 2015). The future of how we perceive beavers is changing as ecologists and land managers have started to recognize the many ecological benefits and services they provide (Bailey et al., 2019). Thompson et al. (2021) conducted an analysis quantifying the

ecosystem services value produced by beaver activity and they found that the monetary value of these services ranges from 1.6 to 133 million dollars annually across the Northern Hemisphere. As the benefits of beaver ponds have become more recognized to landscape designers, ecologists, and land managers, new options are being explored to help increase ecosystem services and ecological benefits in urban areas (Bailey et al., 2019) and designers have started to shift their mindset to accept beaver colonization into restoration project sites (Bailey et al., 2019).

2.3 Phosphorus

Phosphorus occurs in multiple forms including inorganic and organic species in both dissolved and particulate forms. In urban systems, stormwater runoff can have elevated phosphorus concentrations depending on varying geology, land use, and hydrological conditions (Jarvie et al., 2010). Since phosphorus in runoff has two forms including dissolved and particulate, they should both be considered separately since the bioavailability of these two forms differs (Yazdi et al., 2021). Dissolved phosphorus is the main source of directly available phosphorus for algae, but the particulate form can also contain available phosphorus for algae (Boström et al., 1988). Phosphorus released from suspended particulate matter during or after sedimentation could provide a major phosphorus source for algal blooms in depleted dissolved phosphorus conditions. The phosphorus remobilization from suspended particulate matter could be from algae and bacteria (Jin et al., 2023). Phosphorus availability from sediments depends on pH and redox potential. Conditions that favor phosphorus mobilization are high pH, periods of anaerobic conditions in hypo-limnetic conditions. Particulate phosphorus is sensitive to these conditions and generally will be higher in eutrophic ponds (Boström et al., 1988).

Phosphorus is an effective water quality indicator due to its well-established correlation to algal biomass. High phosphorus levels are associated with eutrophication, an increase in algal biomass, and a decline in aquatic species (Yang and Toor, 2016; Correll, 1998; Dodds and Smith, 2016). The U.S Environmental Protection Agency sampled 1,038 lakes and twenty-one percent of the nation's lakes were found to be high in nutrients, especially phosphorus, stimulating aquatic plant growth usually resulting in the depletion of DO (EPA, 2017). Currently rivers have twice the natural concentration of dissolved phosphorus which has led to eutrophication throughout all aquatic systems (Filippelli, 2008). An estimate of total phosphorus inputs into the world's largest lakes was 7% higher during 2005-2010 (Fink et al., 2016).

Phosphorus inputs to urban freshwater ecosystems are impacted by sources and hydrology. Phosphorus is usually associated with fine particles because it readily absorbs into soil particles and organic matter (Ma et al., 2010). In a study by Vaze and Chiew, they determined that phosphorus loads are strongly associated with sediment size and 40-50% of TP from stormwater runoff was associated with sediment sizes between 11- 150 μm (Vaze and Chiew, 2004). Lawn fertilizers can contribute to phosphorus inputs (Yang and Toor, 2016). Having a pet can cause excess nutrients due to their pet waste. A study that was conducted in Saint Paul, Minnesota, found that pet waste contributed to more than 70% of TP inputs in urban waters (Hobbie et al., 2017). Certain hydrologic characteristics can also affect nutrient levels such as frequency and intensity of storms and seasons with high flow usually leading to higher levels of nutrients , such as TP (Li et al., 2015). In a study performed on a stormwater detention pond on the UNC Wilmington campus, researchers found that the majority (>90%) of TP in this pond was associated with sediment and only 1–7% was present in the water column (Cahoon et al., 2015).

2.3.1 Phosphorus in Stormwater Ponds

In that study, typical event mean concentrations (EMC) of TP in urban stormwater runoff from the National Stormwater Quality Database (NSQD) were 0.37 mg/L. A similar EMC of TP taken from the nationwide urban runoff program was (0.32-0.34 mg/L) (U.S. Environmental Protection Agency, 1982; Smullen and Cave, 2002).

Seasonally in Ohio, TP concentrations were found to be significantly higher in spring (0.22 mg/L) and fall (0.23 mg/L) than summer (0.15 mg/L) (Smith et al., 2020). Other seasonal factors such as the rainy season tend to generate more runoff and therefore an elevated phosphorus load. This would make it important to look at rainfall events over the course of the year (Fan et al., 2012; Toor et al., 2017).

A study by Frost et al. (2019) showed that dissolved organic phosphorus (ortho-phosphorus) had high concentrations in urban stormwater pond water and sediments and that this phosphorus form was mobile within sediments.

Stormwater ponds are engineered to be a sink for urban pollutants, but most have a low net nutrient retention (Arias et al., 2013; Rosemond et al., 2015). This could happen because after the breakdown of organic matter in sediments, dissolved P could gather into sediment porewaters and move back into surface waters of stormwater ponds. In addition, dissolved phosphorus may be in inorganic or organic forms (Song et al., 2015). Studies have shown that in stormwater ponds with an impermeable liner, orthophosphate levels in the outflow increased by almost 1.5 times over inflow runoff (Kohlsmith et al., 2021).

2.3.2 Phosphorus in Beaver Ponds

In a study performed in southwestern Wyoming, researchers quantified that during periods of high flow, concentrations of total phosphorus were reduced in water flowing through

beaver ponds. During low flow events, beaver ponds had lower nutrient removal rates. Beavers help reduce these nutrients by trapping particulates (Maret et al., 1987).

A study was done on multiple beaver dams on Taylor creek that flows into Lake Tahoe. All of these dams are destroyed every year by the United States Department of Agriculture Forest Service to allow salmon to spawn. What they wanted to know was whether these beaver ponds helped reduce total phosphorus inputs into the lake. The results showed that before the dam removal the mean total phosphorus levels were 51.0 $\mu\text{g/l}$ and 64.5 $\mu\text{g/l}$ and the impacted sites increased from 70.4 $\mu\text{g/l}$ to 170.5 $\mu\text{g/l}$. These results show a drastic change in total phosphorus levels, which demonstrates the ability of beaver ponds to improve water quality by reducing phosphorus load (Muskopf, 2007).

There are few (to no) studies of dissolved phosphorus in beaver ponds. In a thesis from the Piedmont region (Chapel Hill, NC), beaver pond outlets had lower overall concentrations of phosphate compared to stormwater ponds. Stormwater ponds had an average level of $p=0.037$ versus a $p=0.236$ in beaver ponds, showing that Beaver ponds had a higher statistical significance (Willard, 2023).

2.4 Algae

Algae are a group of organisms that are aquatic, photosynthetic (contain chlorophyll a) and contain no vascular system. Algae do not represent a formal taxonomic group, but are a collection of organisms with representatives in different kingdoms (Wehr et al., 2015).

Algae are found in almost all surface water bodies and these lakes and rivers vary widely in pH, nutrients, trace elements, etc. There is not a specific type of algae that live in freshwater, but they mostly contain greater abundance of Cyanobacteria (which technically are photosynthetic bacteria), Chlorophyta (green algae), and Charophyta (green algae) than other

groups (John et al., 2011; Leliart et al., 2012; Whitton and Potts, 2012). The abundance and diversity of algae varies across freshwater ecosystems and small ponds have very distinct algal species due to the strong impact of local land use on these habitats (Rosowski, 2003).

Light is an important factor for activity and growth of photosynthetic organisms. Algal biomass, production and nutrient removal are influenced by wavelength and light intensity (Blair et al. 2014). Ho et al., (2012) found that biomass in a freshwater system increased at 420 $\mu\text{mol}/\text{m}^2/\text{s}$ from a range of light intensities (140-540 $\mu\text{mol}/\text{m}^2/\text{s}$). Photoinhibition happened after a peak value of 420 $\mu\text{mol}/\text{m}^2/\text{s}$ and decreased in biomass productivity.

There is a well established research history quantifying the relationship correlating chlorophyll a concentration in aquatic systems and nutrient availability (Randolph et al., 2008). Phytoplankton production and biomass in most ponds is controlled by the nutrient supply and most often by phosphorus availability (Schindler, 1978; Hecky and Kilham, 1988). The interaction of many factors such as ratio of ions, trace elements and dissolved organic compounds also determine the presence of any algae species or group (Hutchinson, 1944; Pennack, 1949). Any small change in any of these conditions such as pH can cause specific organisms to become more abundant which is termed a bloom (Whitford, 1958).

Chlorophyll a (Chl-a) is used as a proxy to quantify phytoplankton biomass in freshwater environments. Chlorophyll a is traditionally extracted using a solvent then quantified using spectrophotometry, fluorometry, or using high-performance liquid chromatography (HPCL) (Schwartz and von Elbe, 1982). Chlorophyll a has also been successfully monitored as a water quality parameter using remote sensing (Dube, 2012; Kibena et al., 2014; Rinaldi et al., 2014). This is helpful because an understanding of the spatial and temporal scale of chlorophyll a concentration is helpful for performing estimates of eutrophication (Mahmoud et al., 2023).

2.4.1 Green Algae

Green algae are very common in inland habitats and certain groups have specific ecological requirements. They vary due to water flow and nutrient concentrations. Most green algae is attached to rocks, but some are free-floating (Wehr et al., 2015). Algae help serve as an index of the water quality at a given sampling point. Green algae produce 50% of all oxygen production and are the main producer that aquatic life needs (Chapman, 2013). As water quality degrades, the metabolic activities of the algae is the first parameter to be affected while the community structure responds more slowly as populations readjust (Collins and Weber, 1978).

2.4.2 Green algae in Stormwater ponds

There is limited research on this topic.

2.4.3 Green algae in Beaver ponds

There is limited research on this topic.

2.5 Diatoms

Diatoms (Bacillariophyta) are microscopic and eukaryotic (nucleus-containing). Their walls are made from silicon dioxide, which is clear. Diatoms are abundant and important components of aquatic ecosystems. Their clear walls, also known as frustules and can survive for thousands of years and can turn into a rock form (Chapman, 2013). Diatoms require the element silicic acid (dissolved form of silicon) from surface waters for their shell formation (Werner, 1977). Silicic acid used by diatoms during growth can significantly reduce its concentration in surface waterbodies during blooms (Jørgensen, 1953).

Diatoms can be found in all freshwater habitats in flowing or standing waters. Diatoms are used in freshwater environment bioassessment and to monitor changes in ecological conditions over time (Wehr et al., 2015). For example some species of diatom, such as

Didymosphenia geminata, are a nuisance organism that can impact fish, plants, etc. (Blanco and Ector, 2009; Wehr et al., 2015). Diatoms are great indicators of trophic status (Bennion, 1994). Diatoms are extremely sensitive to water chemistry changes and are very abundant in aquatic environments (Reid et al., 1995). Light, temperature, and flow rate are important factors for the density of diatoms (Werner, 1977).

Light is a density-independent factor that has a big influence on diatom growth. The amount of sunlight needed depends on the species. Diatoms that like a lot of sunlight usually live in shallow areas/ shallow littoral zones (Schroeder, 1939). Diatom populations can also vary due to seasonal weather (Werner, 1977). For example, diatoms tend to grow in shallow water in the winter because they get more light intake under the ice (Godward, 1937).

Different species of diatoms prefer different amounts of nutrients. Oligotrophic diatoms prefer low concentrations of nitrates or ammonia, and phosphates. Diatoms that live in eutrophic conditions prefer high amounts of nitrates or ammonia, and phosphates (Werner, 1977). Alam et al., (2001) found that phosphate concentrations decreased in a freshwater pond when diatoms were the dominant phytoplankton population. This indicates that phosphate could be a controlling factor for diatom abundance. In the piedmont and mountain areas there is an increase in diatoms in low turbidity waters. In these same waters there is a slow increase in diatoms starting in February and reaching their peak abundance in April with the amount of diatoms dropping rapidly in June (Whitford, 1958).

2.5.1 Diatoms in Stormwater Ponds

In a study done on Kiawah Island, a depositional barrier island located 54 km south of Charleston, South Carolina the authors looked at algae composition of two stormwater detention ponds. Diatoms were common in the ponds from June to September. They saw a diatom bloom

occur at a pond in July and at a different pond an August bloom that was composed of diatoms, cyanobacteria, chlorophytes, and euglenophytes (Siegel et al., 2011).

Annual mean total phosphorus is a significant variable in changing the abundance of diatoms (Bennion, 1994).

2.5.2 Diatoms in Beaver Ponds

A study done in Colorado by Whitford and Kim, (1971), showed that a beaver pond algal assemblage was mostly made up of diatoms in the littoral zone. This pond was slightly acidic, which might be a favorable condition for certain diatom species. Further illustrating the presence of diatoms in beaver ponds Correll et al., (2000) found that a beaver pond reduced annual discharge of dissolved silicate by 32%. Dissolved silicate retention peaked in the spring.

2.6 Desmids

Desmids are coccoid, meaning they are unicellular, non-flagellated, and non-amoeboid organisms. Desmids are shaped by two symmetrical halves (semicells) (Lothar et al., 2003; Lewis and McCourt 2004). The best studied group of green algae is desmids, due to their appealing appearance (Coesel and Krienitz, 2009).

Desmids are to be found mostly in acid (pH 4.8-7.0) and soft water situations, areas with less calcium and magnesium. Depending on the type of desmid, these values can vary. *Saccoderm* desmids (*Cylindro-cystis*, *Netrium*) can occur in a wider pH range and may be found in hard water, water with more calcium and magnesium. Some species of *Closterium* and *Staurastrum* appear in pH levels above neutral. Desmids tend to be in habitats such as freshwater wetlands of soft, spongy ground consisting mainly of partially decayed plant matter called peat (Prescott, 1948).

Desmids usually occur in gelatinous masses floating on the surface of shallow warm water. They prefer shallow poorly aerated water with high concentrations of organic matter and an abundance of organic acid. Desmids can live at all altitudes where water chemistry is suitable (Prescott, 1948). Desmids usually begin their spring growth in March and increase in numbers through May (Whitford, 1958).

2.6.1 Desmids in Stormwater Ponds

There is a lack of research on this topic currently.

2.6.2 Desmids in Beaver Ponds

In a study looking at 8 beaver wetlands, desmids contributed to almost $\frac{1}{3}$ of the total algae in the biofilm during July and August. Desmids have shown to correlate with changes in biofilm. These New York Wetlands showed that during these hot months, desmids are more prominent in low nutrient conditions (Domozych and Domozych, 2008).

2.7 Blue-green Algae

Blue-green algae (cyanobacteria) are a prokaryote, very abundant and can survive in almost any habitat. Blue-green algae produce nitrogen through nitrogen fixation (process of breaking covalent bonds and adding other atoms like hydrogen and oxygen to the nitrogen) (Chapman, 2013). Cyanobacteria abundance depends on several factors including nutrient levels, illumination, turbulence, and temperature (Wehr et al, 2015). Some species of cyanobacteria can cause huge surface blooms (harmful algal blooms) and these blooms can produce toxins and affect water quality (Reynolds and Walsy, 1975). Lake characteristics during a toxic algal bloom included higher total phosphorus, decreased water transparency, high water column stability, high surface water temperature and pH, and decreased lake flushing (Jacoby et al., 2000).

A large-scale study of US lakes found potential microcystin-producing cyanobacteria in 95% of the samples (Loftin et al., 2016). Higher overall *Microcystis* over other cyanobacteria occurs with low nitrogen to phosphorus ratios and low nitrate-nitrogen with high ammonium-nitrogen concentrations (Jacoby et al., 2000). Microcystin concentrations were positively correlated with increasing soluble reactive phosphorus levels (1-10 $\mu\text{g}\cdot\text{L}^{-1}$)(Jacoby et al., 2000).

2.7.1 Blue-green Algae in Stormwater Ponds

Cyanobacteria blooms happen often due to excess nutrients running off of anthropogenically altered landscapes. Stormwater runoff is a large source of nutrients in most freshwater bodies and especially in stormwater ponds in urban areas. For the last 25 years, the University of North Carolina Wilmington (UNCW) Aquatic Ecology Lab has kept records of blooms (chlorophyll- $\alpha > 40 \mu\text{g L}^{-1}$) occurring in the city-owned Greenfield Lake and local urban creeks based monthly sampling (<https://uncw.edu/cms/aelab/>). Most algal blooms (61%) occurred in constructed stormwater ponds or other water bodies directly receiving stormwater runoff (Grogan et al., 2023). Their results also showed that out of 87 algal blooms, there was a lot of toxic cyanobacteria genera. All the areas sampled were easily accessible to people, which poses a threat to public health (Grogan et al., 2023).

Key factors to starting these algal blooms are eutrophication and temperature. The southeast is becoming more and more urbanized, which is increasing impervious coverage and an increase in creating more stormwater ponds (Cotti-Rausch et al., 2019). This impervious coverage is transporting excess nutrients such as nitrogen and phosphorus, which help cause these harmful algal blooms (Conley et al., 2009). These ponds are very shallow and stagnant and

over time become very eutrophic, which creates a perfect environment for cyanobacteria (Grogan et al., 2023).

A study looked at the nutrient, microcystin, and chlorophyll-a interactions in three Florida stormwater wet detention ponds with floating treatment wetlands (FTWs) that were recently installed. These FTWs are installed to naturally remove excess nutrients as a form of stormwater management. The results showed a large negative correlation between total phosphorus and microcystin concentrations for both storm and non-storm events across all three ponds. The dominant nutrient species in correlation was total phosphorus. Total phosphorus was correlated positively with chlorophyll-a concentrations at almost all ponds (Hartshorn et al., 2016).

