Water Quality in a Suburban Stormwater Pond: A Continuous Monitoring Study

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by

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LIST OF ABBREVIATIONS

Dissolved oxygen .... DO
Specific conductance .... SPC
Photosynthetically active radiation .... PAR
Daily average air temperature .... DAAT
Einsteins .... E
Potomac Science Center .... PSC
Harmful Algal Bloom .... HAB

ABSTRACT

WATER QUALITY IN A SUBURBAN STORMWATER POND: A CONTINUOUS MONITORING STUDY

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Stormwater ponds are often assumed to be well-mixed reactors. To better understand the water quality of stormwater ponds, the seasonal and diel water quality patterns of the Potomac Science Center stormwater pond were discerned using weekly depth profiles, continuous monitors, light profiles, and local weather stations from July through October of 2020. Water samples were also collected for analysis of total suspended solids, *in situ* chlorophyll *a*, and phytoplankton taxa. Results indicated the pond experienced summer stratification driven by air temperature and solar radiation. For the period July 24 through August 29, biological processes drove the water quality of the pond's 10-day stable periods, which were disrupted by three mixing events. No surface HABs were observed, but the lower layers of the pond experienced hypoxia and a HAB. Ultimately, the pond performs its intended function: to allow the settling of organic matter to the bottom layers so the surface waters maintain good water quality.

INTRODUCTION

Over the past several decades, federal, state, and local agencies have implemented new technologies to reduce the impacts of flooding, to combat erosion, and to trap pollutants. Stormwater ponds were originally developed during the 1970s to manage localized flooding due to heavy rainfall by retaining excess water. At its most basic level, stormwater refers to water resulting from a precipitation event that either flows over ground surfaces or penetrates the ground before reaching a natural or artificial collection system (National Research Council 2008). Within the past few decades, scientists have noticed a degradation of downstream water sources that coincided with land development, leading them to consider the pathways between precipitation's initial contact with the ground and larger bodies of water (National Research Council 2008). Scientists began to consider the effects of different surface types on runoff water quality. For example, urbanization has caused an increase in impervious surfaces, such as roads, which add salts, organic chemicals, and metals to stormwater, while agriculture has also increased nutrient and chemical loads (Jones and Holmes 1985). Because stormwater ponds are now understood to be an integral part of runoff's journey to large bodies of water, their role in environmental management has shifted within the past two decades.

Currently, federal, state, and local agencies expect stormwater ponds to address nonpoint source (NPS) pollution by removing pollutants, such as metals, bacteria, and nutrients, from runoff before draining into downstream water bodies (Drescher et al. 2011). As coastal areas have developed and concerns regarding NPS pollution have increased, the number of stormwater ponds being constructed has significantly increased in the U.S., indicating a preference for stormwater ponds as the primary method of stormwater management (U.S. Environmental Protection Agency 2009). Fairfax County, which is adjacent to Prince William County, now contains at least 2,162 stormwater ponds, of which about half are privately owned (County of Fairfax, Virginia 2017). However, stormwater ponds are not considered state waters under the Clean Water Act and therefore are not subject to regulations or consistent monitoring, making stormwater ponds a "grey" area in scientific literature (U.S. Environmental Protection Agency 2015). Stormwater ponds are expected to filter pollutants, but few studies have considered the effectiveness of the ponds and their ultimate impact not only on downstream water quality and wildlife but also on humans. While stormwater ponds are not intended to be recreational, they are, in fact, often used for recreational purposes, such as fishing or boating, and are marketed as amenities, frequently renamed "lagoons" or even "lakes", in residential communities (Drescher et al. 2011). In recent decades, harmful algal blooms (HABs) have increased in frequency and threaten human health in addition to ecosystems. Stormwater ponds have been shown to experience eutrophication, or the input of excessive nutrients, which allows HABs to flourish, and are often overlooked in scientific studies as they are assumed to be well-mixed and effective pollutant removers. However, a few studies have recently challenged these assumptions, asserting the importance of studying stormwater ponds for both ecosystem health and human health (Drescher et al. 2011, Lewitus et al. 2008, Olding 2000, Serrano and DeLorezo 2008).

Overview of stormwater ponds

There are two types of engineered stormwater ponds: wet and dry (Comings et al. 2000). Wet ponds, also called "retention ponds", maintain a pool of water all year long but can experience large changes in water level immediately after rainfall. They filter entering water through the slow settlement of sediment and through nutrient uptake by plants (Chiandet and Xenopolous 2016). In contrast, dry ponds, also called "detention ponds", look like grassy areas until rainfall occurs. They allow sediment and pollutants to settle by containing the runoff for a short time period, ranging from a few hours to a few days before releasing it (Hogan and Walbridge 2007). Both types of stormwater ponds are intended to filter pollutants and improve downstream water quality. As the Potomac Science Center stormwater pond is a wet pond, the literature reviewed here focuses on retention ponds.

Much of the literature concerning wet ponds investigates the engineering and hydraulics involved to ensure that the water in the pond remains at an optimal level – not too low and not too high (Beckingham et al. 2019, Hogan and Walbridge 2007, Tondera et al. 2018, Watt and Maršálek 1994). Tondera et al. (2018) emphasize the difficulty of managing stormwater due to flow variability. Stormwater ponds can be designed to deal with this variability, but most ponds are designed to manage a specific range of stormwater flows while also handling peak flow for short, often rare, periods through forebays and emergency spillways (Tondera et al. 2018). In temperate climates, stormwater ponds can experience peak flow events in the spring when snow melts and rainfall increases. Ponds may also be subject to high flows as a result of summer thunderstorms. These events can cause a wet pond to overflow into adjacent areas or to act as a flow-through system. When a wet pond overflows, it fails to retain sediments, nutrients, and pollutants, allowing them to enter downstream waters and to degrade water quality. Most wet ponds now include emergency spillways that drain water once it reaches the spillway level so that overflow into adjacent areas is minimal (if the pond is built properly). Still, climate change should be considered in future stormwater pond research for, as extreme weather events become more common, stormwater pond engineers will need to develop designs that effectively manage peak flow events.

Recent investigations into the morphometry, or shape, of stormwater ponds have already led to the renovation of several ponds, usually by adding sediment forebays or by resizing the ponds (Chiandet and Xenopolous 2016). Sediment forebays are small, shallow pools placed upstream of stormwater ponds to help trap sediment and filter pollutants by capturing the runoff first; they can be integrated with the pond or completely separated. While separate forebays are the best way to increase residence time for runoff and to allow settling of sediments, integrated forebays have also been proven to reduce total phosphorus in stormwater ponds just as effectively and are cheaper to build (Chiandet and Xenopolous 2016). Sediment forebays also allow easy access for sediment removal, decreasing the frequency of the main pond's necessary maintenance. Regarding pond size, deep ponds with large surface areas exhibit better water quality; additionally, sinuous shorelines allow vegetation to thrive; the vegetation then traps sediment, ultimately acting as a nutrient and pollutant buffer (Chinadet and Xenopolous 2016).

Water quality in stormwater ponds

Because of the shift to the use of stormwater ponds to manage pollutants, recent studies have measured and identified pollutants in wet ponds to determine their efficiency as pollutant mitigators (DeLorenzo et al. 2011, Drescher et al. 2012, Serrano and DeLorenzo 2007, Vincent and Kirkwood 2014). If sediment forebays were present, they were often sampled as well to compare the effectiveness of the forebay and the system as a whole. Until recently, only ponds that were suspected to have water quality issues were studied and the ultimate impacts of wet ponds on estuaries is still unknown (Drescher et al. 2011). Over time, scientists have developed guidelines for water quality parameters: greater than 4 mg/L of dissolved oxygen (DO), less than 20 ug/L of chlorophyll *a*, less than 0.95 mg/L of total nitrogen, less than 0.09 mg/L of total phosphorus, less than 30 mg/L of total suspended solids, and less than 43 units/100 mL of fecal coliform bacteria (Drescher et al. 2011). Across all of the studies (DeLorenzo et al. 2011, Drescher et al. 2012, Serrano and DeLorenzo 2007, Vincent and Kirkwood 2014), water temperature, DO, salinity, and specific conductance were measured with instruments, such as YSI meters or sondes, while water samples were taken to determine chlorophyll *a* levels, nutrient levels, bacteria taxa, and algae taxa in the lab. Water sampling locations, depths, and frequency varied across the studies. Secchi disks and light meters were also used to determine turbidity and photosynthetically active radiation (PAR). Finally, weather data was collected from local weather stations to record air temperature and rainfall. Studies were conducted during the summer months, generally from May through October, when thermal stratification and algal blooms are likely to occur. The methods were generally consistent in the literature reviewed, but sample sizes, land types, and locations varied widely.

There is an increasing amount of evidence that stormwater ponds are often not effective at managing nutrients and pollutants (Beckingham et al. 2019, Chiandet and Xenopolous 2016, DeLorenzo et al. 2012, Drescher et al. 2011, Lewitus et al. 2008, Serrano and DeLorenzo 2008, Vincent and Kirkwood 2014). They can exhibit poor water quality and discharge this water into estuaries, possibly degrading the ecosystem. Estuaries serve as nurseries for fish, and the ultimate effects of pollution from wet ponds on these fish are currently unknown. Several scientists emphasize the importance of studying wet pond water quality and call for more research to fully understand the drivers of poor water quality. Furthermore, as more nutrients enter wet ponds, they become optimal environments for algal blooms to flourish. For example, Drescher et al. (2011) sampled 112 ponds more than 10 years old along the South Carolina coast from May to October. None of the ponds contained sediment forebays. Several land-use types, drainage area sizes, and pond sizes were included, and water samples were collected at a depth of 1 ft near the stormwater inlets. When the pond exhibited algal bloom conditions, determined either visually or by DO levels, more water samples were taken to identify and quantify the algae. Most ponds displayed a lack of mixing due to thermal stratification and contained high fecal coliform bacteria counts following rain events. 10% of ponds surveyed were hypoxic throughout the water column and 35% were considered eutrophic. 22% were considered hypereutrophic with hypoxic bottom waters; of the hypereutrophic ponds, 84% contained algal blooms and 18% contained at least one toxin-producing bloom (Drescher et al. 2011). Interestingly, dissolved nutrient levels measured in the ponds were low; however, high chlorophyll levels suggested that dissolved nutrients were quickly consumed by the algae. Ultimately, over half of the ponds surveyed along the South Carolina coast were characterized as having poor water quality (Drescher et al. 2011).

To determine the potential damaging effects of a wet pond on its adjacent estuary, Serrano and DeLorenzo (2008) investigated the water quality of a residential stormwater pond that drains directly into an estuary in South Carolina. The drainage area included houses, driveways, roads, and vehicles. Water samples were collected for two years, every ten days from May to October and once per month from November to April, from two locations in the pond: the inflow and outflow areas. Water samples were also simultaneously collected 50 m downstream in the estuary (Serrano and DeLorenzo 2008). The pond was eutrophic all year long with prevalent cyanobacterial blooms during the summer; high levels of nitrogen and phosphorus were also recorded in the estuary during the summer. The cyanobacterial toxin, microcystin, and fecal coliform bacteria levels exceeded health and safety standards while pesticide levels were high during the spring and summer (Serrano and DeLorenzo 2008). The poor water quality was attributed to the use of fertilizers and pesticides by homeowners as well as poor pet waste management. While the estuary received runoff from several sources, the pond's water quality was concerning for the health of the estuary as it continuously discharged water during the two-year study period (Serrano and Delorenzo 2008).

Several studies have shown an increase in eutrophic conditions in stormwater ponds, which has led to an investigation into the prevalence of algal blooms and the threats they pose to the environment and human health. Lewitus et al. (2008) argue that wet detention ponds that exhibit eutrophic conditions are "hot spots" for harmful algal blooms (HABs). They analyzed four years of water quality monitoring and fish kill data from the South Carolina Algal Ecology Laboratory to identify and quantify algal blooms; 1502 pond sites were sampled from both brackish and freshwater wet ponds (Lewitus et al. 2008). The ponds experienced over 200 blooms with 23 different species of algae; raphidophyte and dinoflagellate blooms dominated mid-brackish to marine ponds while cyanobacteria were dominant in low brackish ponds (Lewitus et al. 2008). The study was able to positively determine that these stormwater ponds were indeed local sources for HABs; the authors attributed the eutrophication and HAB prevalence to nutrient loadings from lawn maintenance, particularly that of golf courses. Moreover, pond structure was scrutinized as it affected the amount of nutrients entering the pond; for this study, the increase in nutrients in the ponds could also be attributed to stormwater entering the ponds directly underground through pipes rather than flowing over a forebay or a vegetative buffer. As they were frequented by pets and used for boating and swimming, the wet ponds also presented a threat to environmental and human health, either through biomagnification of toxins in the food web or direct exposure to HABs or coliforms (Lewitus et al. 2008).

Most algal studies of stormwater ponds focus specifically on HABs, and few studies have investigated entire algal communities of stormwater ponds as indicators of runoff pollutants and pond water quality. Algae can improve water quality through nutrient and pollutant uptake, effectively filtering runoff before it enters downstream communities. However, even non-toxic algae can negatively impact biological communities if too abundant as they can deplete oxygen and cause hypoxic conditions, especially in stratified ponds. Moreover, uptake by phytoplankton may reduce dissolved nutrients, but if the algae are washed downstream, the nutrients will still reach receiving waters. One of the few studies to investigate algal communities as water quality indicators was conducted by Olding (2000). He compared the algal communities of two wet ponds in Ontario, Canada during the summer of 1997 to assess the ponds' ability to protect downstream ecosystems. Harding Pond received runoff from a residential community while Rouge Pond received runoff from a highway. Incoming water initially entered the ponds through low vegetation sediment forebays, which were sampled in addition to the wet ponds to compare water quality and identify periphyton communities. Additionally, Olding (2000) determined the biovolumes and taxa of the phytoplankton and periphyton of the two ponds and forebays. Both ponds exhibited stratification, high productivity, and poor water quality as indicated by their algal communities. In Rouge Pond, pollution-tolerant algae thrived, and the bottom waters became anoxic during stratification. While Harding Pond also contained some algae that tolerated pollutants like heavy metals, its algal community was dominated by taxa that thrive in nutrient-rich conditions; Harding Pond also showed anoxic conditions due to stratification. The algal communities characterized the performance of the ponds. Although species richness was poor in the sediment forebays, the algal communities became more diverse in the wet ponds, revealing the ponds' functionality: they effectively decrease the levels of heavy metals and nutrients exiting the ponds. Cyanobacteria were not detected in either pond, meaning the ponds had little potential to produce HABs. This was surprising, especially in the highly eutrophic Harding Pond. Olding (2000) attributes Harding Pond's lack of HABs to the hydraulic design of the pond: the cyanobacteria cannot reside long enough in the pond to bloom due to frequent flushing. The virtual lack of cyanobacteria in these two ponds indicates that stormwater ponds can be designed to reduce HABs and ultimately protect downstream environments.

Most recent literature concerning stormwater ponds reveals the stratification of the water column, whether when studying pollutants, nutrients, or algal communities. Until recently, the U.S. EPA considered wet ponds "completely mixed reactors" and assumed wet ponds were well-mixed horizontally and vertically (U.S. Environmental Protection Agency 1983, U.S. Environmental Protection Agency 2009). Therefore, few studies have specifically investigated the stratification of urban and suburban wet ponds. In 2013, McEnroe et al. used a YSI sonde to monitor water quality parameters and collected samples from both the surface and bottom water of 45 shallow wet ponds in Ontario, Canada twice during the summer. Most of the ponds (62%) exhibited vertical differences in temperature and conductivity (McEnroe et al. 2013). The size of the pond has also been shown to affect stratification as a small surface area means wind action is less likely to mix the pond's water. The impervious surface areas surrounding the ponds could also contribute to water column stratification as runoff collects heat from the pavement before entering the pond. However, during rain events, urban ponds may indeed fit the definition of a "well-mixed reactor" due to physical turbulence flushing. The stratification of the water column in wet ponds appears to be mainly driven by temperature rather than nutrient chemistry, despite lower DO levels in the bottom of the water column (McEnroe et al. 2013).

Continuous monitoring of stormwater ponds

While several studies of stormwater ponds have collected data on water quality parameters, none have implemented continuous monitoring to determine diel patterns and water quality drivers. Jones and Graziano (2013) define continuous monitoring in the field of aquatic ecology as the collection of water quality data during short intervals over long periods of time. An instrument, typically a YSI sonde, is deployed in the water to measure DO, pH, temperature, and specific conductance repeatedly at short time intervals, such as every 15 minutes. Although no continuous monitoring studies of stormwater ponds appear to have been published, continuous monitoring studies of shallow lakes have been conducted. Like stormwater ponds, small lakes have been thought to be homogenously mixed until recently. Continuous monitoring of shallow lakes has revealed diel patterns in the water column during the summer. Shallow lakes have been shown to experience daytime stratification and nocturnal mixing. Additionally, the stratification pattern in one system was correlated with oxygen levels (Andersen et al. 2017). During the day, oxygen levels were elevated at the surface due to photosynthesis conducted by algae and low in the dark, anoxic bottom waters. Nocturnal vertical mixing then reintroduced oxygen from the surface to the bottom. pH and dissolved inorganic carbon (DIC) levels also revealed diel patterns; pH rose with photosynthesis at the surface while DIC decreased (Andersen et al. 2017). Recent continuous monitoring data now shows that shallow lakes experience diel patterns and anoxia of bottom waters, refuting the common perception of well-mixed lakes. The diel patterns have illustrated extreme variations in temperature and oxygen levels, suggesting the water quality conditions of small lakes can be stressful for freshwater species (Andersen et al. 2017).

Continuous monitoring has also been performed in the Potomac River (Graziano and Jones 2017, Jones and Graziano 2013). A comparison of two embayments revealed diel patterns for DO, pH, and water temperature at both sites; photosynthesis was determined to be the driver for DO and pH levels due to their correlation with PAR (Graziano and Jones 2017). Additionally, DO, pH, and temperature were all driven by solar cycles, not tides. However, tide action was responsible for the semi-diel pattern experienced by conductivity levels (Graziano and Jones 2017). High freshwater inflow events due to storms disrupted these patterns, lowering water temperature and conductivity levels; DO and pH diel patterns were able to reestablish within a few days in both embayments. Conversely, conductivity semi-diel patterns took much longer to reestablish; they recovered faster in one embayment due to controlled flows while the other embayment took weeks to recover (Graziano and Jones 2017).

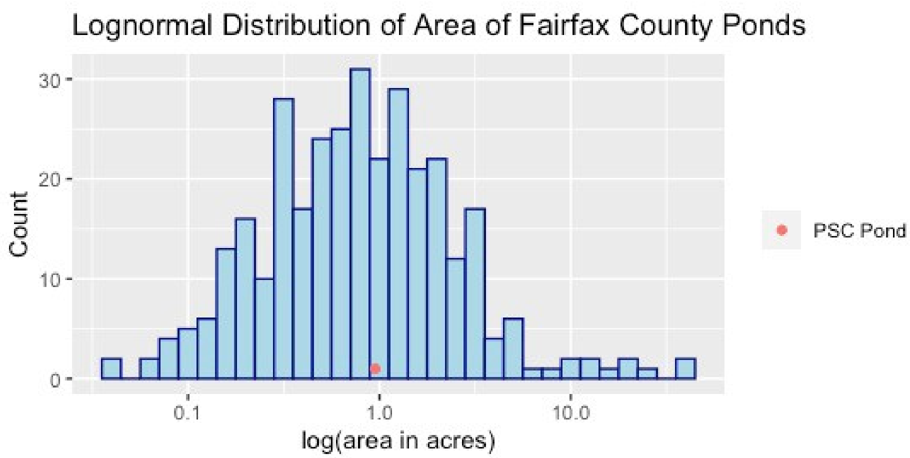
Ultimately, the scientific literature concerning stormwater ponds reveals a gap in continuous monitoring research. The goals of this study were (1) to observe the specific diel and seasonal patterns of the Potomac Science Center (PSC) stormwater pond, (2) to determine the forcing factors driving these patterns and thus the water quality of the pond, and (3) to define the algae taxa present in the pond as indicators of water quality. It was hypothesized that on an annual scale, changes in water quality could be attributed to seasonal changes in solar radiation and air temperature; water quality variables were expected to diverge between upper and lower depths due to summer stratification, also causing differences in algal taxa. On a short time scale, it was hypothesized that water quality variables would exhibit a diel pattern during stable periods due to diel solar radiation forcing. Disruption events, such as rainfall, were expected to cause sudden, short-term changes in water quality variables.

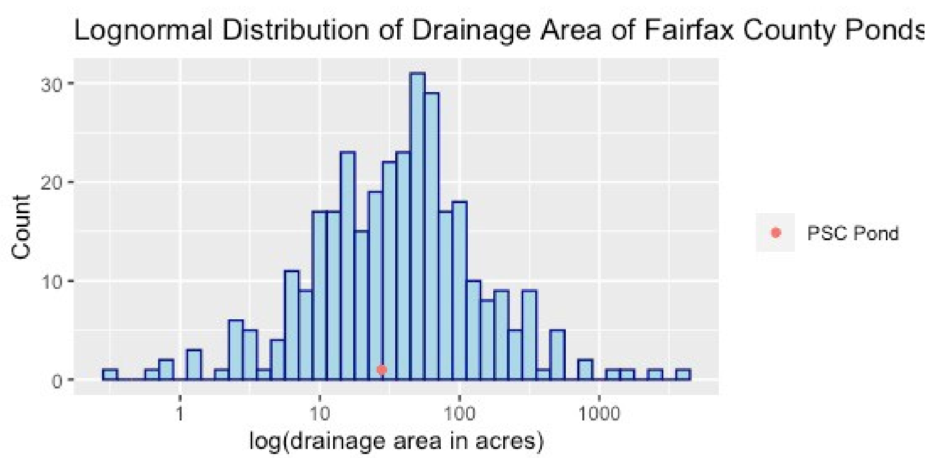
STUDY SITE

The stormwater pond studied is a wet retention pond adjacent to the Potomac Science Center, a teaching and research facility, in Woodbridge, VA. It is approximately 20 years old. The pond is part of a suburban residential community and owned by the developer, who has given permission to study the pond. A former golf course lies north of the pond and is continuing to be mowed even though it was abandoned in 2014. Fertilizers used on the golf course likely influenced the pond's water quality while the golf course was in use. The lasting effects of the nutrients entering the system is unknown. The Potomac Science Center, a 50,000 ft^2 research and education facility run by George Mason University, is located on the other side of the pond. The pond is considered a best management practice (BMP) by the Virginia Department of Environmental Quality to filter pollutants and nutrients from runoff before draining into the Occoquan River (Virginia Water Resources Research Center 2019).

The pond is a simple stormwater pond with no sediment forebay. The stormwater pond contains a drainage area of 129,711 m^2 (27.7 acres). Within that drainage area lie an elementary school with a parking lot as well as several townhouses. Roads between the school, the townhouses, and the Potomac Science Center also lie within the drainage area. The area of the pond is 3,856 m^2 (0.95 acre) and the volume of the pond is 6,512.87 m^3 (5.28 acre-foot); the maximum depth of the pond is 3.66 m while its mean depth is 1.8 m.

To place the PSC pond in context, data from the Stormwater Planning Division of the Fairfax County Department of Public Works and Environmental Services was obtained. Data were provided on 329 wet ponds and included areas, drainage areas, and volumes (Karlee H. Copeland, personal communication, October 14, 2021). The Fairfax pond dataset was plotted as histograms using the log of pond variables on the x-axis. The PSC pond was compared with this distribution. In terms of pond area, the PSC pond was near the median of the Fairfax data set (Figure 1). Its drainage area was also near the median while its volume was somewhat lower than the median of the Fairfax data set.





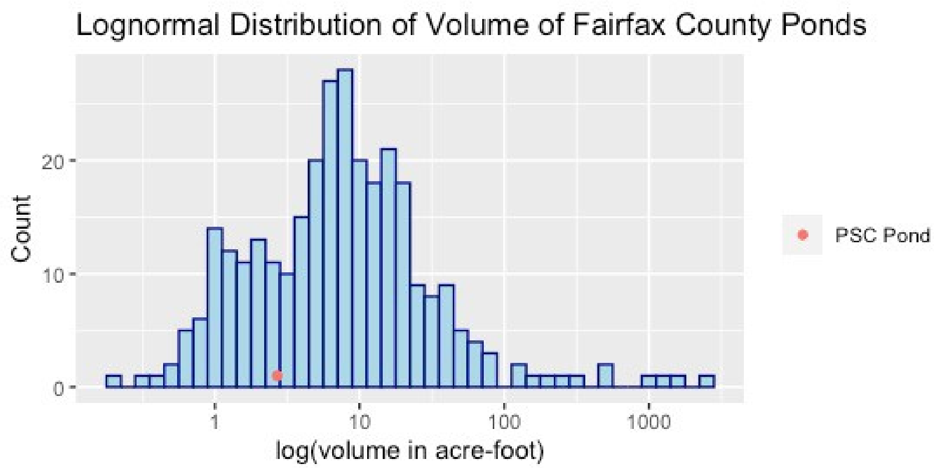


Figure 1: Lognormal distributions of areas, drainage areas, and volumes of Fairfax County stormwater ponds.