Harmful algal blooms (HABs) cause fish to die, hypoxia, toxin production, and fisheries closures (Grogan et al., 2023). The HABs kill fish indirectly through oxygen depletion and directly through production of toxins. In a study comparing three stormwater ponds and three natural shallow lakes, the authors saw more potential toxin producing blue-green algae in stormwater ponds compared to natural shallow lakes (Minelgaite et al., 2020). Several urban ponds in the Northern Kentucky, USA area were monitored for algae and cyanobacteria. Most of the harmful algal blooms observed during this study are primarily of the cyanobacteria genus, *Microcystis* (de la Cruz et al., 2017). It is important to note however, that *Microcystis* abundance does not always directly correlate with microcystin toxin concentration of (de la Cruz et al., 2017; Jacoby et al., 2000).

2.7.2 Blue-green Algae in Beaver Ponds

There seems to be little to no studies done on blue-green algae concentrations in beaver ponds, which gives this paper a chance to improve insight on this topic.

3. RESEARCH GOALS AND QUESTIONS

The *overall goal* of this study is to compare nutrient concentration, algal biomass, and algal composition, in three stormwater and three beaver ponds in the Charlotte-Mecklenburg region. While there are many studies of ponds and other freshwater ecosystems, natural and engineered urban ponds have been understudied, and especially urban beaver ponds.

Q1: How will the algal biomass differ based on pond type?

Ho: I hypothesize there will be no differences between pond types.

H1: I hypothesize that ponds with higher impervious surface area and associated runoff, in combination with favorable environmental conditions (e.g., reduced canopy coverage, increased solar irradiance, and elevated surface water temperatures), will exhibit higher algal biomass. I predict that stormwater ponds will have higher algal biomass due to reduced riparian vegetation and higher impervious surface coverage.

Q2: How will algal biomass and composition vary seasonally between pond types?

Ho: There will be no difference between pond types across seasons.

H2: I hypothesize that differences in pond algal biomass and community composition between pond types will be greater in the summer compared to the winter in both beaver and stormwater ponds. In summer, both types are receiving higher solar irradiance leading to elevated water temperatures that stimulate higher algal growth. Warmer air temperatures in summer also lead to more intense rainfall resulting in increased runoff (and higher nutrient input) from urban surfaces to both ponds. While algal biomass will increase in each pond, the stormwater ponds will have higher biomass than the beaver ponds since they are receiving greater amounts of solar irradiance due to lower tree canopy and higher runoff due less vegetation surrounding the ponds to capture the runoff. I further predict that these differences in

chemistry between the stormwater and beaver ponds will result in differences in community composition of algae. Both ponds will be dominated by green algae throughout the year as this group is the most common algal group in freshwater systems. Blue-green algae will be more common in the stormwater ponds than the beaver ponds in late summer as they represent a late successional species and are commonly found in warm, stagnant freshwater systems (e.g. stormwater ponds). Beaver ponds however, are not “tight” and maintain some flow, even though it may be low in the summer, through the pond and leaving via the beaver dam.

4. STUDY AREA

Three stormwater ponds and three beaver ponds in Mecklenburg County were sampled from 10/27/22-7/3/2023 (Figures 1 and 2): Briar Creek stormwater pond (BC), Beaverdam stormwater pond (BSW), Brocker stormwater pond (CBP), Beaver Dam creek beaver pond (BD), Paw Creek beaver pond (PAW), and the beaver pond on a tributary of McDowell Creek (MC5). All ponds are considered to be in an urban environment (Figures 3-8) due to their surroundings, which are mostly suburban neighborhoods. Watershed area ranged 0.23 - 36.99 sq km (Table 1) and percent impervious cover ranged 11-50 (Table 1: Figure 9). The three stormwater ponds are wet detention ponds. Wet detention ponds are no longer built for stormwater detention in the Charlotte region, however, they are still common in the region from past management practices. Each beaver site is a beaver complex with a diversity of habitats including ponds, wetlands, and beaver canals. I chose the middle beaver pond in each complex for study. Total precipitation during the study period was (882.7 mm) exceeding the 30-year mean (741.6 mm), corresponding to a z-score of 0.78. This places the study period in the 79th percentile of historical observations, indicating moderately wet conditions relative to the long-term record taken from Charlotte Douglas Airport (National Oceanic and Atmospheric Administration, 2024).

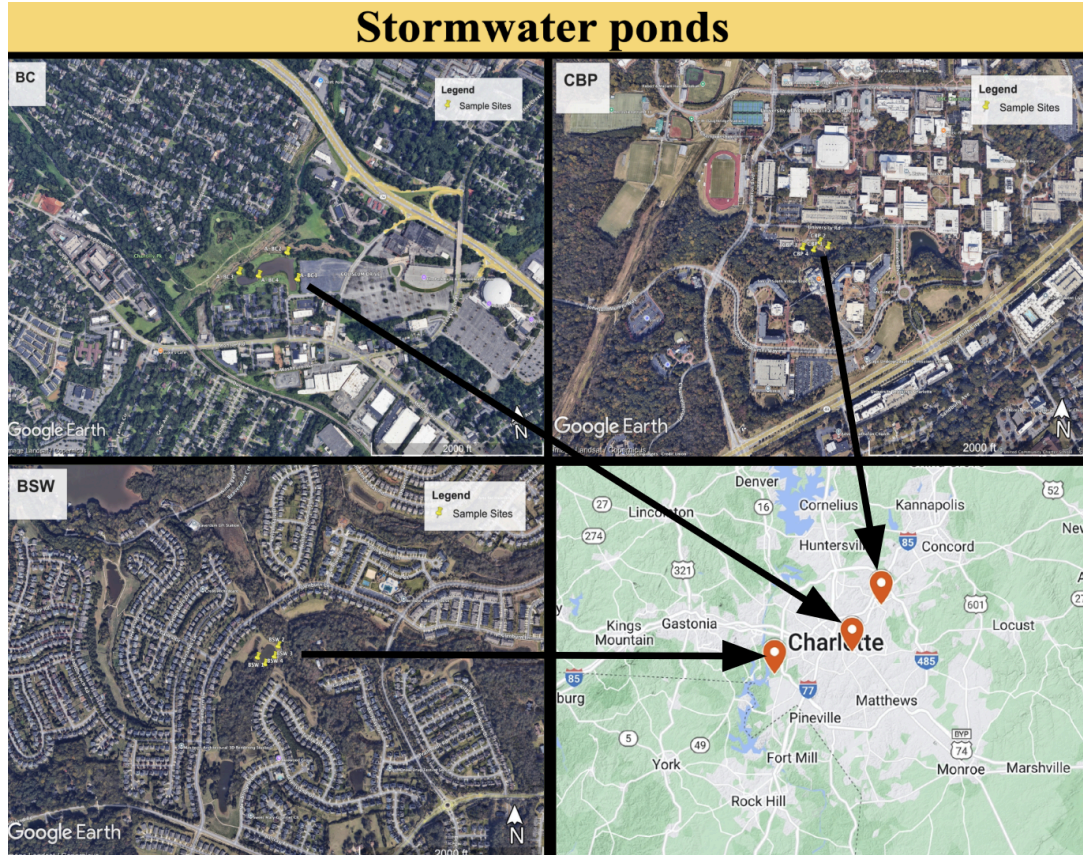


Figure 1: Location of the stormwater pond sites in Mecklenburg County. BC = $35^{\circ}12'23.2''\text{N}80^{\circ}48'14.4''\text{W}$, CBP = $35^{\circ}18'12.9''\text{N}80^{\circ}44'06.2''\text{W}$, BSW = $35^{\circ}09'49.2''\text{N}80^{\circ}59'14.4''\text{W}$.

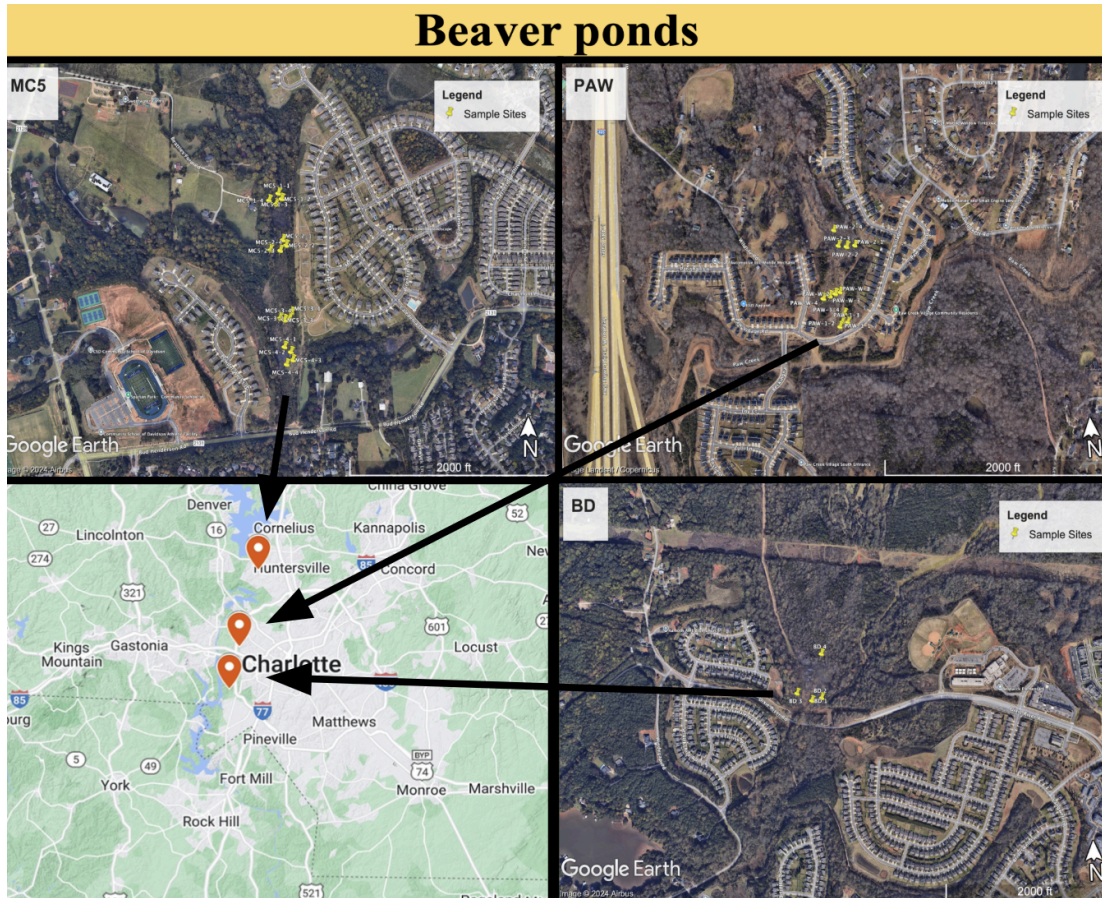


Figure 2: Location of the beaver pond sites in Mecklenburg County. MC5 = $35^{\circ}24'12.9''\text{N}80^{\circ}55'04.1''\text{W}$, PAW = $35^{\circ}15'22.6''\text{N}80^{\circ}57'41.0''\text{W}$, BD = $35^{\circ}10'21.9''\text{N}80^{\circ}59'08.6''\text{W}$.



Figure 3: Briar Creek Stormwater site showing 4 sample locations. This is the most urban pond site located only 5.95 km from Uptown Charlotte. Location: $35^{\circ}12'23.2''\text{N}80^{\circ}48'14.4''\text{W}$.



Figure 4: Campus Broker stormwater pond site showing 4 sample locations. Site located at UNC Charlotte Campus next to dorm rooms and the SOVI cafeteria. The only pond that contains a fountain. Location: $35^{\circ}18'12.9''\text{N}80^{\circ}44'06.2''\text{W}$.



Figure 5: Beaver Dam Stormwater pond showing 4 sample locations. Located in the middle of a suburban neighborhood. Location: $35^{\circ}09'49.2''\text{N}80^{\circ}59'14.4''\text{W}$.



Figure 6: MC5 Beaver pond complex. MC5 is made up of 4 total ponds. Located in a suburban neighborhood and nearby a school and farm. Location: $35^{\circ}24'12.9''\text{N}80^{\circ}55'04.1''\text{W}$.



Figure 7: Paw beaver pond site. Located in a suburban neighborhood and nearby a school.
Location: $35^{\circ}15'22.6''\text{N}80^{\circ}57'41.0''\text{W}$.



Figure 8: Beaver Dam beaver pond site. Located right beside a suburban neighborhood.
Location: $35^{\circ}10'21.9''\text{N}80^{\circ}59'08.6''\text{W}$.

4.1 Pond Characteristics

Table 1: Pond age was attained using Google Earth Pro and used historical imagery to scroll back through the years to see when the pond first appeared. There are some gaps in imagery. Mean Impervious coverage % obtained using ArcGISPro using the “Zonal Statistics Table” tool. Watershed area in sq km obtained using ArcGIS online using the “create watersheds” tool. Pond area obtained using Google Earth Pro and using the ruler icon to trace the pond boundary (ha).

Pond Site	Pond Type	Year Established	Mean Impervious Coverage (%)	Watershed Area (sq km)	Pond Area (ha)
PAW	Beaver	2022	27.50	22.74	0.17
MC5	Beaver	2022	12.29	2.46	0.13
BD	Beaver	2020	11.11	8.42	1.45
BSW	Stormwater	2010	39.83	1.71	0.34
BC	Stormwater	2021	32.92	36.99	1.00
CBP	Stormwater	2013	50.37	0.23	0.22

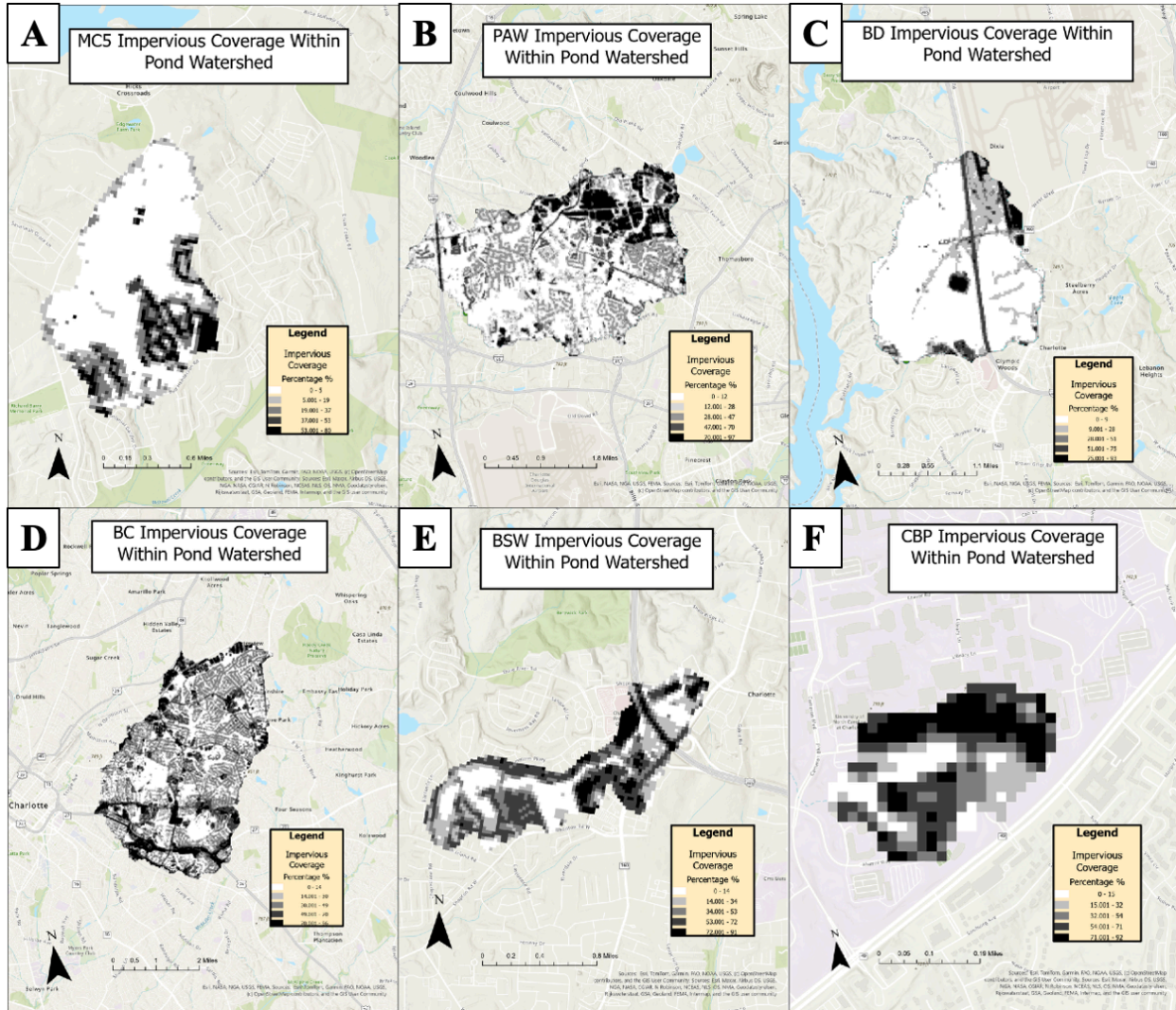


Figure 9: Impervious surface coverage (%) within pond watersheds based on Annual NLCD Fractional Impervious Surface data, summarized using Zonal Statistics in ArcGIS Pro. Each panel corresponds to a study site: (A) MC5, (B) PAW, (C) BD, (D) BC, (E) BSW, and (F) CBP.