As for the structure of the PSC pond, water flows into the pond from the southwest corner before exiting the pond in the northeast corner via a spillway. The pond is dependent on runoff, and inflow and outflow occur predominantly during runoff events. Additionally, the pond's outlet broadens into an emergency spillway, which allows water to overflow into the adjacent Occoquan River during large precipitation events. Some sparse vegetation surrounds the pond and could act as a vegetative buffer. The pond also contains submerged aquatic vegetation (SAV) of the species *Hydrilla verticillata*. During the study, the SAV was sampled via petite ponar at 13 sites distributed throughout the pond. The SAV were rinsed of sediment and debris and then dried in a drying oven at 75 °C for several days. Once the SAV had completely dried, it was weighed to create a representative sample of the SAV in the pond. The average dry weight of the SAV per petite ponar sample was 80.4 g/m^2. Most of the SAV is located near the southeast water entrance and around the dock. The pond is a wildlife habitat for local waterfowl and aquatic fauna, such as turtles, and has been considered for recreational use by the local community. The pond provides an aesthetic appeal due to a walking trail, which is part of the Potomac Heritage National Scenic Trail, winding around the pond.

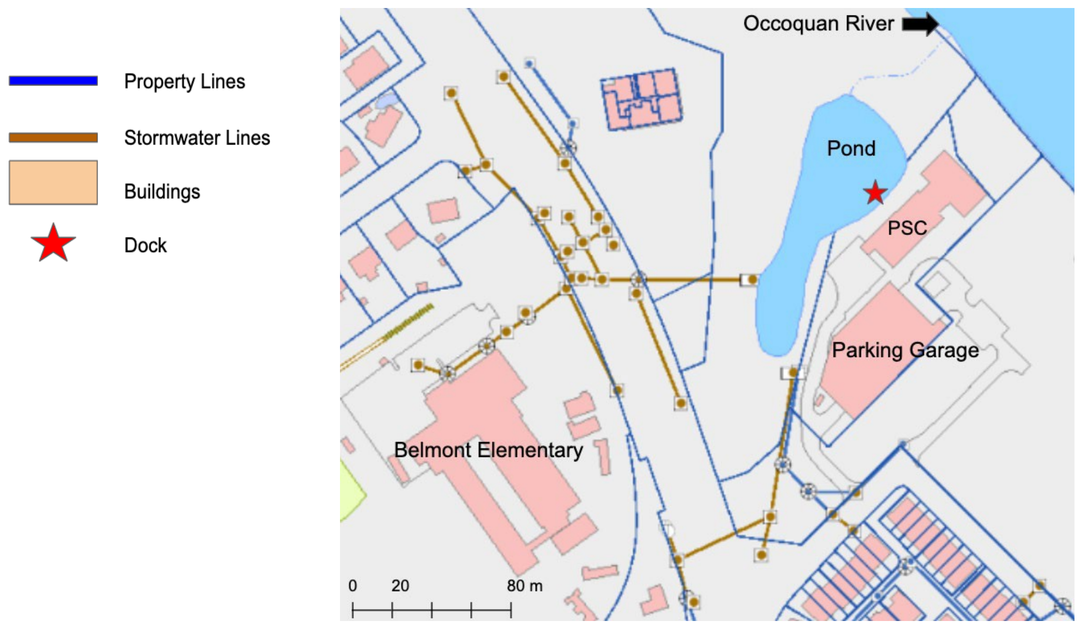


Figure 2: Potomac Science Center stormwater pond inlets and much of the drainage area.

METHODS

Field and laboratory methods

To investigate changes in the water quality of the stormwater pond adjacent to the Potomac Science Center, two continuous monitors, YSI 6600 sondes, were deployed from a dock over the pond at near surface (0.5 m) and near bottom (2.5 m) depths. To deploy the sondes, two loops were knotted into a rope at the appropriate lengths; the sondes were then attached to the rope loops by metal hooks. Finally, the rope was tied to the dock before being lowered into the water. However, rope slippage caused the sondes to dip into deeper water, which led to variation in depth. On July 23, more knots were tied in the rope to ensure the sondes sat at the correct depth levels. In future studies, a different or improved method of securing the sondes would allow for more accurate data collection. The sondes recorded the following parameters every 15 minutes: pH, dissolved oxygen (% sat and mg), specific conductance (mS/cm), turbidity (NTU), in vivo chlorophyll *a* (µg/L) and temperature (°C). The deployed sondes were rotated weekly with freshly calibrated sondes to control fouling and to ensure quality control of the data, which was downloaded each week. Unfortunately, due to the malfunction of some sonde sensors, some data was lost. Due to the variation in depth at the beginning of the study and the data loss later in the study, the continuous monitoring analysis focuses on the period beginning July 23 and ending August 29.

Each week, a YSI EXO handheld sonde was deployed from the dock to create a depth profile of the pond; pH, dissolved oxygen (% sat), specific conductance (mS/cm), turbidity (NTU), and temperature (°C) data were collected at 0.25 m depth intervals. Due to turbidity sensor malfunctions, some turbidity data loss occurred. Secchi depth and light attenuation were also measured weekly from the dock using a secchi disc and a light meter, respectively. Weather data, such as photosynthetically active radiation (PAR), air temperature (°C), and rainfall (mm), were collected by mounting a Hobo weather station from Onset Computer (Model RX3000 WiFi Remote Monitoring Station with air temperature, precipitation, light (PAR), and water level sensors recording continuously) at the study site. The weather station contained a computer that was connected to the Potomac Science Center's Wi-Fi, allowing measurements to become available online in 15-minute intervals.

To further investigate differences in water quality as the water in the pond became stratified, water samples were collected at three depths: near surface (0.5 m), a middle depth (1.5 m), and a near bottom depth (2.5 m). Samples were collected using a Van Dorn sampling bottle, which was deployed from the dock. Defined volumes of water from the water samples were filtered in the lab in triplicate through preashed and tared glass fiber filters (Whatman 984AH) for total suspended solids (TSS) and volatile suspended solids (VSS) analysis. TSS was determined by drying the filters overnight at 75 °C and reweighing them. Then, VSS was determined by ashing the same filters at 500 °C and reweighing them; total VSS was calculated as the difference between the dry weight and the ashed weight.

15 mL water samples were collected in triplicate for each depth (0.5 m, 1.5 m, and 2.5 m) to measure chlorophyll *a* levels with a fluorometer by the standard method

used in PEREC's Freshwater Ecology Lab (Jones et al. 2008). The 15 mL samples were filtered through 0.45 µm GN-6 metricel® membrane filters, preserved in 20 mL plastic scintillation vials, and frozen. The frozen filters were then dissolved by adding acetone. The subsequent solutions were placed in scintillation vials and refrigerated overnight to allow for complete pigment extraction. During the next day, the volume of each solution was measured. Next, an initial fluorometer reading was taken; then, 0.2mL of 2N HCl was added before a second fluorometer reading. The final chlorophyll *a* calculation was determined using the values for the volume filtered, the volume extracted, the two fluorometer readings, and the calibration coefficients.

Additionally, to later identify phytoplankton taxa under a microscope, 20 mL of water from the collected samples was preserved for each depth (0.5 m, 1.5 m, 2.5m) using Lugol's 10% Iodine solution. For each surface sample analyzed, the preserved suspension was placed in a graduated cylinder overnight to allow settling. The supernatant water was siphoned off and the remaining suspension examined using a Palmer cell. The bottom samples did not need to be concentrated and could therefore be immediately examined. Phytoplankton were identified, measured, and counted using standard references available in the PEREC Freshwater Ecology Lab. The biovolumes were calculated using the measured lengths of the phytoplankton and geometric formulas for their shapes. Two slides were created for each depth and the values averaged. The cell counts and biovolumes of green algae, diatoms, and cyanobacteria determined the richness of the pond's algal community and the extent of eutrophication. Finally, the species identified provided insight into the water quality at surface and bottom depths.

Data Analysis

The 15-minute data collected from the sondes were compiled with the 15-minute weather and light data from the weather station. Data trends were analyzed statistically and graphically per the methods outlined in Graziano and Jones (2017) to determine water quality variation over three time scales: seasonal, daily, and precipitation event. The data was examined for outliers due to sonde changes, which were removed, and data was interpolated for sonde change periods to have a complete set of 15-minute readings for analysis. For all 15-minute data readings, R was used to calculate daily means, minima, and maxima for water quality and weather variables and to graph seasonal and time series data. Daily means and depth profile values were used to evaluate seasonal patterns. The 15-minute readings were used to evaluate diel patterns and water quality during precipitation events. For stable periods, SYSTAT 13 was used for autocorrelation and probability plots as well as for correlation analysis. A correlation analysis of daily means using Pearson coefficients was conducted to determine significant relationships between water quality variables.

Light attenuation coefficient (k) values derived from light meter data showed a direct relationship with k values derived from secchi disc readings. Because the secchi disc data showed less variability, the k values derived from secchi disc readings were used for light profile analysis. k values were determined using the formula $k = 1.7 / z_{sd.}$ Photic zone depth was determined from k values using the formula $z_{pz} = (\ln 0.01) / -k$.

Sonde temperature data from the two depths were examined to determine the degree of stratification and the timing of mixing events. Then, the data were examined to determine the impact of stratification and mixing on the water quality parameters. It was hypothesized that during periods of stratification, the values of the water quality parameters would diverge between the two depths.

RESULTS

Seasonal patterns in climatic variables

Seasonal patterns in climatic variables were determined from 15-minute weather station data. Air temperature trends were determined using daily means. In July, daily average air temperature (DAAT) began at 25.4 °C on July 1 and experienced an increase through the middle of July to a maximum of 31.1 °C on July 20 (Figure 3). DAAT exhibited a rapid decline due to the rainfall from July 22 through July 24. After July 24, DAAT quickly rose back up to 29.9 °C on July 26 but then declined slowly through August, marked by periodic drops that coincided with rainfall; on August 1, DAAT was at 26.4 °C, which dropped to 21.4 °C on August 31. In September, DAAT demonstrated a more rapid decline: on September 1, DAAT was at 21.9 °C and by September 20, DAAT had dropped to 13.7 °C (a decline of 8.2 °C). In October, DAAT became relatively constant at about 17 °C. Overall, the seasonal trend for DAAT was fairly constant in July followed by a net decline through early October.

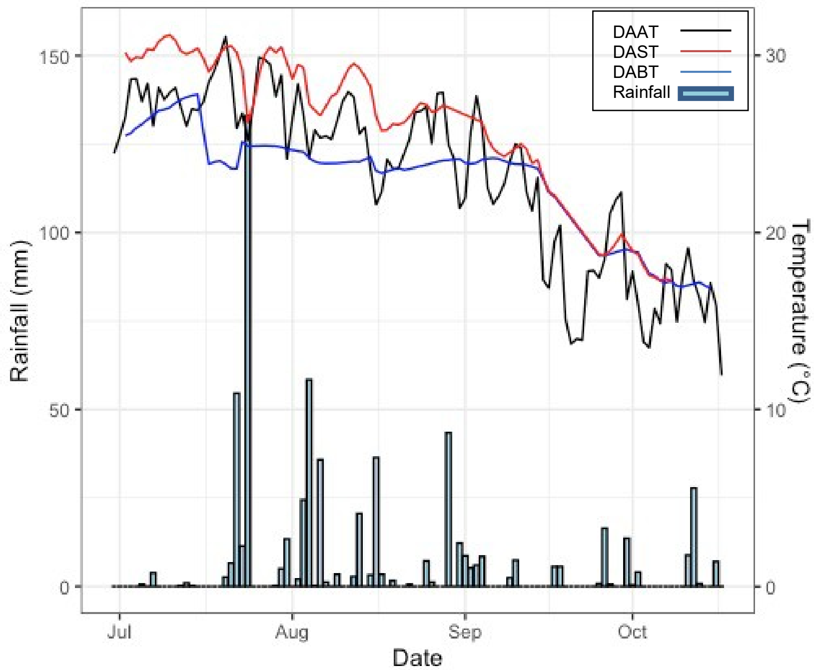


Figure 3: Seasonal changes in weather and water temperature. Daily rainfall totals plotted as a bar graph. Daily average air temperature (DAAT), daily average surface water temperature (DAST), daily average bottom water temperature (DABT) plotted as line graphs.

Precipitation events were observed using daily rainfall totals in mm. July was mostly dry until July 22 when the pond received 54.6 mm of rainfall (Figure 3). The pond experienced a major event on July 24 when it received 133 mm of rainfall. During August, the pond received frequent, moderate rainfall with daily totals ranging from 0.2 to 43.3 mm. September was mostly dry with daily rainfall totals ranging from 0.6 to 16.4 mm. October was mostly dry except for a moderate peak of 27.8 mm on October 12.

PAR was observed using daily totals measured in $E/m^2/day$. In July, PAR was at its maximum potential, reaching a peak of 621.5 $E/m^2/day$ on July 3 (Figure 4). Unfortunately, the mounted weather station experienced data loss for PAR between July 20 and August 13. After PAR reached its peak in July, it declined to an average of 307.0 $E/m^2/day$ during September and reached its minimum on October 12 of 81.6 $E/m^2/day$. Overall, PAR, like air temperature, experienced a seasonal trend of a steady decline as expected. PAR also revealed a mixture of sunny and cloudy days over the entire study period.

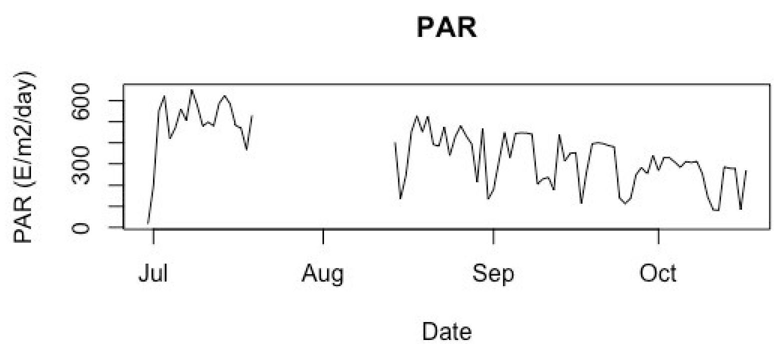


Figure 4: Daily total PAR from July through October.

Seasonal patterns in water quality variables

Seasonal patterns in hydrologic variables were determined using daily mean values of 15-minute sonde readings, weekly depth profile readings, and light profiles. Both the surface (0.5 m) and bottom (2.5 m) average water temperatures gradually declined over the study period (Figure 3). The sondes experienced some data loss during the following periods: August 29 through September 4, September 17 through September

25, and October 8 through October 15. In July, the average surface water temperature began at 30.0 °C, about 5 °C higher than the average bottom water temperature, and gradually decreased through August, mirroring the behavior of DAAT. The average bottom water temperature began at 25.3 °C and gradually rose until the end of July. On July 24, the pond experienced a rainfall event. The average surface water temperature showed a steep decline to 26 °C while the average bottom water temperature rose to 25 °C, indicating the pond experienced temperature-induced mixing. After July 24, average surface water temperature often mirrored the behavior of the average air temperature, but the average bottom water temperature stayed consistent at about 24 °C until the end of September when it dropped to about 17 °C for the remainder of the period. The steep average air temperature decline in September caused the average surface and bottom temperatures to homogenize, which led to temperature-induced mixing. In October, the average surface temperature dropped to about 17 °C as well; at this time, the pond was well-mixed due to temperature-induced mixing.

Data from weekly depth profiles revealed seasonal behavior of water quality variables throughout the water column. In general, water temperature, like air temperature, gradually cooled from July through October (Figure 5). At the beginning of the study, the pond showed temperature-induced stratification between upper and lower depths as indicated by the change in color with depth. The surface and middle depths remained warmer through August and were at their peak temperatures July 9. The bottom temperature began cooler than the surface temperature and rose until the end of July. Throughout August, the bottom of the pond experienced minimal warming and cooling until September, when temperature-driven mixing caused the pond to become homogenized for the remainder of the study. From the middle of September through the middle of October, the overall temperature of the pond cooled significantly.

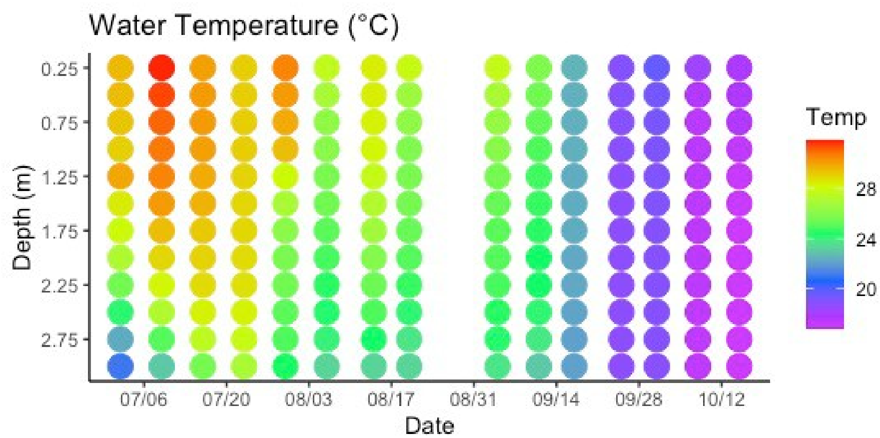


Figure 5: Weekly depth profiles of water temperature.

At the start of the study, specific conductance began at a middling level at the surface and increased with depth to the bottom of the pond (Figure 6). Specific conductance gradually decreased throughout July and was generally homogenized from August through October.

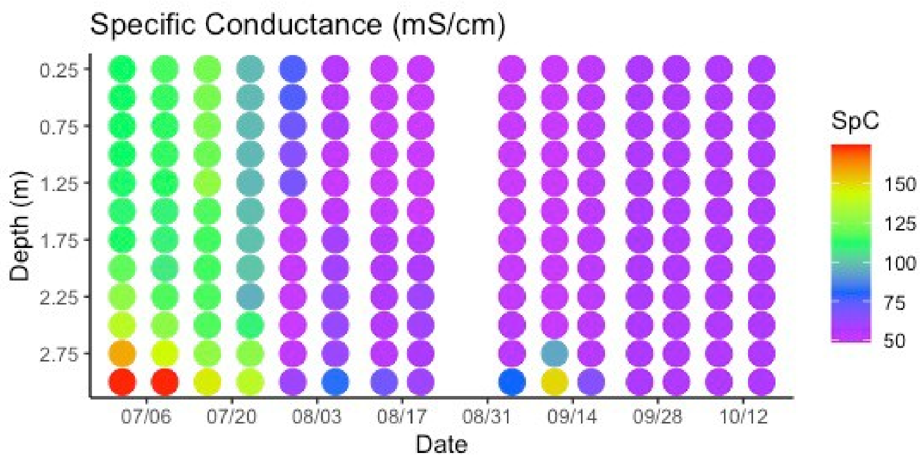


Figure 6: Weekly depth profiles of conductivity.

DO began high at the surface and decreased to 0 as depth increased, revealing the stratification of the pond (Figure 7). During the first few weeks of the study, DO reached the lower regions of the pond to a maximum depth of about 2.5 m. DO dropped throughout the pond due to mixing from the first disruption event at the end of July. Interestingly, DO was higher at 1.25 m than at the surface of the pond at the end of July; an increase in pH coincided with this increase in DO, suggesting there was some photosynthetic activity occurring at a high level at that depth (Figure 8). The surface and bottom DO levels remained stratified until September when the pond experienced consistent mixing due to rain events and a drop in temperature. The pond remained homogenized at a low DO level through October. In July, the surface pH values were significantly higher than the bottom, but they decreased over time. The pH for the whole pond dropped in late August and homogenized through October.

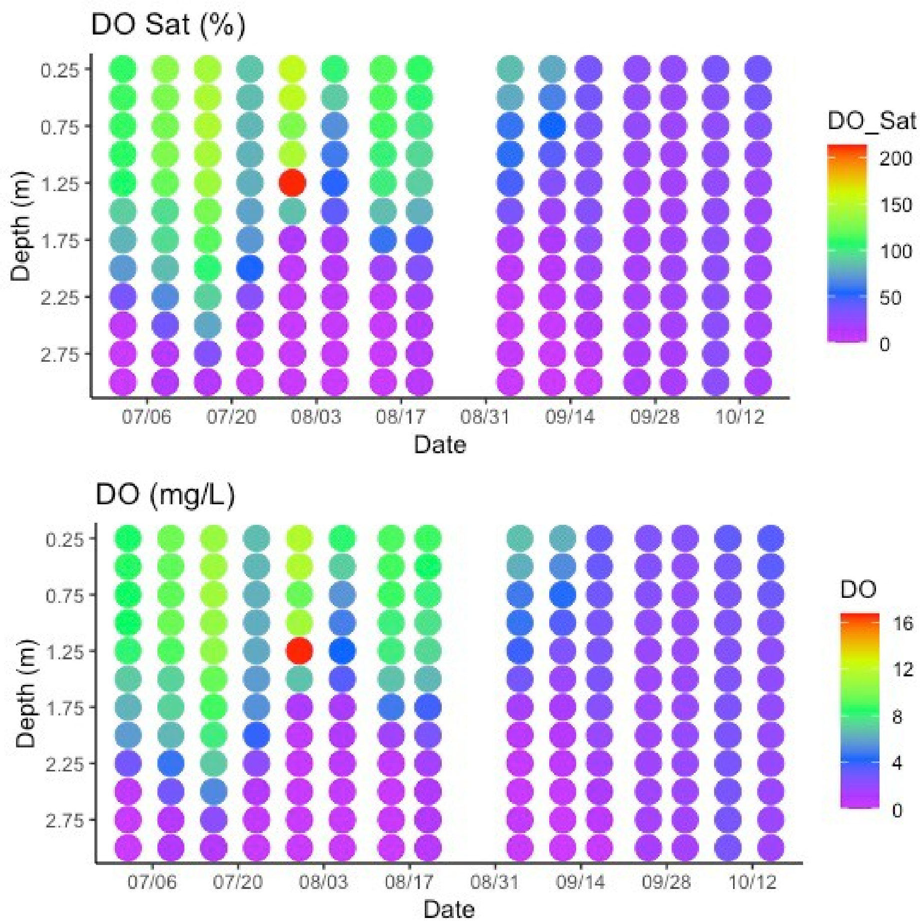


Figure 7. Weekly depth profiles of dissolved oxygen.

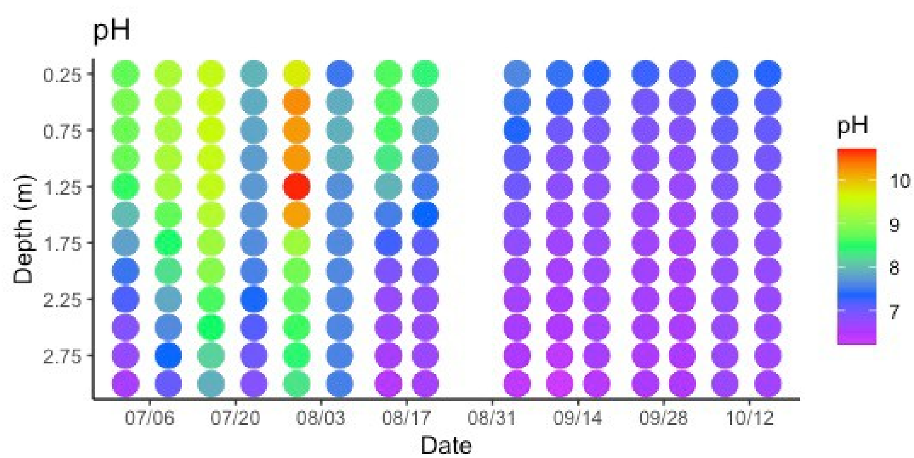


Figure 8: Weekly depth profiles of pH.

Overall, turbidity was low throughout pond and throughout the study (Figure 9). Turbidity is an approximate measure of TSS and was measured in NTU; there are 3 NTU in 1 mg/L. TSS values greater than or equal to 30 mg/L (or 90 NTU) constitute poor water quality. The maximum of the weekly readings occurred in September at 28 NTU near the bottom of the pond. Overall, turbidity was not a concern for the pond for the duration of the study. However, there were malfunctions with the PRO DDS sensor, resulting in data loss for some weeks as denoted in grey (Figure 9).

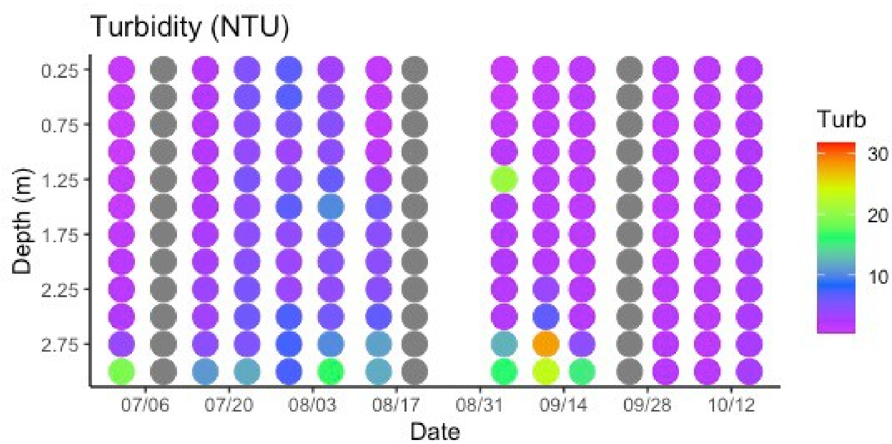


Figure 9: Weekly depth profiles of turbidity.