5. METHODS

5.1 Field Methods

At each site, I collected dissolved oxygen, temperature, and conductivity 5 feet from the edge using EcoSense meters before water sampling. For each site 4, 250 mL samples were taken at equidistant areas surrounding the pond (Figures 3-8). Each sample was taken about 5 feet from the edge of the pond using a dipper stick and was taken right below the water surface. These four samples were combined into one sample as representative of the pond water. Photosynthetically active radiation (PAR) was collected using a LI-250A light meter, at each site location. The sensor is pointed at the sky directly above the water surface for an average of 15 seconds. Then, all 4 sample sites are averaged at each pond.



Figure 10: Example of sampling collection

Water samples were collected from 10/27/2022 - 7/3/2023 approximately every 10 days regardless of weather. The total number of samples collected were: 18 at BC, 35 at BD, 17 at BSW, 15 at CBP, 33 at MC5, 18 at PAW.

5.2 Laboratory Methods

Water samples were filtered through GF/F filters using a vacuum and analyzed for phosphate, nitrate, and ammonium using ion chromatography on a Thermo Fisher Aquion system. Unfiltered samples were analyzed for total phosphorus using the Hach Method 8190 on a Hach DR/4000V Spectrophotometer.

Algae Identification

After returning from the field, and before filtering, 5 ml of each sample was subsampled into a vial and preserved with 5 drops of Lugol's solution. Each sample was put under a slide and algae taxa were identified using a Olympus BX41 Microscope for desmids, diatoms, green algae, and blue-green algae. One slide per sample was analyzed by counting the cells in 40 frames per slide using an up and down pass procedure.

Chlorophyll a

Using the same water samples collected from the pond, I filtered a known volume of water with the filter placed into a dark tube and frozen for at least 24 hours which lyzes the cells. The algal biomass on the filter was extracted as chlorophyll a using the acetone extraction method by putting 10 ml of acetone into each vial and shaking it on a vortex mixer for 15 seconds. The samples were next put into the refrigerator overnight and the chlorophyll a quantified using a Trilogy laboratory fluorometer the next day.

Total Suspended Solids

Approximately 200 mL of pond water from each pond site were filtered through a GF/F filter in a vacuum filtration system. Total suspended solids (TSS) was analyzed by drying the

filter for 24 hours in a drying oven set at 105°C and then the GF/F filter + sediment was weighed. I then subtracted the used filter from the original filter weight to get dry sediment weight.

Limitations in Ammonium Quantification

Only 15/138 samples had a concentration above the detection limit and the rest were not available or non-detectable due to being under the detection threshold of the machine.

Limitations in Phosphate Quantification

Only 8/138 samples had a value above the detection limit of the method and the rest were non-detectable.

NDVI

Figure 11 shows a smoothed NDVI (Normalized Difference Vegetation Index) time series for Mecklenburg across 2022 and 2023, along with estimated leaf-on and leaf-off dates. There is a repeated yearly pattern when directly comparing years 2022–2023. Winter is from January-March, due to low NDVI levels of 0.1-0.3. Spring is from March-May, due to a spike in NDVI levels. Summer is from June-September, due to NDVI peaking at 0.5-0.6. Fall is from September-November, due to NDVI declining in level. Using this NDVI graph, I was able to calculate leaf-on and leaf-off periods for both years. 2022 has a leaf-on date of 4/8 and a leaf-off date of 10/28. 2023 has a leaf-on date of 4/6 and leaf-off date of 11/4.

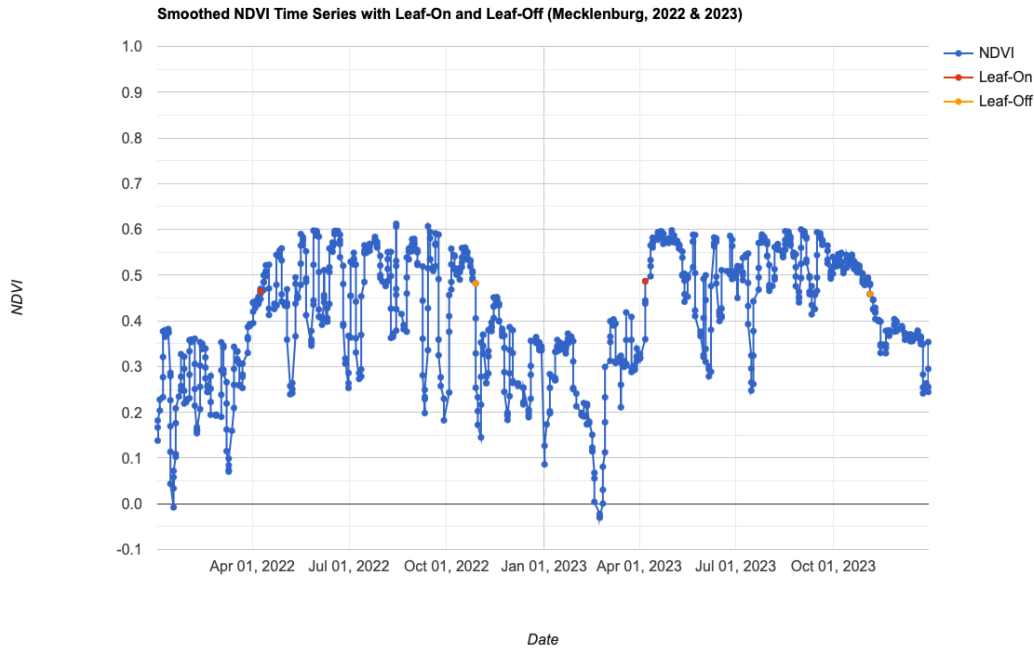


Figure 11: A smoothed NDVI (Normalized Difference Vegetation Index) time series for Mecklenburg across 2022 and 2023, along with estimated leaf-on and leaf-off dates.

5.3 Data Analysis

A listwise deletion method was used for handling missing data. The proportion of omitted data was minimal. The following sample dates were excluded from the analysis: nitrate-2/22/23, 4/19/23; TP-1/11/23, 5/26/23; TSS-11/10/22, 12/19/22, 6/7/23; DO: 11/17/22.

I compared beaver ponds vs. stormwater ponds using boxplots for all parameters to show distribution, medians, and outliers. Boxplots are a useful way to help show spatial distribution of data. Differences among sites were tested using t-test (all beaver vs all stormwater) to tell if the difference is statistically significant or not.

To test differences within seasons, I used boxplots between all parameters showing the leaf-on vs. leaf-off periods. Leaf-on and leaf-off was determined using NDVI (Normalized

Difference Vegetation Index) to help identify when vegetation becomes active (leaf-on) and when it goes dormant (leaf-off). I used Google Earth Engine to select the boundary (Mecklenburg, NC) and then cloud masking to mask clouds and shadows. Next, I used Sentinel-2 surface reflectance collection and used a NDVI calculation. I used a 0.45 threshold for leaf-on/leaf-off, which is a value that made sense in a temperate mixed forest environment like Mecklenburg County. This value is then plotted into a line graph to help get exact dates for the leaf-off and leaf-on periods. All parameters are plotted with time to visualize changes in parameters across seasons. I used the R package ggplot2 to visualize this data.

I used R packages tidyr, dplyr, and ggplot2 to compare algae composition over time as an area plot. I made a bar plot of just blue-green algae between beaver and stormwater ponds over time showing the monthly proportion. I did this using R packages lubridate and ggplot2. Finally, I separated blue-green algae as an independent graph since this type of algae has the highest difference between ponds and is the most detrimental to water quality.

6. RESULTS

6.1 Beaver and Stormwater Pond Comparison

6.1.1 Temperature

Median stormwater pond temperature was 16.2 °C and ranged 7.1-28.8 °C over the entire study. Beaver ponds had a median temperature of 14.0 °C and ranged 4.7-28.8 °C (Figure 12). Stormwater ponds had a statistically insignificant higher median temperature compared to beaver ponds (t-test, $p=0.088$) where stormwater pond temperature was on average 2.2 °C higher than beaver ponds.

Temperature varied within each pond type (Figure 13). Median temperature across the 3 beaver ponds ranged 11.7-14.9 °C where $BD > PAW > MC5$. Median temperature across the 3 stormwater ponds ranged 15.2-17.4 °C where $CBP > BC > BSW$.

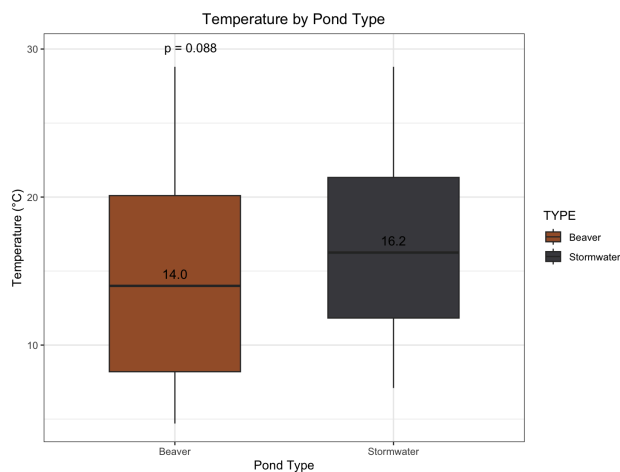


Figure 12: Surface water temperature (°C) in beaver and stormwater ponds across the whole study

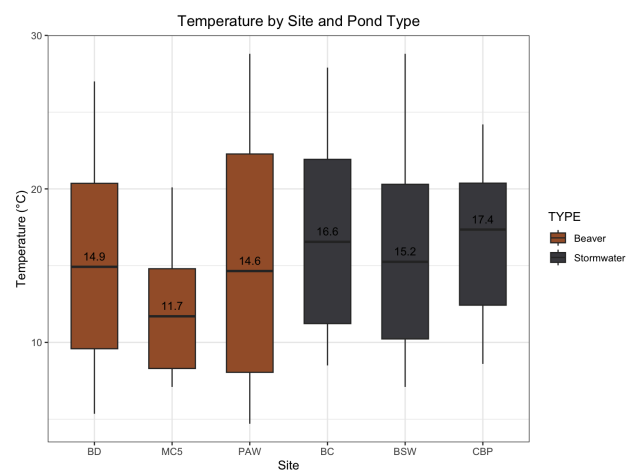


Figure 13: Surface water temperature (°C) across the entire study for each pond

The time series comparison between stormwater and beaver ponds show similar seasonal temperature patterns. Both systems have a typical temperate pattern of cooling from December-January and steadily warming from May-July (Figure 14-15). During the winter months (December-January) stormwater ponds show slightly higher and more variable temperatures, especially at CBP. Stormwater ponds illustrate sharper short-term fluctuations, as exhibited by CBP (Figure 15), while beaver ponds show gradual warming, especially at MC5 (Figure 14).

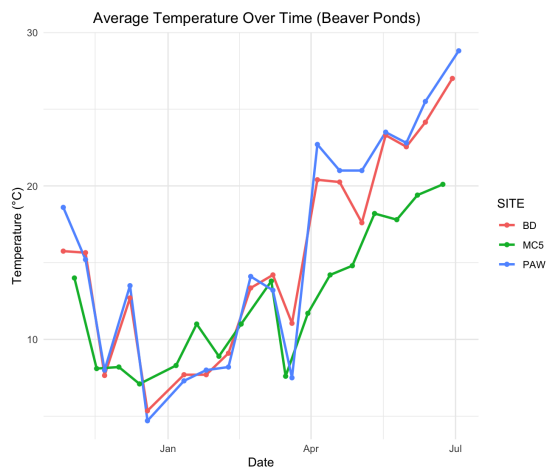


Figure 14: Time series of daily average of water temperature (°C) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023

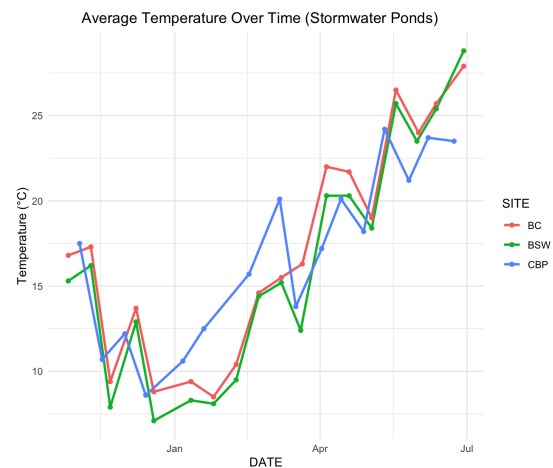


Figure 15: Time Series of daily average of water temperature (°C) at three stormwater pond sites (BC, BSW, and CBP) from October 2022 to July 2023

6.1.2 Temperature Leaf-on vs. Leaf-off

The differences in temperature between beaver pond's leaf-off and leaf-on periods were statistically significant (Figure 16; t-test, $p < 4.6e-11$) and the beaver pond's leaf-on temperature was 11.5 °C higher than the leaf-off period. Median beaver pond temperature during the leaf-off

period was 9.1 °C and ranged 4.7-22.7 °C. Median beaver pond temperature during the leaf-on period was 20.6 °C and ranged from 15.7-28.8°C. The difference in temperature between the stormwater pond's leaf-off and leaf-on periods were statistically significant (Figure 16; t-test, $p=7.4e-11$). The stormwater pond's leaf-on temperature was 10.8 °C higher than the leaf-off period. Median stormwater pond temperature during the leaf-off period was 12.7 °C and ranged from 7.1-22.0 °C. Median stormwater pond temperature during the leaf-on period was 23.5 °C and ranged from 15.3-28.8 °C.

Stormwater pond temperatures were statistically higher than beaver pond temperature during the leaf-off period where stormwater ponds were 3.6 °C higher than beaver ponds (Figure 16; t-test, $p=0.032$). The stormwater leaf-on temperature was 2.9 °C higher than the beaver leaf-on period; however, this difference was not statistically significant (Figure 16; t-test, $p=0.18$).

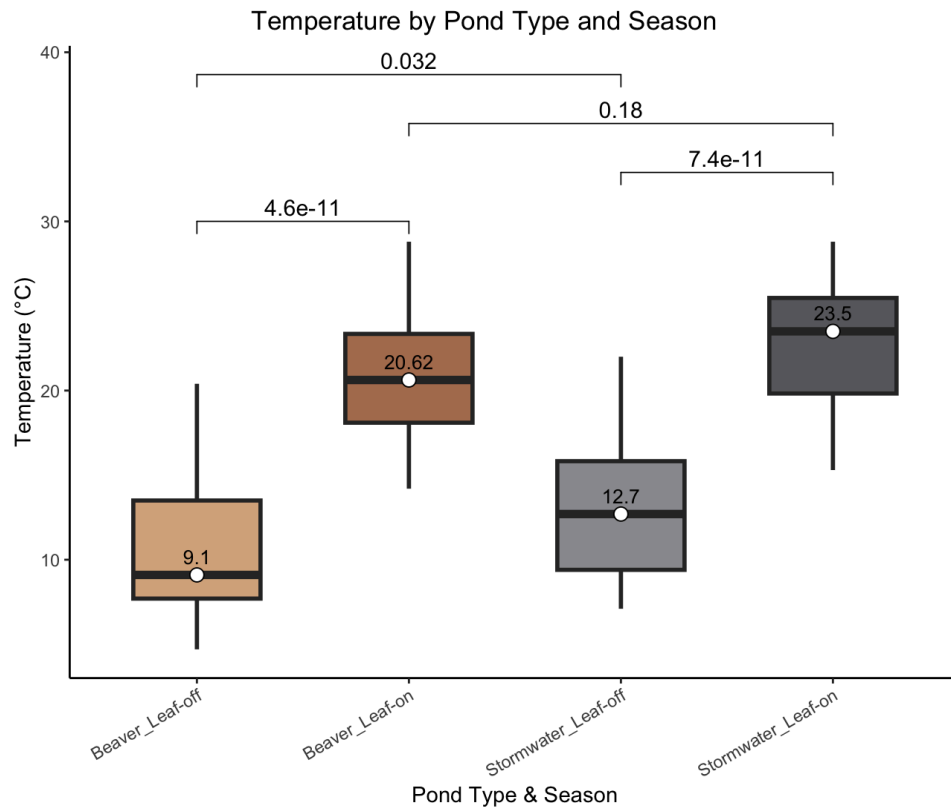


Figure 16: Temperature between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall + winter) seasons

6.1.3 Dissolved Oxygen

Stormwater ponds had a statistically significant higher median DO concentration when compared with beaver ponds (Figure 17; t-test, $p=0.007$). Stormwater pond DO concentrations were 1.63 mg/L higher than beaver ponds. Median stormwater pond DO was 6.05 mg/L and ranged from 0.31- 24.01 mg/L over the entire study. Median beaver pond DO was 4.42 mg/L and ranged from 1.03-8.88 mg/L.