Weekly secchi depth readings were used to derive light attenuation coefficients and photic zone depth (1% of surface light depth). Photic zone depth began at 6.23 m (Table 1). As the maximum depth of the pond is 3.66 m, photosynthesis was able to occur throughout the entire water column at the start of the study. Photic depth reached its peak on July 9 and declined on July 23 to 2.98 m. Photic depth increased slightly to

3.12 m on July 30 and 3.25 m on August 6. On August 14, photic depth increased to 5.15 m and remained high through October 15, suggesting photosynthesis was able to occur throughout the entire water column for the remainder of the study. Overall, light profiles suggest there was enough light to keep phytoplankton alive throughout the entire water column for the duration of the study. TSS, VSS, and chlorophyll *a* analysis of 15 weekly water samples revealed TSS and VSS to be low for the study period (Table 2). TSS and VSS reached a maximum of 23.4 mg/L and 15.3 mg/L, respectively, at 2.5 m on September 11, both under the parameter for poor water quality. Chlorophyll *a* had also reached its maximum of 140 ug/L on September 11, which will be discussed further in the phytoplankton analysis. TSS, VSS, and chlorophyll *a* all increased with depth and reflected the buildup of phytoplankton in the bottom waters of the pond.

Table 1: Weekly secchi readings and photic depth

Date	Secchi (m)	Light Attenuation Coefficient (m^{-1})	Photic Depth (m)
7/2	2.3	0.74	6.23
7/9	2.6	0.66	6.98
7/16	1.9	0.88	5.21
7/23	1.1	1.55	2.98
7/30	1.2	1.48	3.12
8/6	1.2	1.42	3.25
8/14	1.9	0.89	5.15
8/20	2	0.85	5.42
9/4	2.3	0.74	6.23
9/11	2.4	0.71	6.50
9/17	2.2	0.78	5.91
9/25	2.9	0.60	7.72
10/1	1.7	1.03	4.47
10/8	1.9	0.89	5.15
10/15	2.5	0.68	6.77

Table 2: TSS, VSS, and chlorophyll *a* determined from weekly water samples (n =15).

Parameter	Depth (m)	Mean	Max	Min
TSS (mg/L)	0.5	5.7	10.4	2.7
TSS (mg/L)	1.5	6.9	14.7	3.9
TSS (mg/L)	2.5	9.0	23.4	3.9
VSS (mg/L)	0.5	3.2	8.8	0.6
VSS (mg/L)	1.5	3.7	11.6	1.4
VSS (mg/L)	2.5	5.0	15.3	1.4
Chlorophyll *a* (ug/L)	0.5	7.9	23.2	3.0
Chlorophyll *a* (ug/L)	1.5	12.7	33.5	5.7
Chlorophyll *a* (ug/L)	2.5	26.7	140	5.4

In-depth analysis of water quality variables using continuous monitoring

The continuous monitoring analysis of the pond's behavior focuses on the period from July 23 through August 29, which was selected due to stable sonde depths and complete data sets for all variables. During this time period, the pond exhibited a behavior pattern of three stable periods of 10-12 days demarcated by three disruption events. A summarized table of events can be seen in the appendix (Table A1).

Starting Conditions

Daily means calculated from the 15-minute sonde data were used to investigate the starting conditions before the first disruption event of the continuous monitoring study. On July 23, DAAT was high at 26.8 °C. PAR was at its max potential during the study and revealed a mixture of sunny and partly cloudy days. The average surface water temperature was 29.2 °C while the average bottom water temperature was 25.1 °C, indicating some temperature-induced stratification. Average SPC was a bit lower at the surface (103.9 mS/cm) than the bottom (144.2 mS/cm). Average turbidity was low overall: 8.5 NTU at the surface and 16.0 NTU at the bottom. Average pH and average DO were substantially lower at the bottom, 6.2 and 17.4 %, respectively, than the surface (7.7 and 90.8 %)), but chlorophyll *a* was higher at the bottom (62.0 ug/L) than the surface (9.3 ug/L) of the pond.

Disruption Event 1: July 24 Runoff Event

On July 24, the pond received about 4 in (13 cm) of rainfall and experienced major cooling and mixing of the water column. Surface temperature dropped to an average of 26.2°C and a minimum of 25.9 °C (Figure 10). Bottom temperature dropped slightly to an average of 24.9 °C, which was also the maximum. DO and pH levels experienced major mixing between depths and homogenized throughout the pond for the day. DO was at 57 % saturation and 4.7 mg while pH was at 6.6 (Figures 12, 13, and 14). SPC decreased at both depths but became greater at the surface (74.2 mS/cm) than the bottom (48.4 mS/cm) (Figure 11). Chlorophyll *a* also homogenized between depths at 5.7 ug/L (Figure 16). Turbidity increased at the surface and homogenized with the bottom at 12.9 NTU (Figure 15).

Stable Period 1: July 25 through August 3

After the runoff event of July 24, both air temperature and PAR slowly declined. There was a mixture of sunny and cloudy days. The surface temperature showed a stepwise increase in temperature to reach a maximum of 31.2 °C on July 28 (Figure 10). The surface also restarted its diel signal, dropping to a minimum of 26.6 °C on August 1 to create a maximum range of 4.6 °C during this stable period. The bottom temperature remained low with no diel signal, starting at an average of 24.9 °C on July 25 and ending at an average of 24.2 °C on August 4. Surface DO restarted a noisy diel signal with a maximum saturation of 173.4 % and minimum of 55 % on July 26; on most days the range was between about 120% and 170 % (Figures 13). Bottom DO quickly dropped after the first disruption event to 0 % saturation with a brief spike of 35.2 % on July 30, which may have been due to rope slippage during the sonde change. Bottom DO was at 0 for the remainder of the time period. Like DO, surface pH rose and restarted a diel signal with a range of about 1 pH unit (8.8-9.8); the average surface pH was 9.5 for the period (Figure 14). Bottom pH remained low, dropping to 5.9 immediately after the runoff event; bottom pH rose slightly to 6.4 on July 30, coinciding with the spike in DO. SPC remained fairly constant at both depths: the average at the surface was 79.4 mS/cm and the average at the bottom was 56.6 mS/cm (Figure 11). Turbidity homogenized between depths until the end of the period; the average was 9.0 NTU (Figure 15). Surface chlorophyll *a* restarted a diel signal but remained low at an average of 10.1 ug/L (Figure 16). Bottom chlorophyll *a* started lower than the surface at 4.6 ug/L but spiked on July 26 to a maximum of 79.5 ug/L; it then increased to be greater than the surface to about 35.0 ug/L at the end of the period.

Disruption Event 2: August 4 Runoff Event

On August 4, the pond received 2.2 in (5.8 cm) of rainfall. This runoff event coincided with 0.9 in (2.4 cm) of rainfall the day before and 1.4 in (3.5 cm) of rainfall on Aug 6. The pond experienced significant cooling of temperature and the water between depths nearly mixed. The surface temperature dropped to a minimum of 26.6 °C while the bottom temperature reached a maximum of 24.5 °C, which was close to its mean of 24.2 °C (Figure 10). The DO and pH homogenized to about 50.0 % saturation and 6.6, respectively (Figures 11, 12, and 13). The surface experienced an increase in chlorophyll to a maximum of 54.2 ug/L while the bottom experienced a decrease in chlorophyll to a minimum of 4.73 ug/L (Figure 16). Turbidity and SPC homogenized between depths at 6.4 NTU and 64.0 mS/cm, respectively (Figures 15 and 14).

Stable Period 2: August 5 through August 15

During this period, the pond experienced frequent but moderate rainfall. Both air temperature and PAR levels slowly declined over the period. The water temperature at the surface exhibited a steady step function increase to 30.0 °C while the bottom water temperature flatlined at about 23.0 °C, remaining cool (Figure 10). However, the surface experienced a step function decline in temperature starting August 13 for the remainder of the period, ending at a minimum of 26.3 °C on August 16. At the surface, DO and pH varied but steadily rose until August 13 when they declined; DO saturation reached a maximum of 150.7 % while pH reached a maximum of 9.4 9 (Figures 11, 12 and 13). At the beginning of the period, bottom DO quickly returned to 0 while pH declined more gradually to stay at about 6.0. Chlorophyll *a* reached its highest levels in the bottom waters at this stage, rising to a maximum of 98.49 ug/L (Figure 16). At the surface, chlorophyll *a* declined and stayed between 5.0 and 10.0 ug/L. Like chlorophyll *a*, turbidity at the bottom of the pond rose to be greater than the surface: the bottom reached a maximum of 32.6 NTU while the surface dropped to a minimum of 0.3 NTU (Figure 15). SPC homogenized for the first half of the period at about 60.0 mS/cm until the surface rose to a maximum of 67.0 mS/cm and the bottom dropped to a minimum of 44.0 mS/cm (Figure 14).

Disruption Event 3: August 16 Runoff Event

The pond experienced 1.4 in (3.64 cm) of rainfall and slight cooling of air temperature. The surface temperature exhibited a major temperature decline from 29.1 °C to 25.2 °C; the bottom temperature reached a maximum of 24.3 °C, indicating some temperature-induced mixing (Figure 10). Throughout the pond, DO and pH exhibited wide variation and became nearly homogenized between depths at about 50.0 % saturation and 6.5, respectively (Figures 11, 12, and 13). At the bottom, chlorophyll *a* declined quickly to a minimum of 7.68 ug/L to become lower than the surface level, which reached a maximum of 24.7 ug/L (Figure 16). Turbidity at the bottom declined and became homogenized between depths at about 10.0 NTU (Figure 15). SPC increased at the bottom of the pond to homogenize with the surface at about 60.0 mS/cm (Figure 14).

Stable Period 3: August 17 through August 29

The pond received frequent but moderate rainfall. Both the air temperature and PAR exhibited a slow decline. Conversely, the temperature at the surface rose slowly from 25.8 °C to 27.1 °C (Figure 10). The surface DO and pH levels were higher than at the bottom levels and showed some diel signal; surface DO fluctuated between about 50.0 % and 100.0 % saturation while pH fluctuated between about 7.5 and 6.8 (Figures 11, 12, and 13). The bottom temperature remained low and constant at a mean of about 24.0 °C. DO at the bottom rose at the beginning of the period to about 15.5 % saturation but dropped to 0 and experience small, short-term fluctuations between 0 and 10.0 % saturation. pH at the bottom remained low at about 6.3. SPC homogenized between depths at about 60.0 mS/cm (Figure 14). The chlorophyll *a* and turbidity at the bottom depth both increased to be greater than the surface from August 21 to August 29; at the surface, turbidity stayed low at about 1.0 NTU while the bottom increased to a maximum of 14.5 NTU (Figure 15). Surface chlorophyll *a* started with a small diel pulse and decreased to a mean of 5.8 ug/L for the remainder of the period while bottom chlorophyll *a* started a larger diel pulse and consistently rose to be greater than the surface to reach a maximum of 67.8 ug/L (Figure 16).

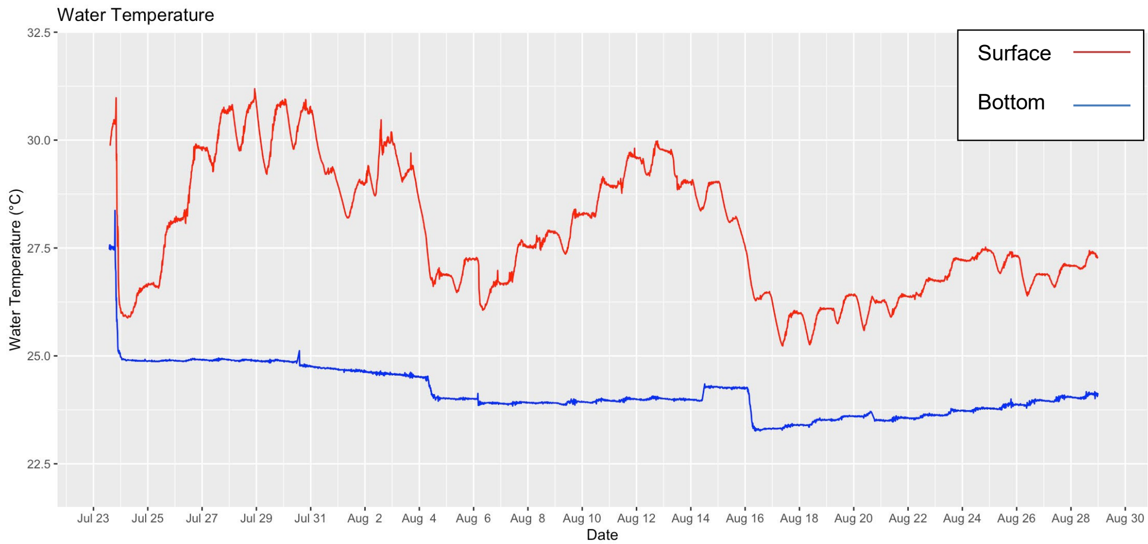


Figure 10: 15-minute water temperature data for the period of intensive analysis.

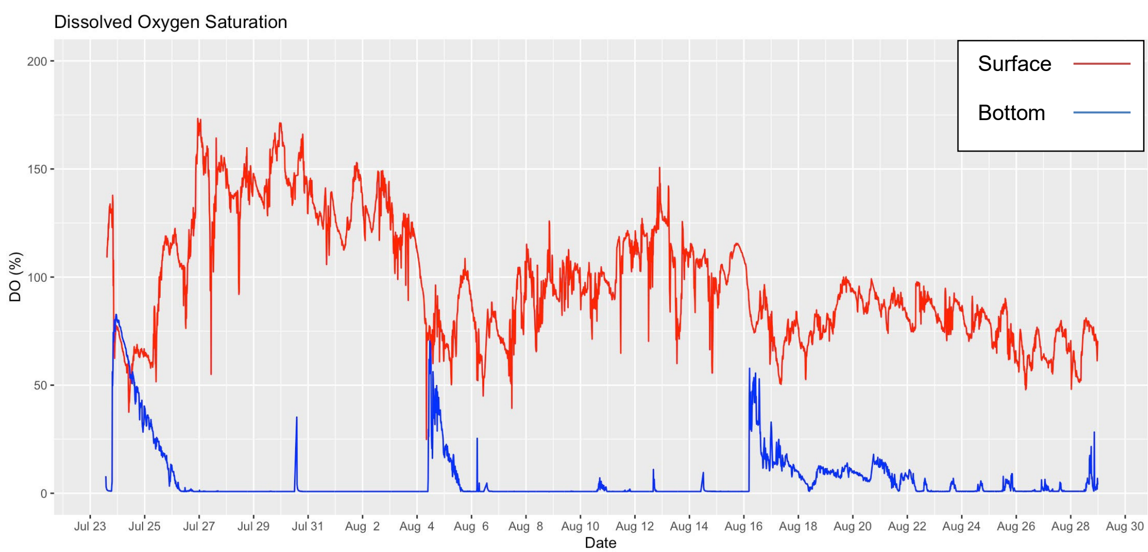


Figure 11: 15-minute dissolved oxygen saturation data for the period of intensive analysis.

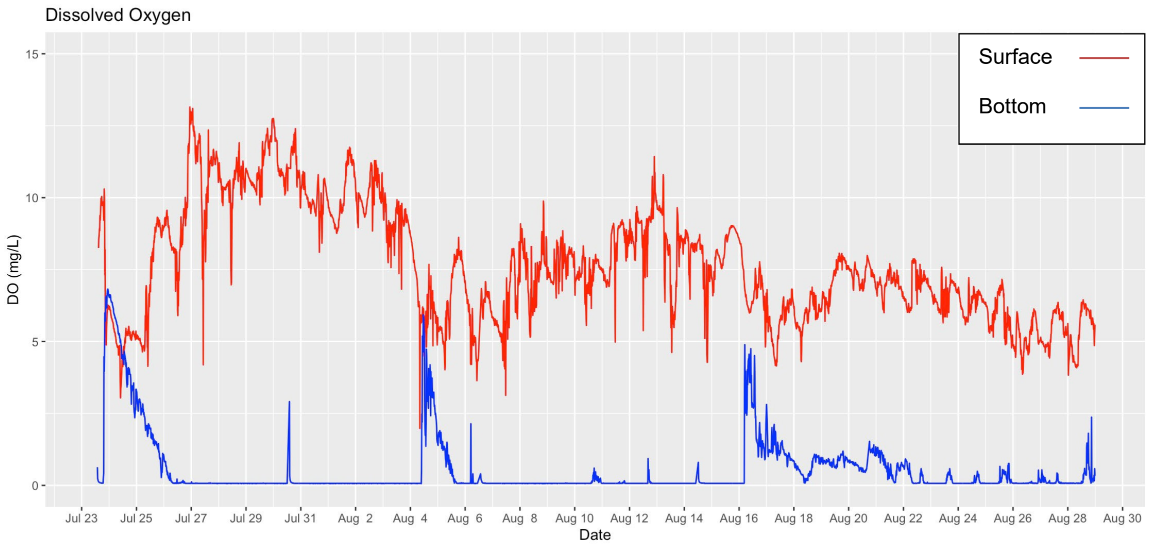


Figure 12: 15-minute dissolved oxygen (mg/L) data for the period of intensive analysis.

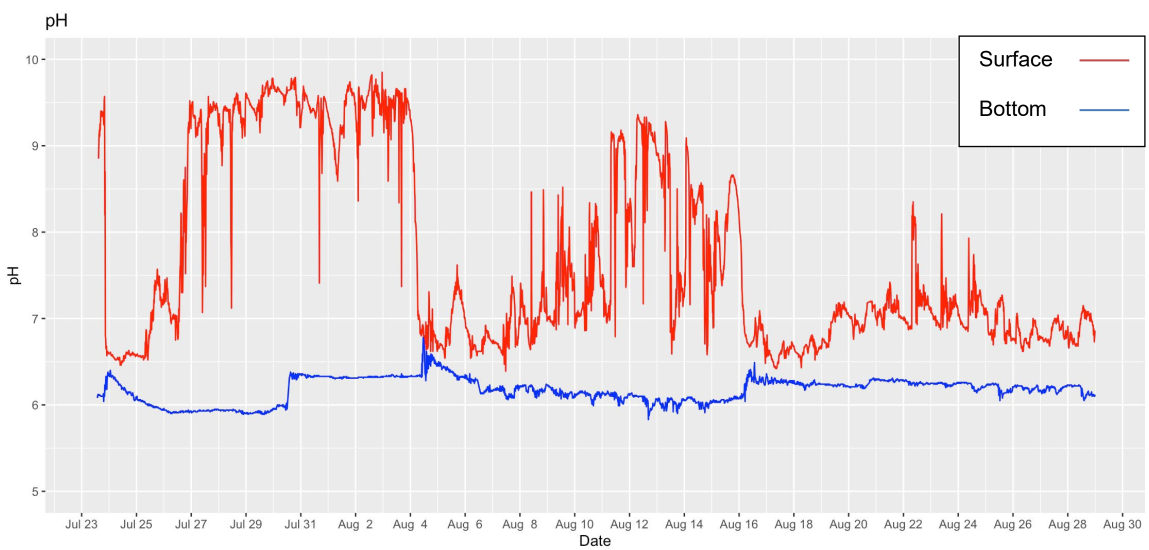


Figure 13: 15-minute pH data for the period of intensive analysis.

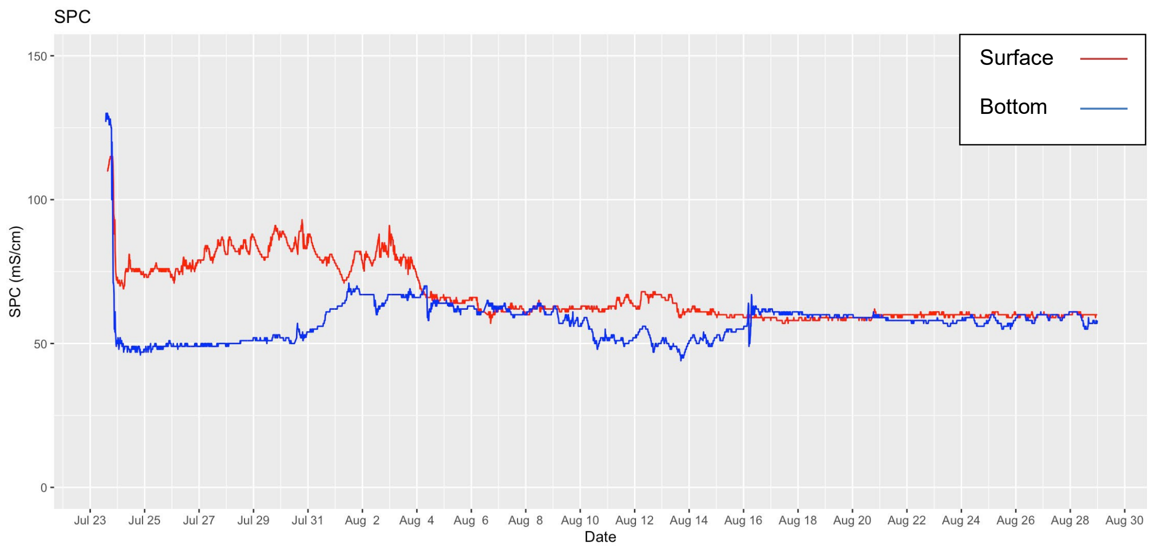


Figure 14: 15-minute conductivity data for the period of intensive analysis.

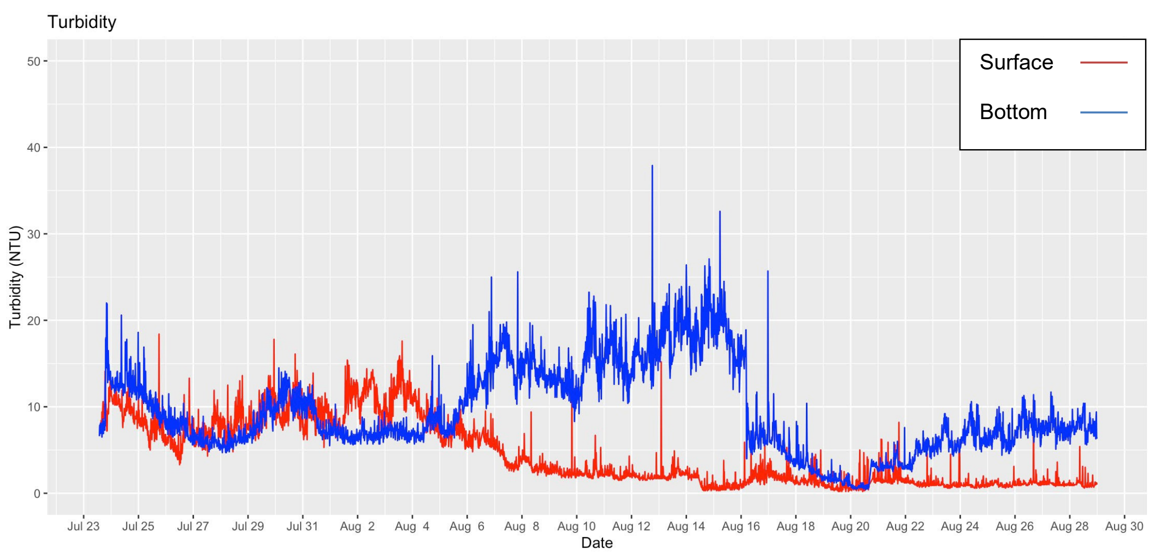


Figure 15: 15-minute turbidity data for the period of intensive analysis.

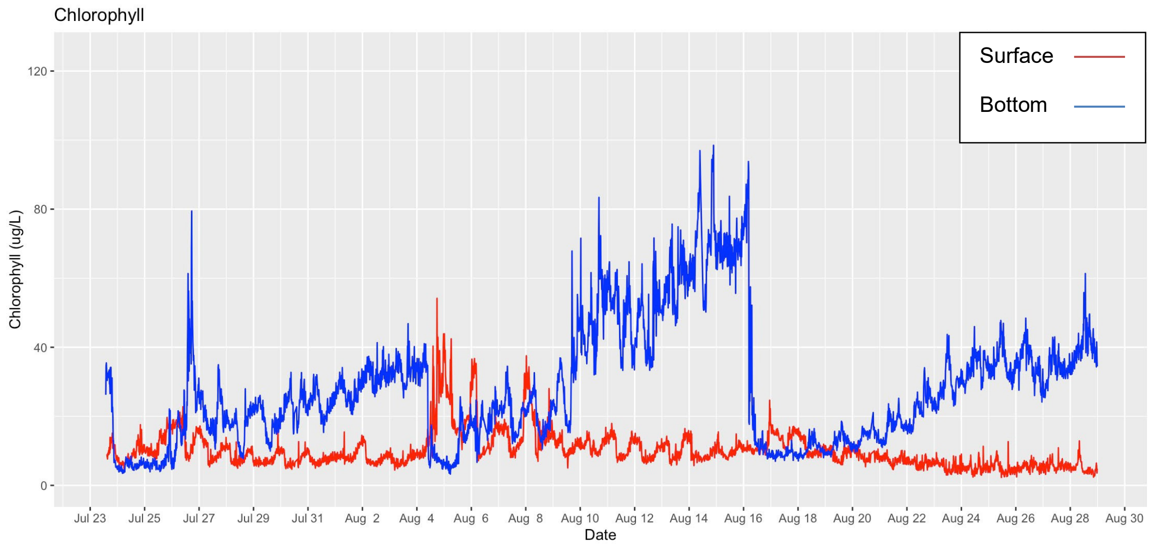


Figure 16: 15-minute chlorophyll *a* data for the period of intensive analysis.