DO concentrations varied across the individual stormwater pond sites where CBP had a much higher overall DO concentration with an extremely high outlier of 24.01 mg/L, while BC had much lower DO concentrations (~1–4 mg/L) compared to all pond sites (Figure 18). BSW had moderately high DO concentrations (~7–10 mg/L). In contrast, all beaver ponds tend to have lower DO concentrations (~3–6 mg/L) (Figure 18).

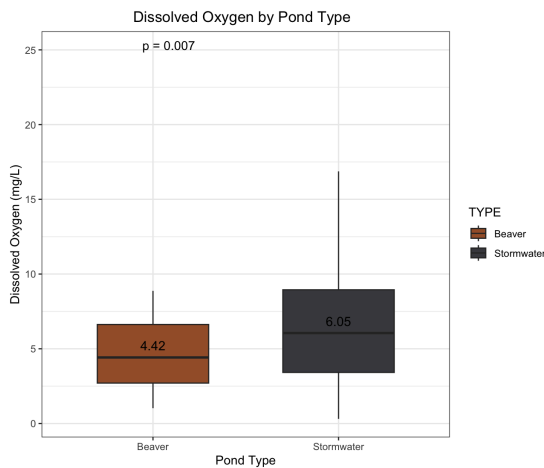


Figure 17: Dissolved Oxygen

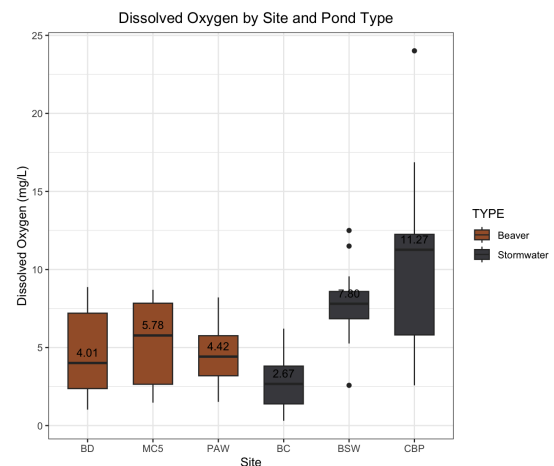


Figure 18: Dissolved Oxygen (mg/L)

(mg/L) in beaver and stormwater ponds across the whole study

across the entire study for each pond

Both pond systems exhibit seasonal fluctuations, but the patterns vary in timing (Figure 19-20). Beaver ponds' dissolved oxygen concentration rises through the winter, peaking around January-March and experiencing a sharp decline in concentrations starting in the spring into the summer months (Figure 19). Stormwater ponds show a more spiky and erratic trend. There is a decline of dissolved oxygen concentration in the summer months. CBP shows large and sudden spikes in oxygen that do not follow the same seasonal curve in comparison to the other stormwater ponds (Figure 20).

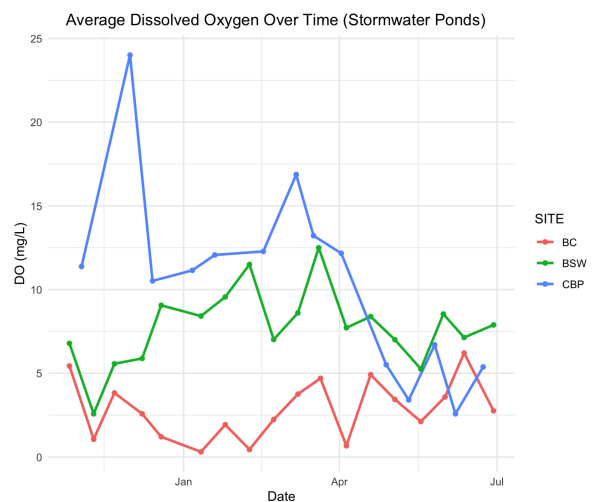
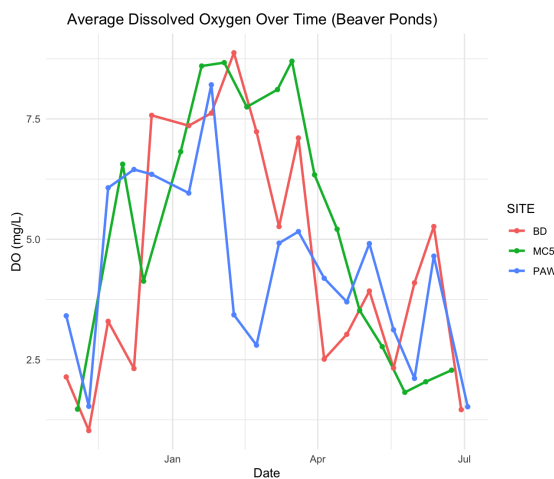


Figure 19: Time series of daily average dissolved oxygen (mg/L) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023

Figure 20: Time series of daily average dissolved oxygen (mg/L) at three stormwater pond sites (BC, BSW, and CBP) from October 2022 to July 2023

6.1.4 Dissolved Oxygen Leaf-on vs. Leaf-off

Dissolved oxygen concentrations for beaver ponds were significantly different for the leaf-off and leaf-on periods (Figure 21; t-test, $p=6.2e-06$). The beaver pond's leaf-off dissolved oxygen concentration was 4.27 mg/L higher than the leaf-on period. Median beaver pond dissolved oxygen concentrations during the leaf-off period were 6.34 mg/L and ranged 1.03-8.88 mg/L. Median beaver pond dissolved oxygen concentrations during the leaf-on period were 3.07 mg/L and ranged 1.46-5.27 mg/L. The difference in dissolved oxygen between the stormwater pond's leaf-off and leaf-on periods were not statistically significant (Figure 21; t-test, $p=0.057$). The stormwater pond's leaf-off dissolved oxygen concentration was 2.28 mg/L higher than the leaf-on period. Median stormwater pond dissolved oxygen during the leaf-off period was 7.72 and ranged 0.31-24.01 mg/L. Median stormwater pond dissolved oxygen during the leaf-on period was 5.44 mg/L and ranged 2.12-8.54 mg/L.

The difference between stormwater vs. beaver pond leaf-off period was not statistically significant (Figure 21; t-test, $p=0.09$). The stormwater leaf-off dissolved oxygen was 1.38 mg/L higher than the beaver leaf-off period. The difference between stormwater vs. beaver pond leaf-on period was statistically significant (Figure 21; t-test, $p=0.0002$). The stormwater leaf-on dissolved oxygen was 2.37 mg/L higher than the beaver leaf-on period.

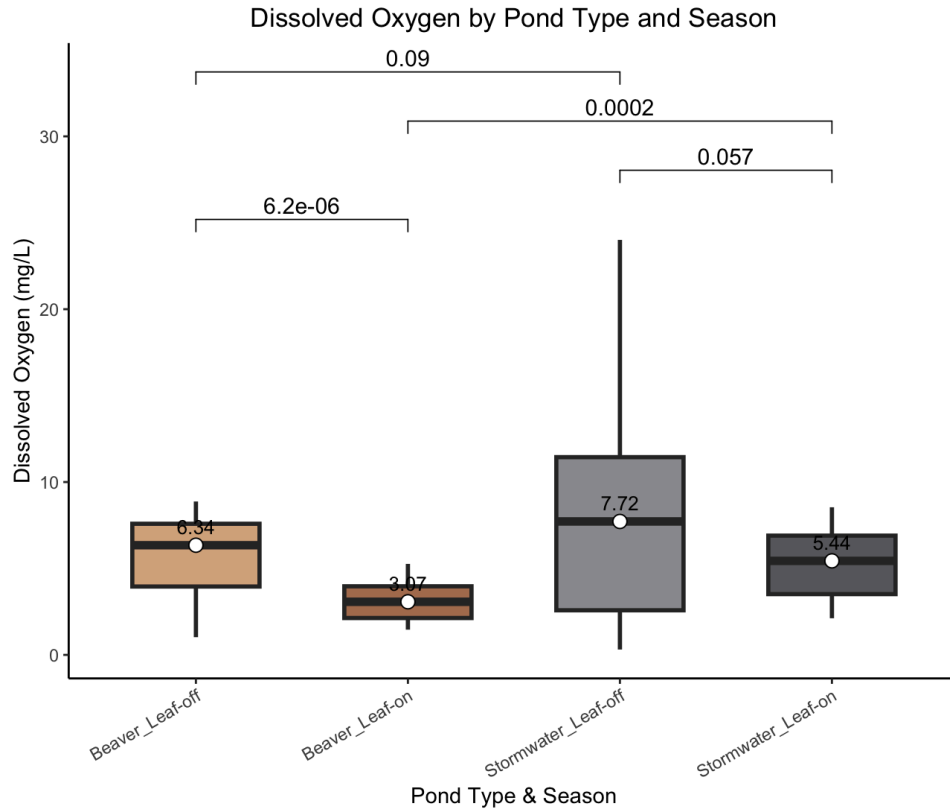


Figure 21: Dissolved oxygen concentrations between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall +winter) seasons

6.1.5 Total Suspended Solids

There is no statistically significant difference in TSS concentrations between beaver and stormwater ponds (Figure 22; t-test, $p=0.348$). Median stormwater pond TSS concentrations were 10.530 mg/L and ranged 0.800-59.600 mg/L over the entire study. Median beaver pond TSS concentrations were 8.048 mg/L and ranged from 1.525-75.450 mg/L. TSS across pond sites had substantial variability within sites, especially for stormwater ponds (Figure 23). Median TSS concentrations across the 3 stormwater ponds ranged 9.200-15.125 mg/L where $BC > BSW > CBP$. Median TSS concentrations across the 3 beaver ponds ranged 7.350-11.062 mg/L where $BD > PAW > MC5$. Stormwater ponds are more variable compared to beaver ponds.

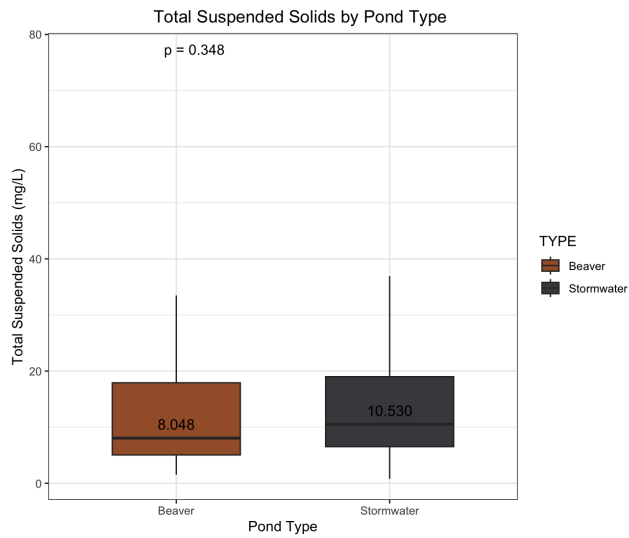


Figure 22: Total suspended solids (mg/L) beaver and stormwater ponds across the whole study

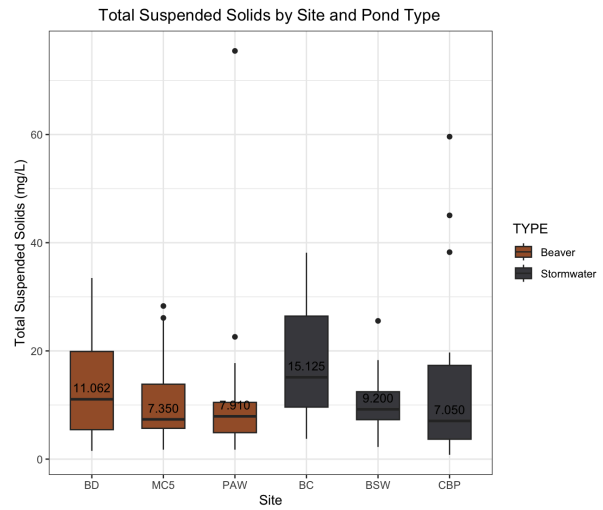


Figure 23: Total suspended solids (mg/L) across the entire study for each pond

Beaver pond sites TSS concentrations stay relatively low and show similar seasonal patterns except for PAW with a large outlier of 75.450 mg/L in early spring (Figure 24). Stormwater pond sites over time show much more variability between sites (Figure 25).

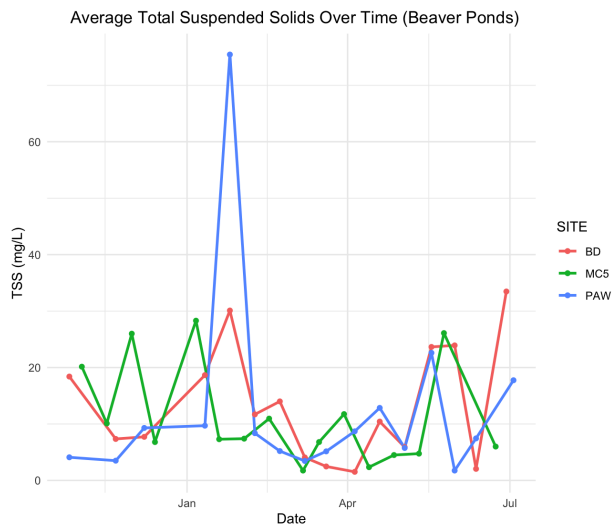


Figure 24: Time series of daily average total suspended solids (mg/L) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023

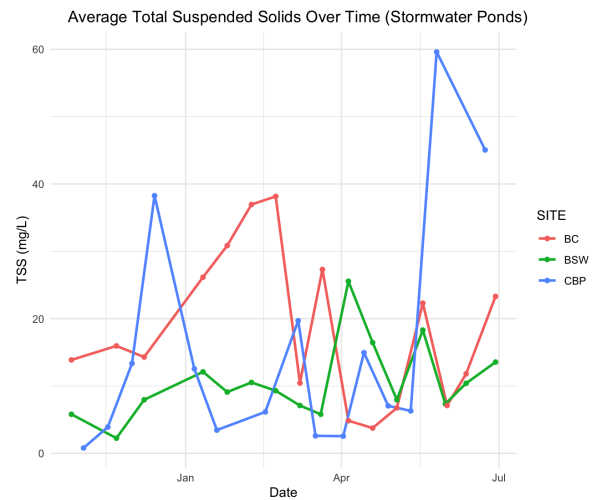


Figure 25: Time series of daily average total suspended solids (mg/L) at three stormwater pond sites (BC, BSW, CBP) from October 2022 to July 2023

6.1.6 Total Suspended Solids Leaf-on vs. Leaf-off

The difference in TSS between the beaver pond leaf-off and leaf-on periods were not statistically significant (Figure 26; t-test, $p=0.95$). Median beaver pond TSS during the leaf-off period was 8.370 mg/L and ranged 1.525-75.450 mg/L. Median beaver pond TSS during the leaf-on period was 7.450 mg/L and ranged from 1.750-33.475 mg/L. The difference in TSS between the stormwater pond leaf-off and leaf-on periods were also not statistically significant (Figure 26; t-test, $p=0.67$). Median stormwater pond TSS during the leaf-off period was 10.490 mg/L and ranged 0.800-38.250 mg/L. Median stormwater pond TSS during the leaf-on period was 11.800 mg/L and ranged 3.750-59.600 mg/L. There were no statistically significant differences between stormwater vs. beaver pond leaf-off period (Figure 26; t-test, $p=0.63$) and the leaf-on period (Figure 26; t-test, $p=0.37$).

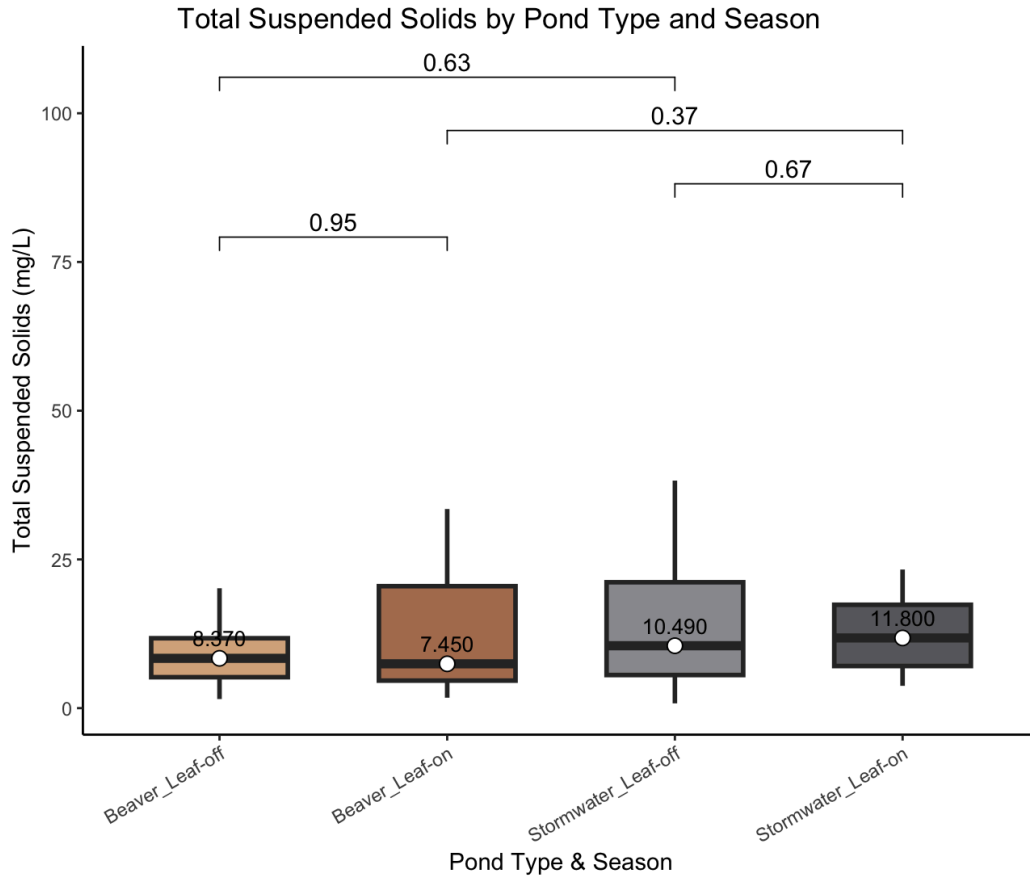


Figure 26: Total suspended solids concentrations between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall + winter) seasons

6.1.7 Conductivity

There is no statistically significant difference between the average conductivity of beaver ponds and stormwater ponds (Figure 27; t-test, $p=0.684$). Beaver ponds had a conductivity value that was $4.0 \mu\text{S}/\text{cm}$ higher than stormwater ponds. Median stormwater pond conductivity concentrations were $93.0 \mu\text{S}/\text{cm}$ and ranged from 29.5 - $350.9 \mu\text{S}/\text{cm}$ over the entire study. Median beaver pond conductivity concentrations were $97.0 \mu\text{S}/\text{cm}$ and ranged from 45.5 - $198.6 \mu\text{S}/\text{cm}$.

There was greater variability between sites for stormwater ponds as compared to beaver ponds (Figure 28). Median conductivity concentrations across the 3 beaver ponds ranged 90.7-112.7 $\mu\text{S}/\text{cm}$ where PAW>BD>MC5. Median conductivity concentrations across the 3 stormwater ponds ranged 41.0-157.6 $\mu\text{S}/\text{cm}$ where CBP>BSW>BC.

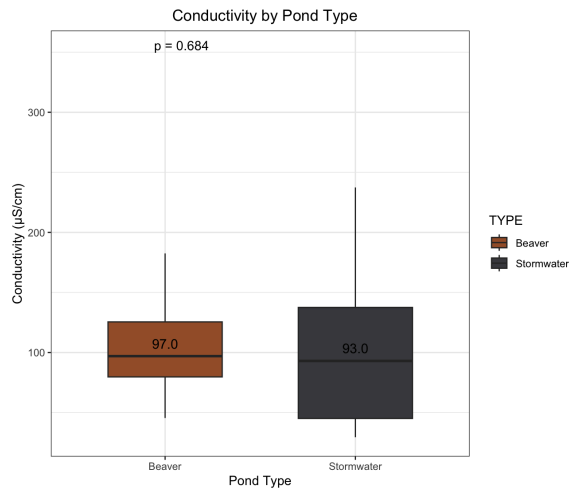


Figure 27: Conductivity ($\mu\text{S}/\text{cm}$) in beaver and stormwater ponds across the whole study

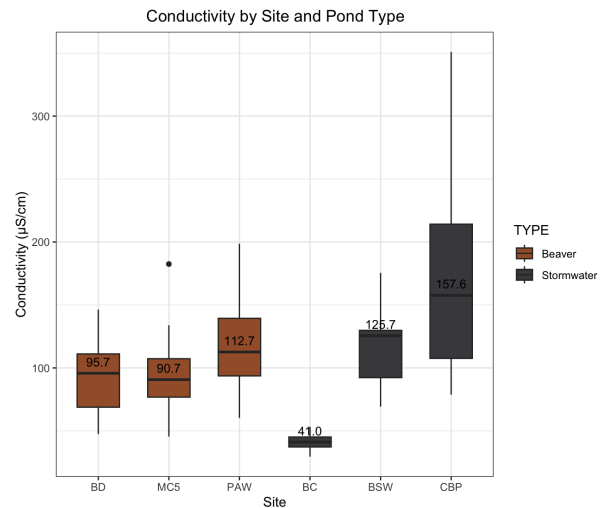


Figure 28: Conductivity ($\mu\text{S}/\text{cm}$) across the entire study for each pond

This time series graph indicates average conductivity over time for the three beaver pond sites (Figure 29). There is a high degree of synchronicity between these sites. There is a clear seasonal trend across all three sites. In the winter months conductivity levels drop significantly. In March, conductivity starts to rise. PAW has the highest peak values and MC5 shows a very large spike at 200 $\mu\text{S}/\text{cm}$ in late October.

This time series graph shows average conductivity for the three stormwater ponds (Figure 30). These sites are very different from each other. CBP is extremely variable and has massive

spikes, with the largest spike in January at 350 $\mu\text{S}/\text{cm}$. BC stayed consistent at levels between 30 and 60 $\mu\text{S}/\text{cm}$. BC is lower and more stable than the beaver ponds.

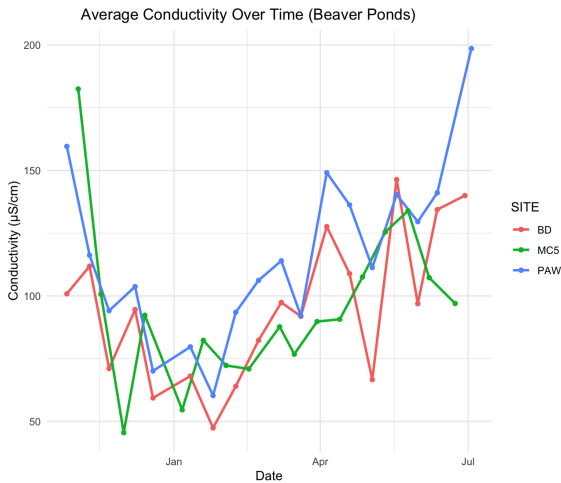


Figure 29: Time series of daily average conductivity ($\mu\text{S}/\text{cm}$) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023

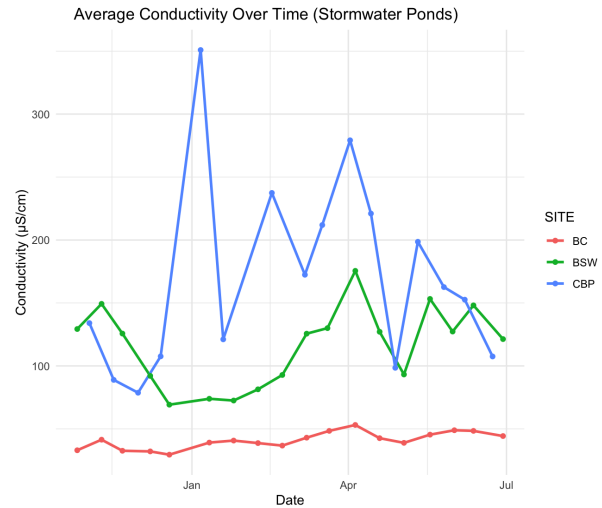


Figure 30: Times series of daily average conductivity ($\mu\text{S}/\text{cm}$) at three stormwater pond sites (BC, BSW, CBP) from October 2022 to July 2023

6.1.8 Conductivity Leaf-on vs. Leaf-off

The difference in conductivity between beaver pond's leaf-off and leaf-on periods were statistically significant (Figure 31; t-test, $p=0.00014$). The beaver pond's leaf-on conductivity was 37.8 $\mu\text{S}/\text{cm}$ higher than the leaf-off period. Median beaver pond conductivity during the leaf-off period was 89.8 $\mu\text{S}/\text{cm}$ and ranged 45.5-182.5 $\mu\text{S}/\text{cm}$. Median beaver pond conductivity during the leaf-on period was 127.6 $\mu\text{S}/\text{cm}$ and ranged 66.7-198.6 $\mu\text{S}/\text{cm}$. The difference in conductivity between the stormwater pond's leaf-off and leaf-on periods were not statistically significant (Figure 31; t-test, $p=0.97$). The stormwater pond's leaf-on conductivity was 29.2 $\mu\text{S}/\text{cm}$ higher than the leaf-off period. Median stormwater pond conductivity during the leaf-off

period was 85.2 $\mu\text{S}/\text{cm}$ and ranged 29.5-350.9 $\mu\text{S}/\text{cm}$. Median stormwater pond conductivity during the leaf-on period was 114.4 $\mu\text{S}/\text{cm}$ and ranged 33.0-221.0 $\mu\text{S}/\text{cm}$.

The difference between stormwater vs. beaver pond leaf-off period was not statistically significant (Figure 31; t-test, $p=0.25$). The beaver pond leaf-off conductivity was 4.6 $\mu\text{S}/\text{cm}$ higher than the stormwater leaf-off period. The difference between stormwater vs. beaver pond leaf-on period was not statistically significant (Figure 31; t-test, $p=0.25$). The beaver leaf-on conductivity was 13.2 $\mu\text{S}/\text{cm}$ higher than the stormwater leaf-on period.

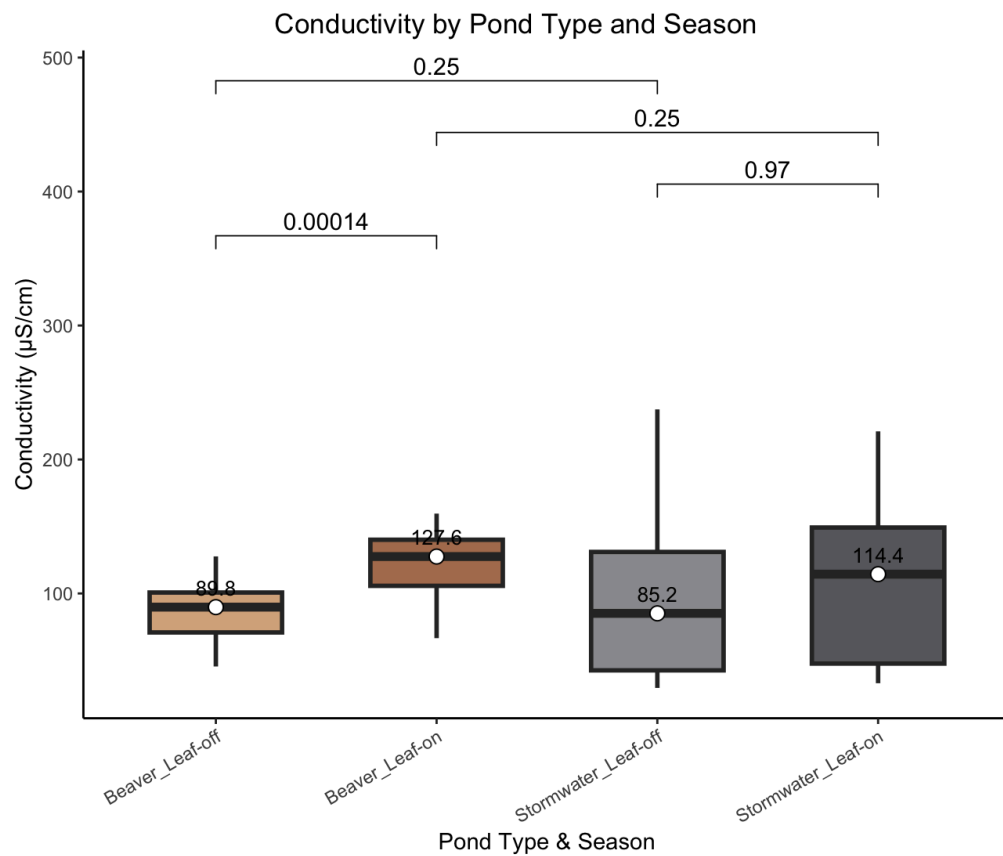


Figure 31: Conductivity concentrations between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall + winter) seasons

6.1.9 Total Phosphorus

Stormwater ponds had a statistically significant higher median of TP when compared to beaver ponds (Figure 32; t-test, $p=0.039$). Stormwater ponds TP concentrations were 0.09 mg/L higher than beaver ponds. Median stormwater pond TP was 0.22 mg/L and ranged from 0.03-0.60 mg/L over the entire study. Median beaver pond TP was 0.13 mg/L and ranged 0.03-0.92 mg/L.

Total phosphorus (TP) concentrations varied across different sites (Figure 33). Median TP across the 3 beaver ponds ranged 0.11-0.20 mg/L where PAW>MC5>BD. Median TP across the 3 stormwater ponds ranged 0.16-0.27 mg/L where BSW>BC>CBP.

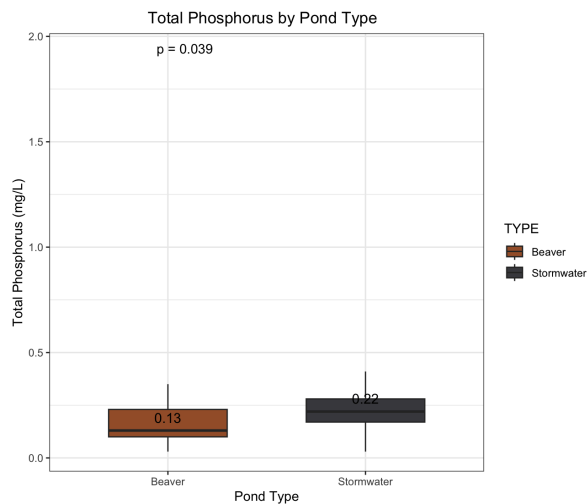


Figure 32: Total phosphorus (mg/L) in beaver and stormwater ponds across the whole study

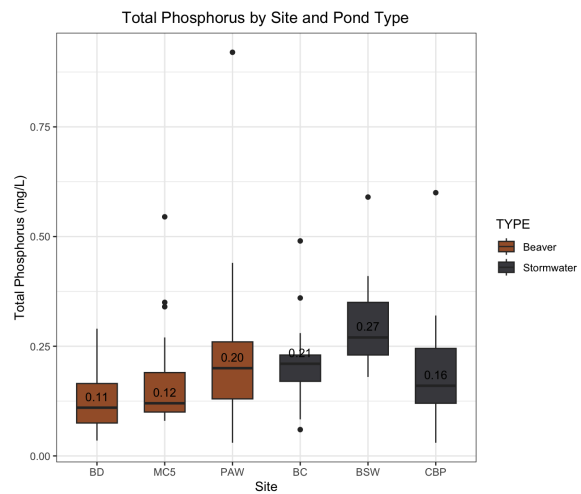


Figure 33: Total phosphorus (mg/L) across the entire study for each pond

This time series graph shows average TP levels across three beaver pond sites (Figure 34). PAW is the most variable beaver pond site. PAW has a massive spike in early February at 0.92 mg/L and has shown higher peaks throughout the sampling period. MC5 shows moderate fluctuations and has shown higher peaks throughout the sampling period. MC5 shows moderate fluctuations and has several small peaks at around 0.30 mg/L in the fall and late spring. BD looks

to be the most stable site out of all the beaver ponds. BD stays mostly below 0.25 mg/L. All three sites show rising levels during the spring.

When looking at average TP over time across stormwater pond sites (Figure 35), this graph shows much higher baseline levels and synchronicity between sites. BSW had the highest levels of TP that were mostly above 0.20 mg/L and peaked at 0.60 mg/L in late December. CBP shows the most extreme spike jumping from almost 0 to 0.60 mg/L in mid-April.

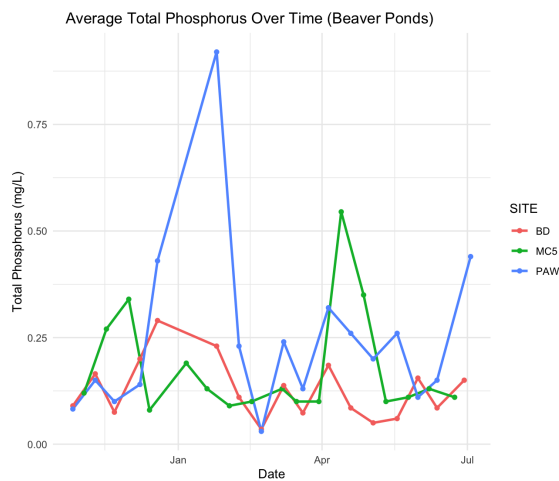


Figure 34: Time series of daily average total phosphorus (mg/L) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023.

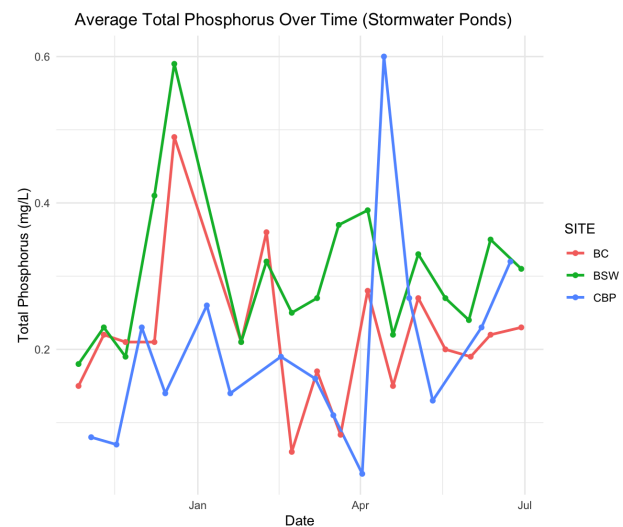


Figure 35: Time series of daily average Total phosphorus (mg/L) at three stormwater pond sites (BC, BSW, CBP) from October 2022 to July 2023.