Time series analysis of continuous monitoring data

A correlation analysis of 15-minute sonde readings was conducted to assess significant relationships between water quality variables for the three stable periods. Diel patterns were investigated using an autocorrelation analysis, which measures the relationship between a variable's values at different points in time. The lag interval for this study was 15 minutes, so a 24-hour diel period consists of 96 lag units. All water quality variables for the surface revealed autocorrelation plots indicative of diel patterns as seen in two representative plots (Figures 17 and 18). The correlation coefficients of temperature, DO, pH, SPC, turbidity, and chlorophyll *a* declined to a minimum after about 48 lag units (12 hours) and increased to high values after 96 lag units (24 hours), indicating a cyclical pattern with a 24-hour time period. Autocorrelation analysis was conducted on the data for the bottom of the pond, but it did not reveal any patterns.

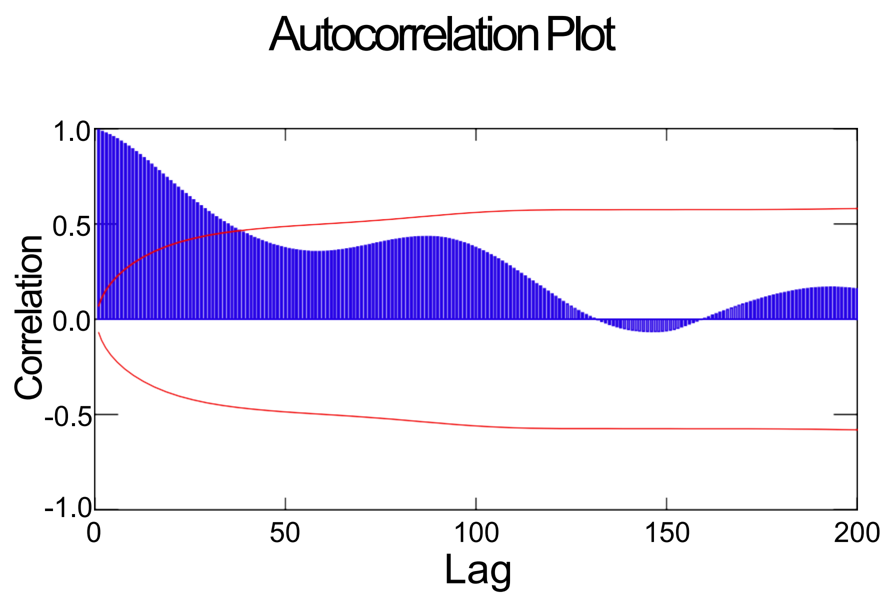


Figure 17: Surface temperature autocorrelation plot**.**

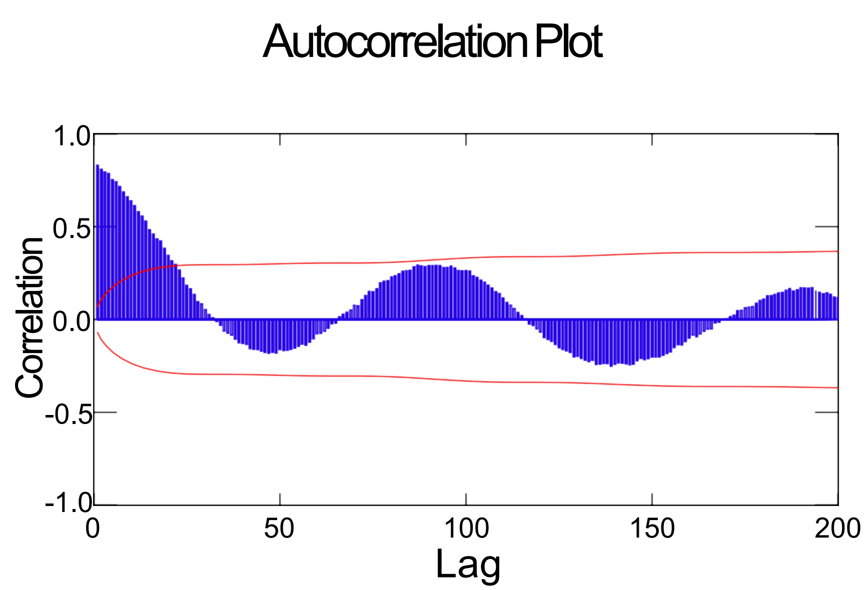


Figure 18: Surface chlorophyll *a* autocorrelation plot.

Correlation analysis of continuous monitoring data

Normal probability plots were created for all water quality variables, and they were generally normally distributed, so the correlation analysis was conducted using Pearson coefficients on the surface data of the three stable periods. Normal probability plots for the bottom of the pond did not show any clear relationships. Stable Period 1 consisted of 812 cases; Stable Period 2 consisted of 825 cases, and Stable Period 3 consisted of 1,120 cases. An r value of 0.5 was used to determine significance for all stable periods. During Stable Period 1, temperature was highly correlated with SPC, DO saturation, and DO (Table X). Specific conductance was also highly correlated with DO saturation and DO. pH was correlated with DO saturation and DO. Because DO correlated with temperature but chlorophyll *a* did not, further research will need to be conducted to determine the organisms primarily responsible for photosynthesis as not all phytoplankton contain the *a* pigment.

Table 3: Correlations (Pearsons' r) among water quality variables for the surface of the pond during Stable Period 1 (n = 812).

Parameter	Water Temp (°C)	SPC (mS/cm)	pH	Turbidity (NTU)	Chlorophyll *a* (ug/L)	DO (% sat)	DO (mg)
Water Temp (°C)	1.000						
SPC (mS/cm)	0.856	1.000					
pH	0.266	0.450	1.000				
Turbidity (NTU)	-0.176	0.005	0.371	1.000			
Chlorophyll *a* (ug/L)	0.106	-0.066	-0.143	-0.182	1.000		

DO (% sat)	0.657	0.654	0.580	-0.058	0.340	1.000	
DO (mg)	0.587	0.602	0.592	-0.043	0.352	0.996	1.000

During Stable Period 2, temperature positively correlated with conductivity and pH as well as DO saturation and DO (Table X). Temperature was negatively correlated with turbidity. pH was positively correlated with DO saturation and DO, revealing some photosynthetic activity. Again, temperature correlated with DO but chlorophyll *a* did not.

Table 4: Correlations (Pearsons' r) among water quality variables for the surface of the pond during Stable Period 2 (n = 825).

Parameter	Water Temp (°C)	SPC (mS/cm)	pH	Turbidity (NTU)	Chlorophyll *a* (ug/L)	DO (% sat)	DO (mg)
Water Temp (°C)	1.000						
SPC (mS/cm)	0.579	1.000					
pH	0.753	0.676	1.000				
Turbidity (NTU)	-0.664	-0.343	-0.484	1.000			
Chlorophyll *a* (ug/L)	-0.350	-0.337	-0.411	0.390	1.000		
DO (% sat)	0.737	0.509	0.823	-0.466	-0.091	1.000	
DO (mg)	0.691	0.480	0.802	-0.439	-0.060	0.998	1.000

Stable Period 3 showed fewer relationships than the first two stable periods. Temperature positively correlated with SPC but negatively correlated with chlorophyll *a*.

pH strongly correlated with DO saturation and DO. Finally, DO correlated highly with DO saturation.

Table 5: Correlations (Pearsons' r) among water quality variables for the surface of the pond during Stable Period 3 (n = 1,120).

Parameter	Water Temp (°C)	SPC (mS/cm)	pH	Turbidity (NTU)	Chlorophyll *a* (ug/L)	DO (% sat)	DO (mg)
Water Temp (°C)	1.000						
SPC (mS/cm)	0.499	1.000					
pH	0.194	0.152	1.000				
Turbidity (NTU)	-0.176	-0.009	-0.062	1.000			
Chlorophyll *a* (ug/L)	-0.669	-0.491	-0.343	0.140	1.000		
DO (% sat)	-0.275	-0.205	0.694	-0.004	0.144	1.000	
DO (mg)	-0.334	-0.232	0.667	0.008	0.184	0.998	1.000

Phytoplankton analysis

Chlorophyll *a* lab analysis of weekly water samples yielded two dates with high levels of chlorophyll *a* (greater than 60 ug/L) at the bottom of the pond: August 14 and September 11. Samples were examined for the two dates to determine differences in phytoplankton communities at 0.5 m and 2.5 m. On August 14, the dominant species at the surface was a coccoid green algae, followed by centric diatoms and the cyanobacteria *Aphanizomenon* (Table X). The surface was dominated by green algae but, interestingly, *Aphanizomenon* made up 15.2 % of the biovolume. While the bottom depth technically had more coccoid cells, the biovolume was dominated by the cyanobacteria *Oscillatoria* and *Aphanizomenon*. Because the hypolimnion of the pond was hypoxic, cyanobacteria species were expected to be present. By September 11, coccoid green algae strongly dominated the surface community, comprising 92.6 % of the biovolume. *Oscillatoria* became the dominant cyanobacteria but made up only 2.4 % of the biovolume. At the bottom, coccoid algae had the greatest number of cells, but the community biovolume was divided between cyanobacteria, *Cryptomonas*, and diatoms. Interestingly, centric diatoms made up 43 % of the biovolume. *Oscillatoria* increased, becoming the dominant cyanobacteria, and *Aphanizomenon* significantly decreased. As expected, green algae counts and biovolume were low at the bottom of the pond.

Table 6: August 14 surface phytoplankton cell counts and biovolume.

Taxa	Average Number of Cells (per mL)	Average Total Biovolume (um^3/mL)	Average Percent Biovolume (%)
Coccoid green	485.1	2316098	42.6
Centric diatom	50.6	234996	4.3
Aphanizomenon	48.4	828729	15.2
Merismopedia	20.9	2	< 1
Staurastrum	12.1	496870	9.1
Micrasterias	8.8	1038400	19.1
Cryptomonas	6.6	2270	< 1
Ceratium	4.4	519200	9.5
Monoraphidium	1.1	1892	< 1
Selenastrum	1.1	189	< 1

Table 7: August 14 bottom phytoplankton cell counts and biovolume.

Taxa	Average Number of Cells (per mL)	Average Total Biovolume (um^3/mL)	Average Percent Biovolume (%)
Coccoid green	13000	17888780	29.1
Oscillatoria	1280	26320424	42.7
Aphanizomenon	630	12590906	20.4
Selenastrum	270	46440	< 1
Cryptomonas	140	1926477	3.1
Centric diatom	105	1155886	1.9
Actinastrum	55	22484	< 1
Merismopedia	30	3	< 1
Staurastrum	25	1026591	1.7
Ceratium	5	590000	< 1
Monoraphidium	5	8600	< 1

Table 8: September 11 surface phytoplankton cell counts and biovolume.

Taxa	Average Number of Cells (per mL)	Average Total Biovolume (um^3/mL)	Average Percent Biovolume (%)
Coccoid green	10345.4	13491924	92.6
Cryptomonas	80.8	500024	3.4
Merismopedia	62.1	6	< 1
Centric diatom	28.1	130270	< 1
Staurastrum	8.5	349041	< 1
Oscillatoria	8.5	67089	2.4
Aphanizomenon	1.7	26317	< 1
Pediastrum	0.9	558	< 1

Table 9: September 11 bottom phytoplankton cell counts and biovolume.

Taxa	**Average Number of Cells (per mL)**	**Average Total Biovolume (um^3/mL)**	**Average Percent Biovolume (%)**
Coccoid green	12200	7981148	8.4
Merismopedia	3280	392	< 1
Cryptomonas	1435	19746389	20.8
Oscillatoria	1385	24496025	25.7
Monoraphidium	280	724522	< 1
Centric diatom	235	40890000	43.0
Aphanizomenon	30	464419	< 1
Actinastrum	20	8176	< 1
Staurastrum	20	821273	< 1

DISCUSSION

The first objective of this study was to determine the seasonal patterns of stratification and water quality in the PSC stormwater pond. From July through October, a clear gradual net decline was observed in air temperature and PAR, which was also reflected in water quality variables, revealing air temperature and solar radiation to be driving forces of the pond's water quality. In July, air temperature, PAR, and water temperature at both the surface and bottom waters were at their peaks. From July through October, changes in air temperature were strongly reflected by the surface water while the bottom water showed a more gradual decline and remained constant for long periods. Surface SPC, DO, and pH all showed seasonal declines and were closely correlated with surface water temperature. Turbidity remained low throughout the pond from July through October. In July, air temperature-driven thermal stratification of the epilimnion and the hypolimnion of the pond was apparent, which continued through August. In September, the temperature of the pond cooled at the surface, which allowed major mixing to occur with bottom waters; the pond did not experience thermal stratification for the remainder of the study period (through the middle of October).