6.1.9 Total Phosphorus Leaf-on vs. Leaf-off

The difference in TP between beaver pond's leaf-off and leaf-on periods were not statistically significant (Figure 36; t-test, $p=0.77$). The beaver pond's leaf-off TP was 0.02 mg/L higher than the leaf-on period. Median beaver pond TP during the leaf-off period was 0.14 mg/L and ranged from 0.03-0.92 mg/L. Median beaver pond TP during the leaf-on period was 0.12

mg/L and ranged from 0.05-0.55 mg/L. The difference in TP between the stormwater pond's leaf-off and leaf-on periods were not statistically significant (Figure 36; t-test, $p=0.47$). The stormwater pond's leaf-on TP was 0.02 mg/L higher than the leaf-off period. Median stormwater pond TP during the leaf-off period was 0.21 mg/L and ranged 0.03-0.59 mg/L. Median stormwater pond TP during the leaf-on period was 0.23 mg/L and ranged 0.13-0.60 mg/L.

The difference between stormwater vs. beaver pond leaf-off period was not statistically significant (Figure 36; t-test, $p=0.26$). The stormwater leaf-off TP was 0.07 mg/L higher than the beaver leaf-off period. The difference between stormwater vs. beaver pond leaf-on period was statistically significant (Figure 36; t-test, $p=0.044$). The stormwater leaf-on TP was 0.11 mg/L higher than the beaver leaf-on period.

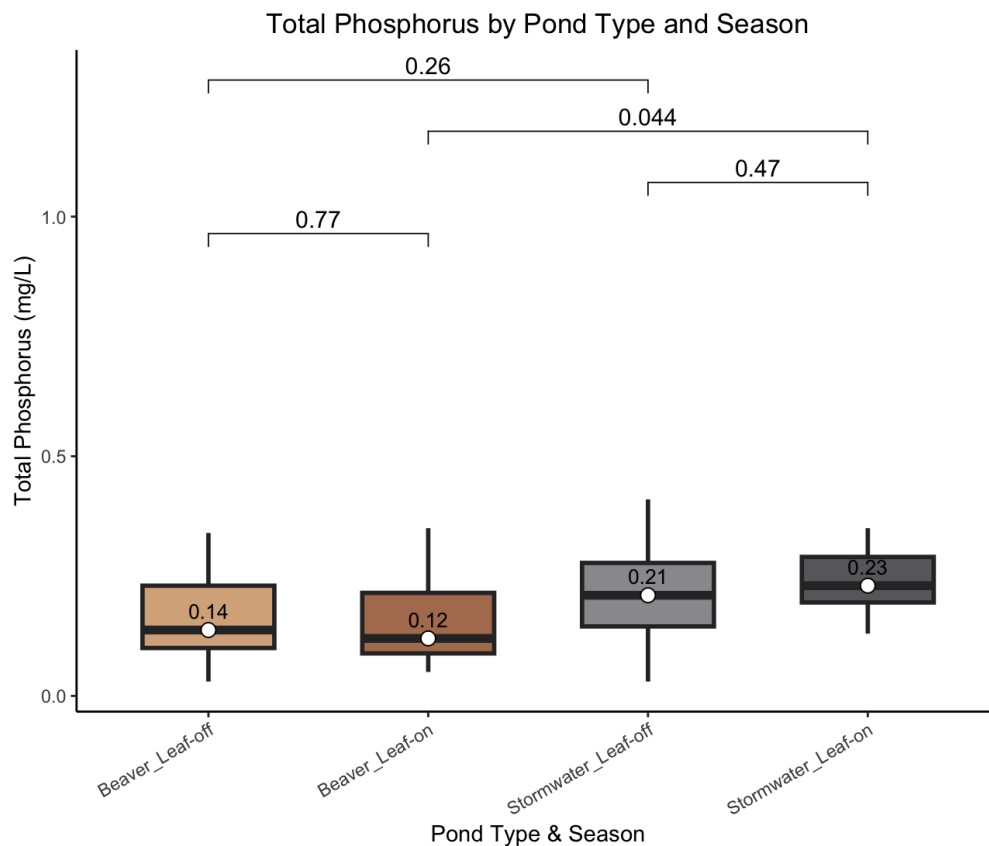


Figure 36: Total phosphorus concentrations between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall + winter) seasons

6.1.11 Nitrate

Beaver ponds had statistically significant higher median nitrate concentrations compared to stormwater ponds (Figure 37; t-test, $p=0.020$). Beaver pond nitrate concentrations were 0.006 mg/L higher than stormwater ponds. Median beaver pond nitrate concentrations were 0.058 mg/L and ranged 0.025-0.458 mg/L over the entire study. Median stormwater pond nitrate concentrations were 0.052 mg/L and ranged 0.006-0.274 mg/L.

Nitrate levels by site varied (Figure 38). Median nitrate across the 3 beaver ponds ranged 0.053-0.078 mg/L where $MC5 > BD > PAW$. Median nitrate across the 3 stormwater ponds ranged 0.041-0.067 mg/L where $CBP > BSW > BC$.

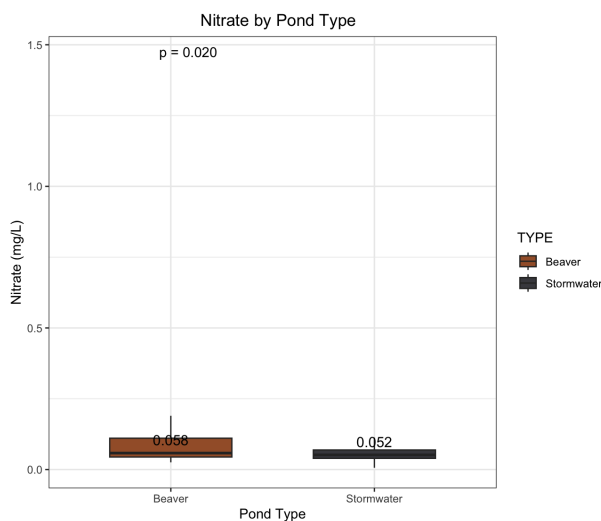


Figure 37: Nitrate (mg/L) in beaver and stormwater ponds across the whole study

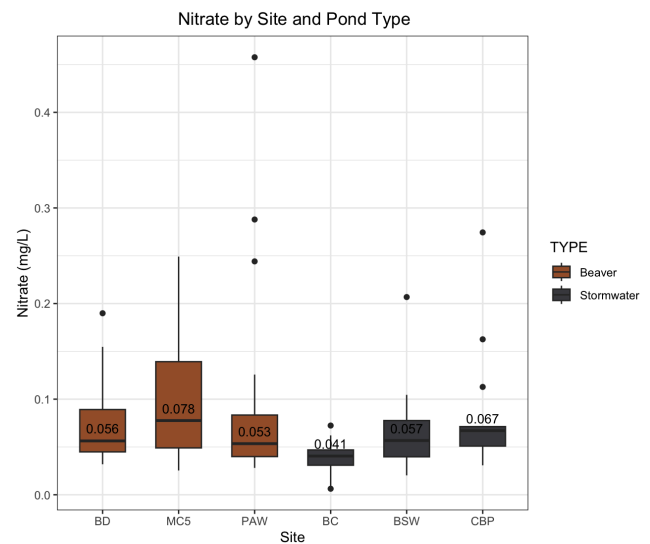


Figure 38: Nitrate (mg/L) across the entire study for each pond

Figure 39 shows average nitrate over time for the three beaver pond sites (BD, MC5, and PAW). There is a large peak in nitrate at all three sites between December and March. PAW has a large peak in mid-February at 0.45 mg/L. MC5 has two distinct peaks, one in early winter and one in late February. In April, all three lines plummet and stay at 0.05 mg/L through July.

Figure 40 shows nitrate over time for all three stormwater ponds (BC, BSW, and CBP). The stormwater ponds seem to be not synchronized. CBP had a large spike at 0.30 mg/L in late April. BSW shows large peaks in December and early March. BC remains low and flat at levels around 0.05 mg/L throughout the entire year.

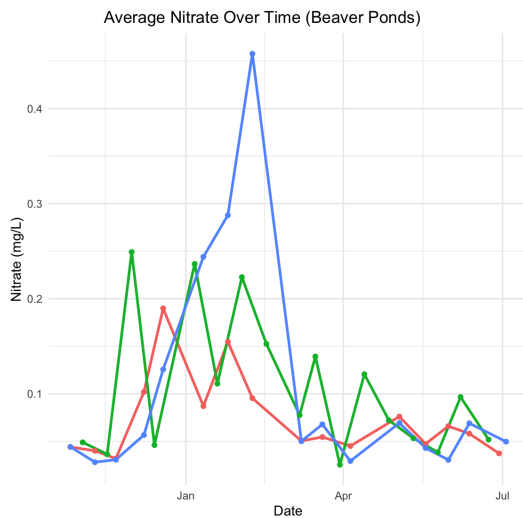


Figure 39: Time series of daily average nitrate (ppm) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023

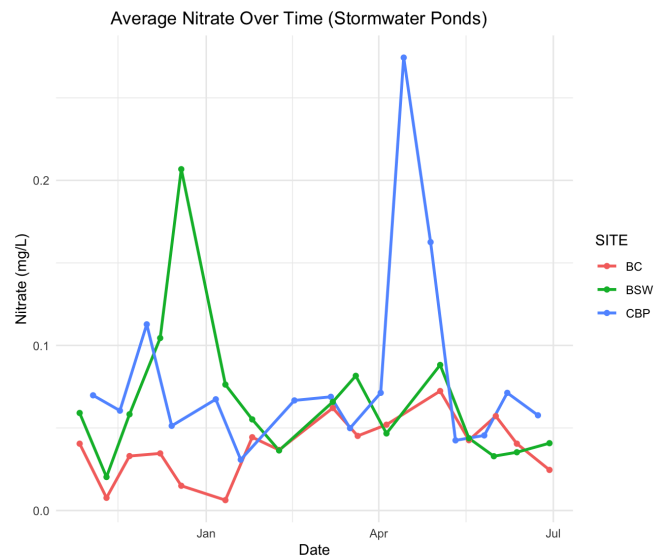


Figure 40: Time series of daily average nitrate (ppm) at three stormwater pond sites (BC, BSW, CBP) from October 2022 to July 2023

6.1.12 Nitrate Leaf-on vs. Leaf-off

The difference in nitrate between beaver pond's leaf-off and leaf-on periods were statistically significant (Figure 41; t-test, $p=0.0051$). The beaver pond's leaf-off nitrate was 0.03 mg/L higher than the leaf-on period. Median beaver pond nitrate during the leaf-off period was 0.08 mg/L and ranged 0.025-0.458 mg/L. Median beaver pond nitrate during the leaf-on period was 0.05 mg/L and ranged 0.031-0.121 mg/L. The difference in nitrate between the stormwater pond's leaf-off and leaf-on periods were not statistically significant (Figure 41; t-test, $p=0.51$).

The stormwater pond's leaf-off nitrate was 0.01 mg/L higher than the leaf-on period. Median stormwater pond nitrate during the leaf-off period was 0.05 mg/L and ranged 0.006-0.207 mg/L. Median stormwater pond nitrate during the leaf-on period was 0.04 mg/L and ranged 0.025-0.274 mg/L.

The difference between stormwater vs. beaver pond leaf-off period was statistically significant (Figure 41; t-test, $p=0.005$). The beaver leaf-off nitrate was 0.03 mg/L higher than the stormwater leaf-off period. The difference between stormwater vs. beaver pond leaf-on period was not statistically significant (Figure 41; t-test, $p=0.55$). The beaver leaf-on nitrate was 0.01 mg/L higher than the stormwater leaf-on period.

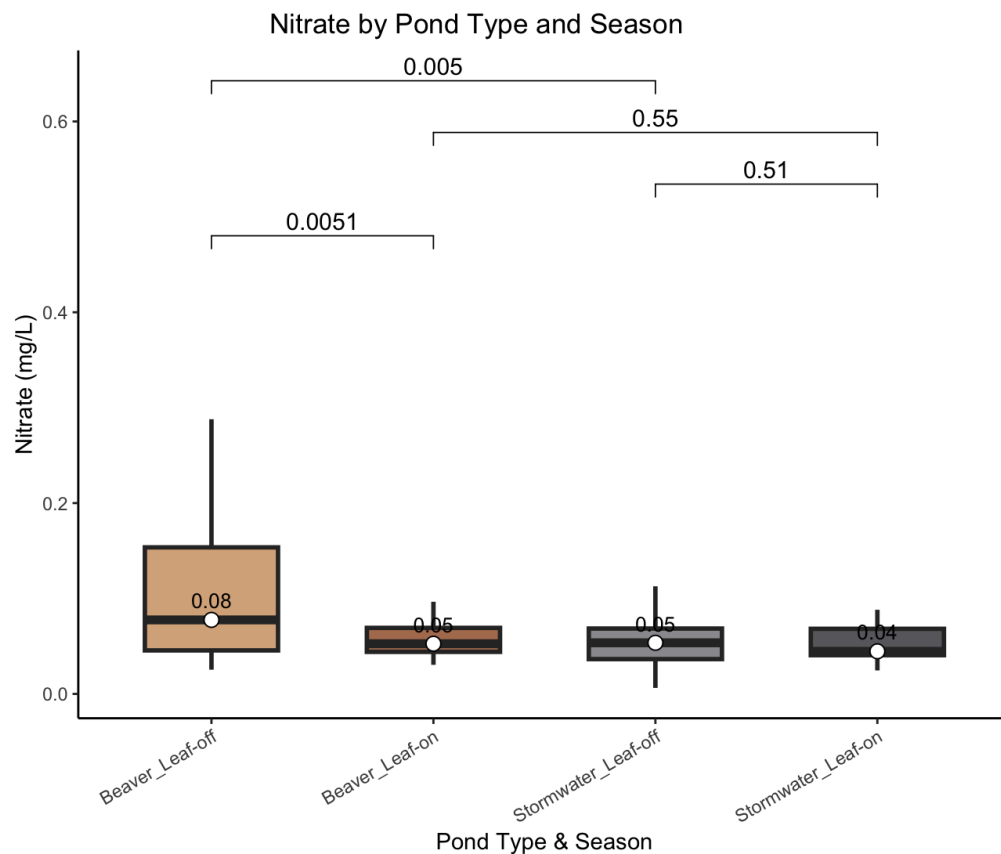


Figure 41: Nitrate concentrations between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall + winter) seasons

6.2 Algal Biomass and Algae Composition

6.2.1 Chlorophyll-a

Stormwater ponds had a statistically significant higher median chlorophyll-a concentration when compared to beaver ponds (Figure 42; t-test, $p=0.001$). Stormwater pond chlorophyll-a concentrations were $9.37 \mu\text{g/L}$ higher than beaver ponds. Median stormwater chlorophyll-a concentrations were $14.79 \mu\text{g/L}$ and ranged $0.79\text{-}159.72 \mu\text{g/L}$ over the entire study. Median beaver pond chlorophyll-a concentrations were $5.42 \mu\text{g/L}$ and ranged from $0.90\text{-}38.81 \mu\text{g/L}$.

Chlorophyll-a varied by site (Figure 43). Median chlorophyll-a across the 3 beaver ponds ranged from $3.17\text{-}7.90 \mu\text{g/L}$ where $\text{BD} > \text{MC5} > \text{PAW}$. Median chlorophyll-a across the 3 stormwater ponds ranged from $5.80\text{-}24.99 \mu\text{g/L}$ where $\text{BSW} > \text{BC} > \text{CBP}$.

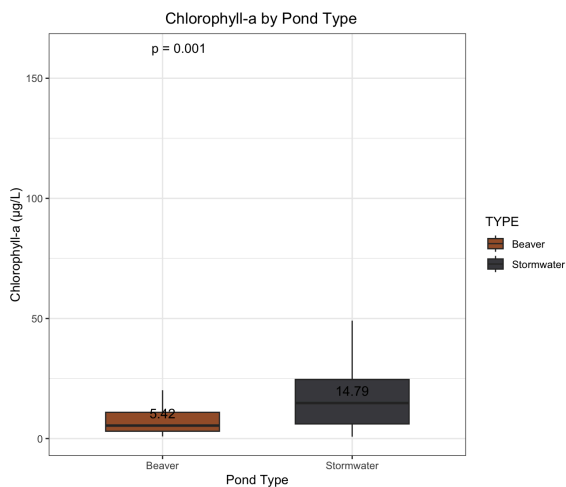


Figure 42: Chlorophyll-a ($\mu\text{g/L}$) in beaver and stormwater ponds across the whole study

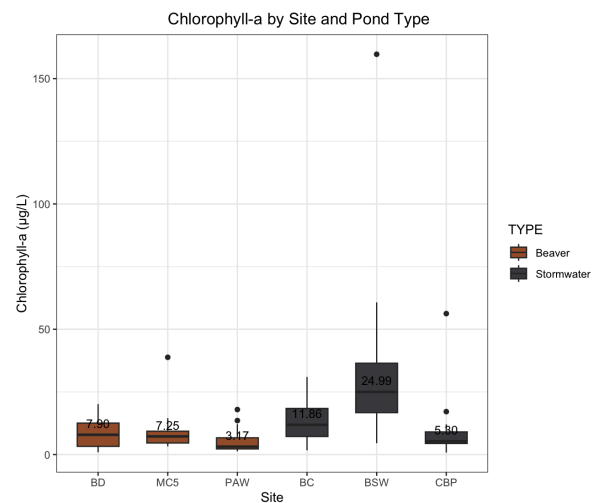


Figure 43: Chlorophyll-a ($\mu\text{g/L}$) across the entire study for each pond

Stormwater ponds had higher chlorophyll-a levels throughout the time series when compared to beaver ponds (Figure 44). Chlorophyll-a concentration varied over the sampling period in both stormwater and beaver ponds with greater variability at stormwater pond sites than beaver ponds (Figure 45). In all ponds chlorophyll-a concentration was highest during spring and summer months. BSW had the highest chlorophyll-a concentrations throughout the study period.

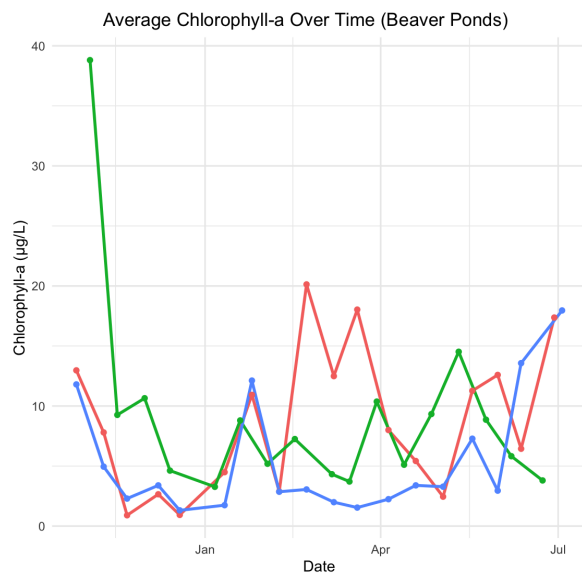


Figure 44: Time series of daily average chlorophyll-a ($\mu\text{g/L}$) at three beaver pond sites (BD, MC5, and PAW) from October 2022 to July 2023

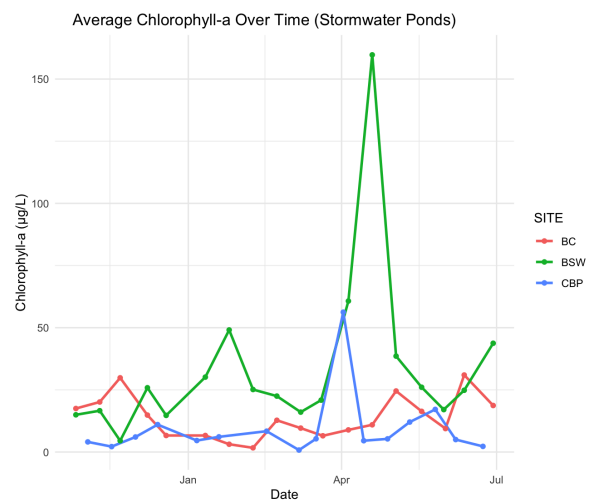


Figure 45: Time series of daily average chlorophyll-a ($\mu\text{g/L}$) at three stormwater pond sites (BC, BSW, CBP) from October 2022 to July 2023

6.2.2 Chlorophyll-a Leaf-on vs. Leaf-off

Chlorophyll a in the beaver ponds was $3.58 \mu\text{g/L}$ higher during leaf-on compared to leaf-off; however, this difference was not statistically significant (Figure 45; t-test, $p=0.31$). Median beaver pond chlorophyll-a concentrations during the leaf-off period were $4.49 \mu\text{g/L}$ and ranged from 0.90 - $38.81 \mu\text{g/L}$. Median beaver pond chlorophyll-a concentrations during the

leaf-on period were 8.07 $\mu\text{g/L}$ and ranged 2.45-17.96 $\mu\text{g/L}$. The difference in chlorophyll-a concentrations between the stormwater pond leaf-off and leaf-on periods were not statistically significant (Figure 46; t-test, $p=0.27$). The stormwater pond's leaf-on chlorophyll-a concentrations were 6.78 $\mu\text{g/L}$ higher than the leaf-off period. Median stormwater pond chlorophyll-a concentrations during the leaf-off period were 10.32 $\mu\text{g/L}$ and ranged from 0.79-60.72 $\mu\text{g/L}$. Median stormwater pond chlorophyll-a concentrations during the leaf-on period were 17.10 $\mu\text{g/L}$ and ranged 2.27-159.72 $\mu\text{g/L}$.

The difference between stormwater vs. beaver pond leaf-off period was statistically significant (Figure 46; t-test, $p=0.0048$). The stormwater leaf-off chlorophyll-a concentrations were 5.83 $\mu\text{g/L}$ higher than the beaver leaf-off period. The difference between stormwater vs. beaver pond leaf-on period was also statistically significant (Figure 45; t-test, $p=0.046$). The stormwater leaf-on chlorophyll-a concentrations were 9.03 $\mu\text{g/L}$ higher than the beaver pond leaf-on period.

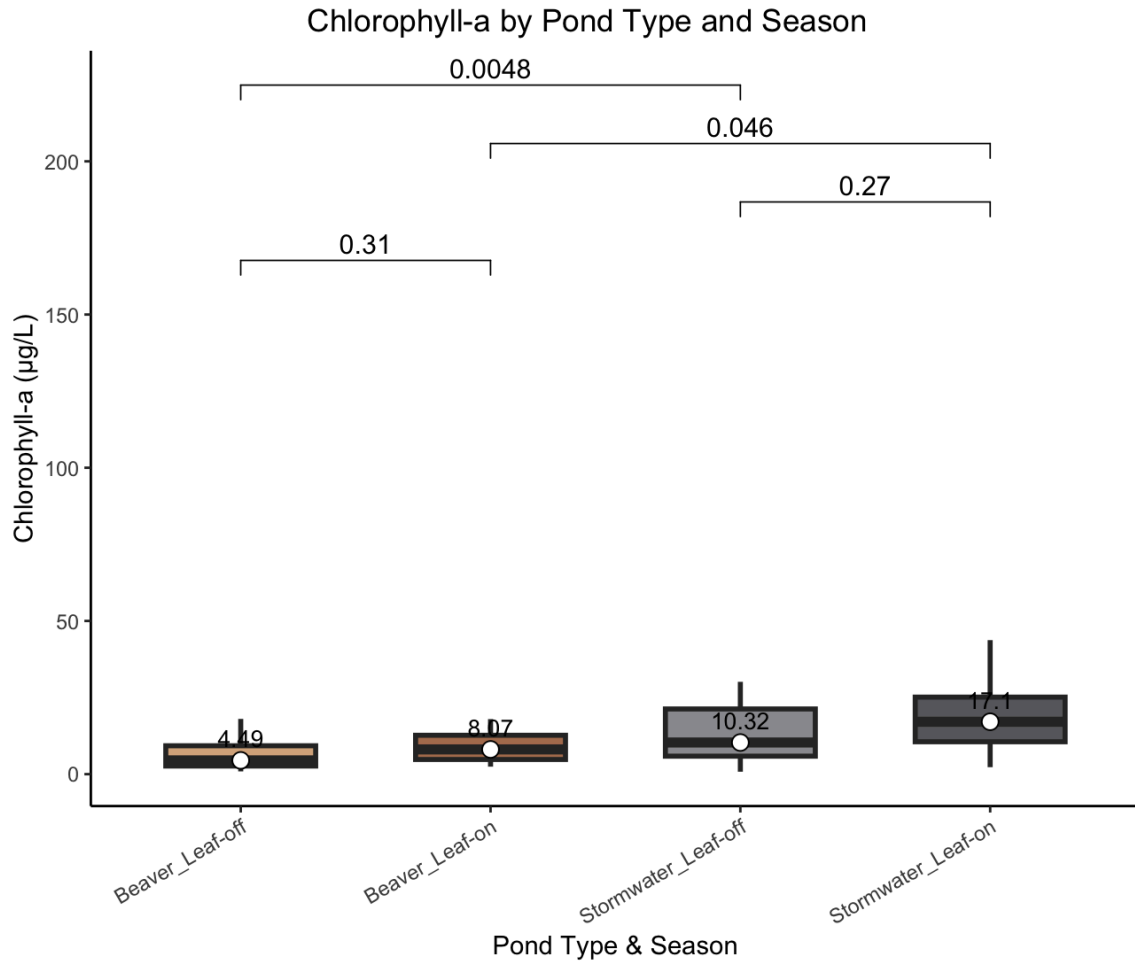


Figure 46: Chlorophyll-a concentrations between and across beaver and stormwater ponds during leaf-on (spring + summer) and leaf-off (fall + winter) seasons

6.2.3 Algae Composition and Relative Abundance

Figure 46 illustrates the relative abundance of green algae, desmids, diatoms, and blue-green algae in beaver and stormwater ponds throughout the study period. In both beaver and stormwater ponds, green algae appear to be the dominant algal group for the majority of the study period. Beaver ponds have nearly 100% relative abundance of green algae from May-July. Stormwater ponds also illustrate high relative abundance of green algae in the summer. Beaver ponds show a clear successional shift in green algae to diatoms between December 2022 and

March 2023. Diatoms during this period exceed 50% relative abundance and as the season progresses into April and May, Diatoms are replaced again by green algae. Stormwater ponds show a prolonged presence of diatoms. High relative abundance of diatoms from November 2022-February 2023. Green algae begin to dominate from May 2023-July 2023, which is also seen in beaver ponds, but happens more gradually in beaver ponds. Blue-green algae are more prevalent in stormwater ponds, particularly in June and July 2023. Desmids appear sporadically in both stormwater and beaver ponds.

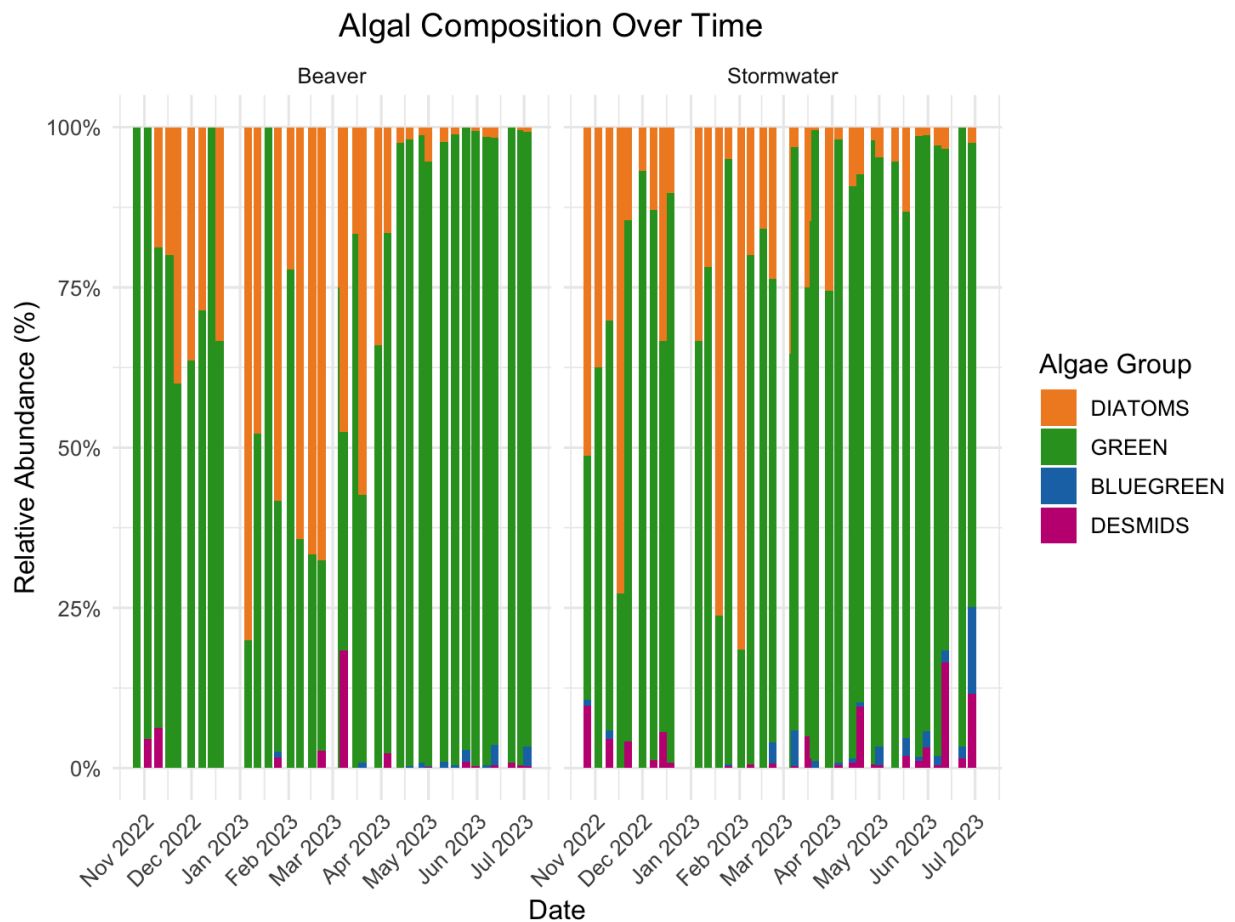


Figure 47: Relative abundance (%) of algal composition in beaver and stormwater ponds over time (October 2022–July 2023). Values represent site-averaged proportions for each sampling date

6.2.4 Mean Proportion of Monthly Blue-green Algae

There was a higher relative abundance of blue-green algae at stormwater ponds throughout the entire study period, except for January. The highest relative abundance of blue-green algae was observed in July at 8% at stormwater ponds. There is a high outlier of blue-green algae in October for stormwater ponds at 3% relative abundance. Beaver ponds see a gradual increase in blue-green relative abundance from January-July where beaver ponds have more sporadic relative abundances throughout the seasonal period (Figure 48).

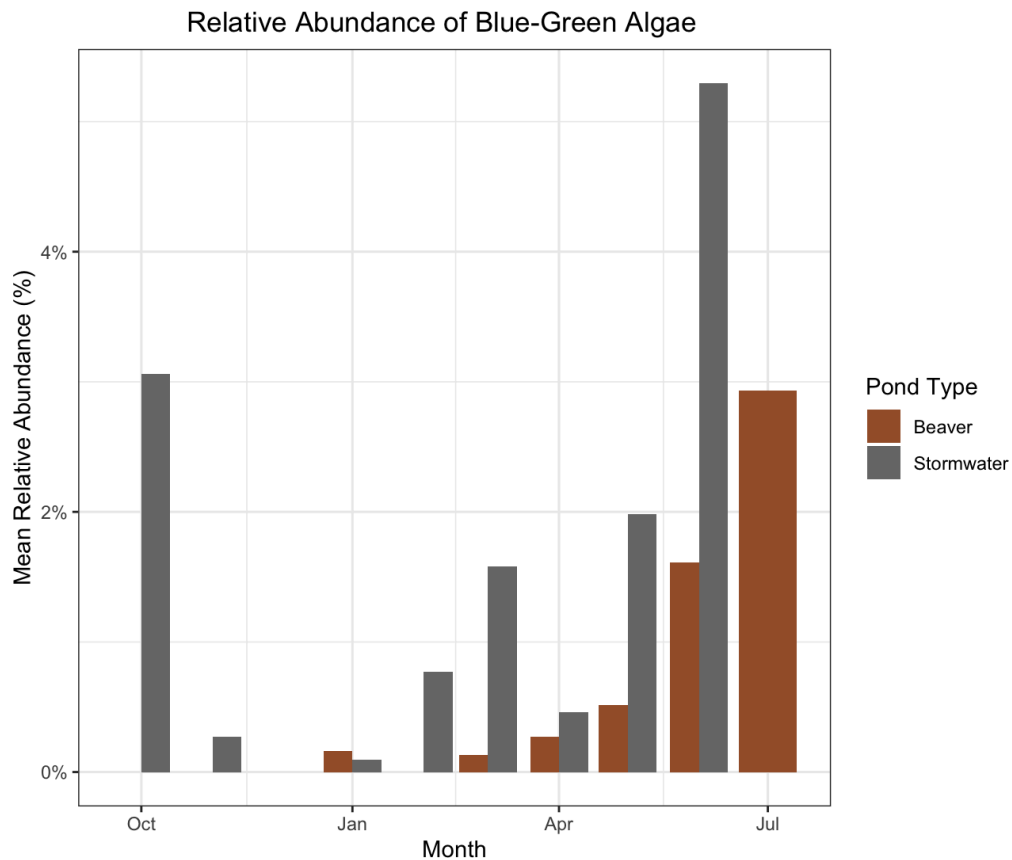


Figure 48: Mean relative abundance % of blue-green algae

7. DISCUSSION

The main objective of this study was to evaluate the differences in algal biomass and composition in natural beaver ponds and engineered stormwater ponds. While both systems are designed to retain water and manage surface runoff, they vary greatly in algal biomass and composition.

Algal Biomass and Pond Type

Stormwater ponds are generally warmer than beaver ponds, with a median average of 16.2 °C compared to beaver ponds with a median average of 14.0 °C. Stormwater ponds do not have a large amount of canopy cover around the ponds compared to the remnant riparian vegetation found around the beaver ponds examined in this study as evidenced by the comparing the canopy cover in the aerial photos taken from Google Earth (Figures 1 and 2). Wet detention ponds most likely have little canopy coverage due to the design requirements for wet ponds in North Carolina specifically stating that trees and woody shrubs shall not be allowed (North Carolina Department of Environmental Quality, 2017). Having less sunlight reach the water can be beneficial due to the fact that more sunlight would cause higher temperatures in the water and cyanobacteria have a specific temperature range (20-25°C) for maximum growth (Carruthers, 2021). Stormwater ponds reach higher maximum temperatures and this higher thermal baseline could accelerate metabolic rates, supporting higher algal biomass. Higher temperatures don't just affect the algae; they affect the chemistry of the water. A study showed that elevated water surface temperatures increase the release of nitrogen and phosphorus from the sediment. This increased internal loading provides more nutrients for phytoplankton growth (Mei et al., 2022).

Unexpectedly, stormwater ponds had a statistically significant higher median of DO when compared with beaver ponds, since stormwater ponds had higher overall water surface

temperature and water holds less oxygen as it warms. Our data matches up with other studies that have shown that DO concentrations are much lower in beaver ponds when compared with non-beaver ponds (Vehkaoja et al., 2015). However, the stormwater DO data is much more stretched with massive outliers reaching up to 24 mg/L. The observed outliers of high DO concentration can be indicative of photosynthetic supersaturation driven by high algal density. Algae could possibly be adding a large amount of oxygen into the water during daylight hours. According to Hanson et al., (2003), TP was an important driver of metabolism in lakes. In this study, the extreme DO peaks in stormwater ponds suggests that high phosphorus loading from impervious runoff has caused these stormwater systems to be in a state of high gross primary production.

There were no significant differences in conductivity among the ponds, potentially due to all sites having an urban influence.

Interestingly, there were no significant differences in TSS as I expected TSS to be higher in stormwater ponds due to the increased algal biomass. Pond type did not have a significant impact on the concentration of TSS across the study period. Since TSS is the same in both systems, we can rule out light limitation as a reason for variances in algal biomass.

Stormwater ponds had a statistically significant higher median TP when compared to beaver ponds. The stormwater ponds had a median TP of 0.22 mg/L. This data is very similar to a study where 800 lakes were sampled and were mostly eutrophic and had a mean TP of 0.26 mg/L (Søndergaard et al., 2005). These high levels of TP help explain the extreme DO spikes seen earlier due to the phosphorus helping sustain high algal biomass. A study recorded mean TP levels before and after dam removal. Mean total phosphorus concentrations were 51.0 µg/l and 64.5 µg/l before dam removal and increased to 70.4 µg/l to 170.5 µg/l after dam removal. These

results illustrate that beaver ponds can significantly reduce streamwater phosphorus concentrations (Muskopf, 2007).

Nitrate was higher in beaver ponds compared to stormwater ponds. Beaver pond complexes help slow the flow of stream water, which can increase the amount of nitrate retained (Saunders and Kalff, 2001). These higher levels of nitrate in beaver ponds are not always a negative impact to surface water quality since beaver ponds have high denitrification rates where nitrate transformation results in the formation of nitrogen gas (Lazar et al., 2015).

Stormwater ponds have higher median chlorophyll-a concentration and a much larger range.

Seasonal Variation and Composition

Both pond types had statistically significant differences between leaf-on and leaf-off periods and illustrate as expected, seasonal conditions strongly influence surface water temperature. Both systems show a significant jump in water surface temperatures between leaf-off (winter) and leaf-on (spring/summer). Beaver ponds jump from 9.1 °C to 20.6 °C , while stormwater ponds jump from 12.7 °C to 23.5 °C. Surface water temperature is overall higher at both pond types during the leaf-on period due to increased incident solar radiation, which occurs during the summer. The pattern of stormwater ponds being warmer than beaver ponds holds across seasons where stormwater ponds are warmer than beaver ponds in both the winter and summer periods. During the leaf-on period (summer), stormwater ponds have a higher median surface water temperature of 2.5 °C compared to beaver ponds and beaver ponds stay significantly cooler during the summer than stormwater ponds. The beaver ponds seem to buffer surface water temperature changes, while stormwater ponds have more erratic temperatures. Stormwater ponds could be warmer because they are surrounded by more impervious coverage

(and less tree coverage) than the beaver pond sites; runoff from heated parking lots during summer storms can cause an increase in warmer water going into receiving water bodies (Hester and Bauman, 2013). Beaver ponds could also be cooler possibly due to having an increased interaction with cool groundwater. Dam building can increase water storage and reduce stream temperatures (Dittbrenner et al., 2022). Stormwater ponds might be warmer because they are often shallow. In the Charlotte-Mecklenberg region stormwater ponds are built to store and not infiltrate water so they do not interact with the groundwater system. The stormwater ponds elevated algal biomass during the leaf-on (spring/summer) period is likely a result of higher maximum water surface temperatures. As noted by Carruthers (2021), cyanobacteria have a specific temperature range (20-25°C) for maximum growth.

In the leaf-on (spring/summer) period, DO levels drop significantly in both systems. Beaver ponds drop from a healthy 6.34 mg/L to hypoxic 3.07 mg/L. DO was lowest in October-November at 1-3 mg/L and in June-July 2-5 mg/L for beaver ponds. Low dissolved oxygen concentrations could cause some implications to freshwater fish because they may begin to experience oxidative stress at DO concentrations <7 mg/L and severe harm below 5 mg/L (Davis, 1975). This drop in DO occurs exactly when green algae reach 100% relative abundance. This could be due to beaver ponds having high organic matter, from beaver activity, which consumes oxygen through decomposition faster than the algae can produce it, leading to low DO concentration in the summer.

Both pond types show higher conductivity during the leaf-off (winter), likely due to road salt runoff. There was a sharp drop in the leaf-off (spring/summer) period due to precipitation patterns possibly diluting the water. The high conductivity in stormwater ponds suggests a steady supply of ions and nutrients, creating a nutrient-rich environment that supports higher algal

biomass. The only statistically significant difference was in conductivity between beaver pond's leaf-off and leaf-on periods which were statistically significantly different. The beaver pond's leaf-on conductivity was 35.8 $\mu\text{S}/\text{cm}$ higher than the leaf-off period.

Both pond types maintained similar median TSS concentrations regardless of season. This indicates that both pond types are receiving similar sediment loads.

There were no seasonal differences in TP concentrations within pond type; however there was a statistically significant difference between beaver pond vs. stormwater pond during leaf-on and leaf-off periods. TP increases in the leaf-on (spring/summer) period in beaver ponds, while decreasing in stormwater ponds. Seasonality within pond type was not statistically significant, suggesting that seasonal variation did not have a significant difference of TP concentrations within each pond type. Thirty-one stormwater ponds sampled from October-December, in southeast England had TP concentrations that displayed no overall seasonal pattern in concentration (Bennion and Smith, 2000).

Nitrate levels drop significantly during the leaf-on (spring/summer) period in both systems. When looking at the nitrate leaf-on vs. leaf-off data, there is a much steeper drop in nitrate in the beaver ponds in the summer months. Nitrate concentration was highest during October-February for beaver ponds and nitrate decreased from February onward. A study showed that there was an increased retention of nitrate in the winter and summer of a beaver pond (Correll et al., 2000).

Chlorophyll-a spikes during the leaf-on (spring/summer) period. This correlates with the nitrate drawdown we see. The algae are consuming the nitrate, but the stormwater ponds are more efficient at turning nutrients into biomass because they have lower TSS. Both systems

show a rise in chlorophyll-a from winter to spring. This spike in chlorophyll-a aligns with the algal composition data showing the transition from diatoms to green algae.

Outliers

Site BC (stormwater) was a major outlier throughout the study. It had the lowest median DO concentration at 2.67 mg/L and the highest median temperature at 16.6 °C compared to the other stormwater sites.

Site CBP (stormwater) had the highest median DO at 11.27 mg/L and the most extreme oxygen spikes in the time series. This could be indicative of high algal productivity. This could be due to this pond having a fountain in the middle, which can increase dissolved oxygen levels in a pond by propelling water into the air, which enhances surface turbulence, breaks surface tension, and improves gas exchange with the atmosphere. This might be why stormwater ponds had a higher average overall, due to that outlier. This site also showed consistently high nitrate and TP spikes, supporting its status as the most productive algal site in this study. This is further supported with having the highest chlorophyll-a levels.

While TSS averages were the same, there were some outliers within the data. Site PAW (beaver) had a sharp and large spike of TSS in early spring at 75.450 mg/L. Site CBP (stormwater) had a sharp spike in the early summer at 59.600 mg/L. Even though the median TSS concentrations were identical, both systems seem to have event-based spikes. These are likely driven by location-based events, such a storm event combined with CBP's 50% impervious coverage or a dam breakage at PAW.

Algal composition overview

Chlorophyll-a

Stormwater ponds had a statistically significant higher median chlorophyll-a concentration when compared to beaver ponds. Chlorophyll-a concentrations are important because they provide an idea of the eutrophication levels, which can be used to interpret water quality levels (Mahmoud et al, 2023). Lake characteristics during a toxic algal bloom included higher total phosphorus, decreased water transparency, high water column stability, high surface water temperature and pH, and decreased lake flushing (Jacoby et al., 2000). The study stormwater ponds also had higher temperatures and total phosphorus levels. Urban stormwater ponds are often eutrophic and have periods of harmful algal blooms.

Green algae

Green algae was present at both pond types throughout the study period. There was overall higher abundance at the stormwater pond sites. Green algae produce 50% of all oxygen production and are the main producer that aquatic life needs (Chapman, 2013). This might make sense why stormwater ponds had much higher dissolved oxygen concentrations due to having much more green algae abundance.

Desmids

When comparing desmid concentrations between stormwater ponds and beaver ponds, there are more desmids in beaver ponds. Desmids were more abundant in March-April for beaver ponds. Other studies also found that desmids usually begin their spring growth in March (Whitford, 1958). Desmids prefer shallow poorly aerated water with high concentrations of organic matter (Prescott, 1948). Beaver ponds had very low DO levels and usually contained a significant amount of organic matter, which matches up with that study.

Diatoms

Diatoms were most abundant in stormwater ponds from October- April. They were also most abundant during the same months for beaver ponds. Diatoms can be difficult to analyze when not analyzing at lower taxonomic levels. Since different species of diatoms prefer different ratios of nutrients. Oligotrophic diatoms prefer low concentrations of nitrates or ammonia, and phosphates. Diatoms that live in eutrophic conditions prefer high amounts of nitrates or ammonia, and phosphates (Werner, 1977).

Blue-green Algae

While blue-green algae (cyanobacteria) was overall a low relative abundance (0-8%), cyanobacteria emerged early seasonally in stormwater ponds. In contrast, the beaver ponds illustrate a delayed emergence of cyanobacteria. This suggests a higher degree of ecological resilience. When looking exclusively at blue green-algae, we see a large increase in the summer months for just stormwater ponds. Algal blooms usually happen when chlorophyll-a $> 40 \mu\text{g L}^{-1}$ (<https://uncw.edu/cms/aelab/>). The time series graph for both pond types (Figure 44, Figure 45) shows that stormwater ponds exceed this value during June-July. Cyanobacteria abundance depends on several factors including nutrients, light, turbulence, and temperature (Wehr et al, 2015). Lake characteristics during a toxic algal bloom included higher total phosphorus and high surface water temperature (Jacoby et al., 2000). This statement coincides with the fact that stormwater ponds had both higher overall total phosphorus and surface water temperatures when compared with beaver ponds.

Evaluation of Eutrophication

The trophic level index and trophic state index have been widely recognized for the evaluation of eutrophication of lakes and reservoirs (Zhang et al., 2021). The trophic state index for lakes and the index number can be calculated from parameters such as chlorophyll and total

phosphorus. The formula for Total Phosphorus is: $TSI = 14.42 \ln (TP) + 4.15$. The formula only works for units in $\mu\text{g/L}$, so I had to convert mg/L to $\mu\text{g/L}$ before calculating. Stormwater ponds had a median TP TSI of 82, which is considered hypereutrophic. Beaver ponds had a median TP TSI of 73, which is considered upper eutrophic. The formula for chlorophyll-a is: $TSI = 9.81 \ln (\text{Chl-a}) + 30.6$. Stormwater ponds had a median chlorophyll-a TSI of 57, which is considered eutrophic. Beaver ponds had a median chlorophyll-a TSI of 47, which is considered upper mesotrophic (Carlson, 1977). Beaver ponds TP TSI had eutrophic conditions, while chlorophyll-a TSI had mesotrophic conditions. This contradiction between nutrient availability and algal biomass suggests that primary production may be limited by other factors than just phosphorus availability.

Area-to-impervious Ratio

The southeast is becoming increasingly urbanized, which is increasing impervious coverage and in response more stormwater ponds are being constructed (Cotti-Rausch et al., 2019). The increase in impervious coverage is transporting excess nutrients such as nitrogen and phosphorus to surface waters, which help cause harmful algal blooms (Conley et al., 2009). The impervious coverage mean percentage was obtained using ArcGISPro using the “Zonal Statistics Table” tool. The mean impervious coverage (%) varied greatly across all pond sites. Stormwater pond CBP has a mean impervious coverage of 50.37%. Stormwater pond BSW has a mean impervious coverage of 39.83%. Stormwater pond BC has a mean impervious cover of 32.92%. Beaver pond PAW has a mean impervious coverage of 27.5%. Beaver pond MC5 has a mean impervious coverage of 12.29%. Beaver pond BD has a mean impervious coverage of 11.11%. Stormwater ponds had an overall average of 41.04% and beaver ponds had an overall average of

16.97%. Stormwater ponds had a higher overall mean impervious coverage (%) when compared to beaver ponds.

BC has a large watershed area of 36.99 sq km, which is significantly larger than any other site. Even though BC has the largest watershed, it has the lowest conductivity concentrations. This might suggest a dilution effect because the watershed is so large that the volume of water moving through the system may be so high that it dilutes the ions and pollutants, resulting in low conductivity despite its 32% impervious coverage. CBP has the highest impervious coverage at 50.37%, but the smallest watershed at 0.23 sq km. In our previous look at graphs, CBP was the high conductivity and high chlorophyll-a outlier. This is a concentration effect because the watershed is so small with over half of it paved, so there is very little non-contaminated surface flow or groundwater to dilute this runoff. PAW has the highest impervious coverage (27.5%) compared to the other beaver pond sites that ranged from 11.11-12.29%. PAW was also the beaver pond with the highest TSS and TP spikes. PAW is under the most urban stress compared to all the beaver sites. Its high TSS spikes could be a combination of its large watershed area (22.74 sq km) and that over a quarter of that area is impervious, which could lead to more erosive runoff.

Stormwater Pond Age

It is important to note the age of the stormwater pond sites because a study done by Sønderup et al. (2016) found that stormwater ponds lose almost all of their nutrient reduction capabilities after 5-10 years. The nutrient capture function can decrease over time due to high amounts of sediment from urban runoff causing a reduction in water storage volume, which decreases retention time (Shukla et al., 2017). At the time of this study, pond site CBP was established 13 years and 10 months ago, BSW was established 16 years and 2 months ago, and

BC was established 5 years and 4 months ago. This shows us that these stormwater pond sites may have lost a lot of their nutrient capture functions over time.

Management Implications

As urban areas expand, more human-beaver conflicts have started to occur, which causes people to dislike beavers. More information is needed before taking action on these conflicts. Beavers are considered a pest in the State of North Carolina, which means they are allowed to be euthanized and have their dams destroyed. Beavers are often removed due to causing trees to fall, flooding areas, which causes human conflicts, especially in urban areas. These removals have been exacerbated as urban growth starts to move into the natural environment and beavers expand their current range. Another issue with most environmental management is the cost of restoration projects. To help save money, the use of the Economic production function theory (Heaney et al., 1976; Nix et al., 1983; and Behera et al., 1999) is used to find the most cost efficient solutions based on estimating the benefits of outputs and costs of the inputs.

Constructed detention ponds can sometimes be located on valuable land and involve initial construction and maintenance costs (Behera and Teegavarapu, 2015). The U.S is funding only one third of its water infrastructure requirements and would need to invest \$123 billion per year for ten years to have current systems at good standing. As of now there is an \$82 billion per year national water infrastructure gap, which is expected to keep rising in the future (Value of Water Campaign, 2017).

Conclusion

Stormwater ponds, especially site CBP, support significantly higher algal biomass. Since, TSS is the same in both systems, I can rule out light limitation as a reason for the different algal biomasses. If both pond types have the same TSS concentrations, but stormwater ponds

have higher chlorophyll-a, then the difference must be driven by nutrients or hydrology. Since TSS concentrations were the same and we saw a sharper drop in nitrate in beaver ponds than in stormwater ponds, denitrification is a likely driver. Beaver ponds had much lower algal biomass, so the only component that could be removing this extra nitrogen in the beaver ponds is a microbial process like denitrification. The driver of high algal biomass is likely a combination of high impervious coverage and chronic phosphorus loading in stormwater systems that creates the perfect environment for algal growth. While wet detention ponds, like the ones in this study, are no longer built for stormwater water management in the Charlotte-Mecklenburg region (only dry detention ponds are currently being constructed), there are legacy ponds that will require management for the algal issues I have quantified in these 3 ponds. Retrofitting ponds to function more like beaver ponds may be one solution. Where beavers are expanding into urban areas, allowing beavers to remain and build beaver complexes could be an inexpensive solution for treating urban runoff.

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