Surface DO and pH exhibited a seasonal trend related to surface water temperature. In July, the surface waters were supersaturated with DO due to photosynthesis. In the hypolimnion, DO was low during stratification (between 0 and 4 mg/L), and when the pond experienced major mixing in September, oxygen-depleted bottom waters mixed with the surface waters to homogenize the pond at a low DO of about 2 mg/L through the middle of October, which suggests poor water quality (Drescher et al. 2011). Immobile benthic organisms would find the pond to be stressful from July through October if not adapted to low DO levels, but mobile organisms could escape the hypolimnion for areas of the pond with higher DO (from the surface to about 1.5 m). However, even mobile aquatic organisms, such as fish, would find the pond's DO from September through October stressful. A longer study period through the winter would be able to discern when the pond's waters become reoxygenated to higher levels.

On an annual scale, the average pH range for the pond appeared to be between 6 and 8 and showed elevated levels at the surface in July, reflecting photosynthetic activity. The peak pH levels occurred in late July. After the July 24 runoff event, the pond's biological processes restarted, and the pond exhibited a high pH of 10 at the surface to a depth of 1.5 m on July 30. DO was also elevated, suggesting a high level of photosynthetic activity in the top half of the pond. pH then dropped down to 7 and remained between 6 and 8 for the remainder of the study period.

The second objective of this study was to determine the short-term and diel patterns of the pond using continuous monitoring of water quality variables at 15-minute intervals. Due to data loss, the less extensive period from July 23 through August 29 was selected for analysis. Water quality variables exhibited a pattern of three 10-day stable periods driven by biological processes punctuated by three 1-day disruption events driven by physical processes, such as air cooling and rainfall. Autocorrelation and correlation analyses using Pearson coefficients were conducted on the three stable periods. Before the first disruption event, the pond was stratified, and air temperature and PAR were at their maxima. On July 24, the pond experienced major cooling and mixing of the water column due to air cooling and rainfall. DO, pH, and chlorophyll *a* became low throughout the pond, reflecting the mixing and flushing of the pond. Turbidity increased at the surface, as expected during a runoff event, but was low overall. The surface temperature then warmed to be slightly warmer than the bottom, which was reflected by SPC. It is possible some salts entered the pond through runoff, but surface SPC was closely correlated with surface temperature, indicating dissolved solids and salts did not appear to have much effect on the pond's water system.

During Stable Period 1, the pond experienced a reset, becoming stratified again, and biological processes drove water quality. Surface temperature increased and restarted a diel signal while the bottom temperature remained low and constant. Surface DO restarted its diel signal, and surface waters quickly became supersaturated while bottom waters quickly became anoxic. Surface pH also restarted its diel signal and was elevated with an average of 9.5. Both DO and pH levels were indicative of photosynthetic activity at the surface of the pond. Interestingly, surface chlorophyll *a* restarted a diel signal but remained low while bottom chlorophyll *a* rose throughout the whole period. SPC and turbidity remained low and relatively constant throughout the water column.

On August 4, the pond experienced its second disruption event due to air cooling and rainfall. Again, the pond experience significant cooling and mixing throughout the water column. Water temperature, DO, and pH were all at about the same values as the first disruption event (26 °C, 50 %, 6.6). However, chlorophyll *a* responded differently during this event, and the levels at each depth inverted: the bottom chlorophyll *a* plummeted while the surface chlorophyll *a* rose, suggesting mixing brought algae from the bottom of the pond to the surface. SPC and turbidity remained low and constant throughout the water column, likely due to a smaller amount of rainfall than on July 24.

During Stable Period 2, the pond exhibited the same pattern of a reset of biological processes and stratification. Surface temperature increased and restarted a diel signal again until it began to decline on August 13. The surface temperature maximum was slightly lower than Stable Period 1 due to decreasing air temperature and PAR, and its diel signal was more irregular. Surface DO and pH restarted noisy diel signals with slightly lower maximums than Stable Period 1 but high values signaling photosynthetic activity. Again, bottom DO quickly became anoxic, and bottom pH declined and stayed constant at about 6. At this point, chlorophyll *a* rose to be greater than the surface and reached its highest level throughout the continuous monitoring analysis period. As chlorophyll *a* levels above 60 ug/L indicate poor water quality, the chlorophyll *a* values coupled with the DO values of this second stable period suggest poor water quality at the bottom of the pond. Turbidity at the bottom of the pond also increased to be greater than the surface, reflecting the algae growth. SPC stayed low and relatively constant.

On August 16, the pond experienced its third runoff event, which caused a major temperature decline in the surface waters and some temperature-induced mixing. Like during the two previous disruption events, DO and pH homogenized at about 50% saturation and 6, respectively. Like during the second disruption event, the high levels of chlorophyll *a* at the bottom declined rapidly while the surface level increased, suggesting the bottom algae were brought to the surface through mixing. Turbidity throughout the pond decreased while SPC remained homogenized and constant, likely due to the small amount of rainfall.

During Stable Period 3, the pond experienced a lesser reset than that of the first two stable periods due to the seasonal decline in air temperature and PAR. The surface temperature still rose, but its maximum was lower; it also restarted a weak diel signal with irregular ranges. The pond became stratified again as the bottom temperature remained low and constant. Surface DO and pH restarted diel signals with irregular ranges. During this period, bottom DO exhibited longer periods of anoxia in the bottom waters punctuated by brief, small spikes in DO. This could be caused by photosynthesis suggested by the rise in chlorophyll *a* at the bottom of the pond: chlorophyll *a* restarted with a large diel pulse and consistently rose to be greater than the surface. As in Stable Period 2, these high levels of chlorophyll *a* and DO indicate poor water quality at the bottom of the pond, especially during stratification. Bottom turbidity also rose to be greater than the surface as in Stable Period 2 while SPC remained low and constant.

Overall, the surface of the pond showed more variation than the bottom and exhibited clear trends in water quality parameters. Surface temperature, DO, and pH all began high during Stable Period 1, then decreased to a medium level during Stable Period 2, and decreased to a lower level during Stable Period 3 (Table 10). The surface waters of the pond reflected a close relationship with air temperature and solar radiation. SPC also began higher during Stable Period 1 and declined to a near constant level for the remainder of Stable Periods 2 and 3. Turbidity and chlorophyll *a* levels were low at the surface for Stable Periods 1, 2, and 3. The bottom of the pond showed very little change in temperature, DO, and pH, which were all low for Stable Periods 1, 2, and 3 (Table 11). Like the surface, SPC started a bit higher during Stable Period 1 and became low for Stable Periods 1 and 2. However, chlorophyll *a* reflected the buildup of phytoplankton at the bottom of the pond, beginning at a medium level during Stable Period 1, becoming high during Stable Period 2, and declining to a medium level during Stable Period 3. Turbidity reflected some of this buildup, staying at a medium level during Stable Periods 1 and 2 and declining during Stable Period 3.

Table 10: Levels of surface water quality parameters for the three stable periods.

Stable Period	Temp (°C)	DO	pH	Chl *a* (ug/L)	Turb (NTU)	SPC (mS/cm)
1	high	high	high	low	low	medium
2	medium	medium	medium	low	low	low
3	low	low	low	low	low	low

Table 11: Levels of bottom water quality parameters for the three stable periods.

Stable Period	Temp (°C)	DO	pH	Chl *a* (ug/L)	Turb (NTU)	SPC (mS/cm)
1	low	low	low	medium	medium	medium
2	low	low	low	high	medium	low
3	low	low	low	medium	low	low

Diel patterns were further investigated by autocorrelation analysis to confirm that the surface water quality variables exhibited diel patterns that declined to minima after 12 hours and increased to maxima after 24 hours, indicating a cyclical pattern driven by solar radiation. Ultimately, the pond behaved as expected on a short time scale, displaying diel signals during stratified periods and experiencing sudden changes in water quality due to disruption events.

The third objective was to determine the phytoplankton taxa present at the surface and bottom of the pond. Analysis of two dates, August 14 and September 11, further underscored the differences in water quality between the 0.5 m and 2.5 m depths. The surface was dominated by green algae with small populations of cyanobacteria present on both dates. On August 14, the bottom was dominated by cyanobacteria (63.1% biovolume), which was when chlorophyll *a* levels were at their highest during Stable Period 2. By September 11, the phytoplankton populations became more diverse as *Cryptomonas* and centric diatoms increased; *Oscillatoria* appeared to outcompete *Aphanizomenon* as the dominant cyanobacteria in the pond. Although nutrient analysis was outside the scope of this study, dominance by a single taxa and high abundance has indicated eutrophic conditions in stormwater ponds in the past, while a diverse, more balanced community has indicated low nutrients (Olding 2000). The phytoplankton analysis on September 11 suggests the surface exhibited more eutrophic conditions while the bottom exhibited lower amounts of nutrients at that time. However, chlorophyll *a,* another indicator of eutrophic conditions, was much higher in the bottom waters. Furthermore, *Cryptomonas* is a pollution-tolerant species that can thrive in stormwater ponds as it did at the bottom of the PSC pond (Olding 2000).

Phytoplankton analysis of these two dates indicate better water quality at the surface and further confirm the low DO conditions, and thus poor water quality, at the bottom of the pond. No surface harmful algal blooms were observed during the study, suggesting no immediate threat to the residential community. However, the high levels of chlorophyll *a* and the high biovolume of cyanobacteria suggest a HAB in the bottom waters of the pond. The long periods of anoxia at the bottom of the pond are a cause for concern as they promote the growth of cyanobacteria, which can produce toxins. During disruption events, the pond experiences mixing and turnover, bringing the bottom water to the surface. Phytoplankton analysis of the surface reflected this mixing as small amounts of cyanobacteria were present. Weekly depth profiles suggested the poor water quality of the bottom waters can affect the whole pond in the fall when the pond mixed and became hypoxic. However, the decomposition of SAV in the fall likely contributed to the hypoxia. It is unclear from the results how the cyanobacteria build up in the bottom of the pond between the disruption events. It is likely due to a combination of factors: settling of phytoplankton from the surface, light penetration, and the release of phosphorous from the sediment due to hypoxia. Further investigation of cyanobacteria and dissolved nutrients would provide more insight into the pond's water quality and the role of HABs.

Stormwater ponds are an understudied area of aquatic ecology, and this study appears to be one of the first to employ 15-minute interval continuous monitoring. The EPA does not regulate stormwater ponds and has considered them well-mixed in the past (US. Environmental Protection Agency 2009). The results of this study indicate that stormwater ponds, despite being small bodies of water, do indeed stratify in the summer. The PSC pond exhibited the typical seasonal pattern of summer stratification and fall mixing driven by air temperature and solar radiation. Continuous monitoring revealed the impacts of stratification on water quality variables: the pond became hypoxic in the lower water layers, which is stressful for aquatic organisms and promotes harmful algal growth by increasing nutrient release from the sediment. At the end of the study in October, mixing lowered the DO throughout the water column to less than 4 ug/L, which is concerning for the aquatic life of the pond. In the future, a longer study period would determine when the pond reoxygenates. The continuous monitoring results point to a pattern of 10-day stable, stratified periods punctuated by 1-day disruption events. This pattern can guide future monitoring and sampling of the pond in the summer. Continuous monitoring studies of other stormwater ponds would provide more insight into the short-term patterns of stormwater ponds in general.

As the size of the PSC pond is close to the median for Fairfax County ponds, the results may be representative for stormwater ponds in the local area. Further study of local stormwater ponds is needed to better understand the accumulation of phytoplankton in the lower layers observed in this study. In addition, a common database for scientists to access data on local ponds would facilitate better management of wet ponds in the region. Ultimately, the pond performs its intended function of allowing organic matter to settle in the pond, which enables the surface waters to maintain good water quality. In the event that the pond overflows and drains into the Occoquan River, surface water would be released and likely have little effect on the river's water quality. Furthermore, there is no threat to the local community as residents use the surface waters for recreational activity. Finally, if poor water quality persists in the bottom layers or the water quality of the surface waters begin to decline, management suggestions include installing a sediment forebay to allow further settling of sediments and an aerator to oxygenate the pond.

APPENDIX

Table of Events

Events	Forcing Functions	Water Quality Attributes
Starting Conditions July 23	• High air temperature at its maximum • High PAR at its maximum	• Surface temperature, DO, and pH were high • Surface chlorophyll was low • Bottom temperature and pH were lower than the surface • Bottom DO was low, but chlorophyll was high • SPC was about the same between depths • Turbidity was low
Runoff Event July 24	• Significant drop in air temperature and PAR • 4 in (13 cm) rainfall	• Cooling throughout water column • Major mixing • DO, pH, chlorophyll homogenized • SPC decreased at both depths • Turbidity increased at both depths
Stable Period 1 July 25 through Aug 3	• High air temperature • High PAR • Mixture of sunny and cloudy days	• Surface temperature increased and restarted a diel signal • Bottom temperature remained low with no diel signal • Surface DO restarted a diel signal • Bottom DO dropped to 0 after mixing event • Surface pH rose and restarted a diel signal • Bottom pH remained lower • SPC remained fairly constant at both depths • Turbidity homogenized between depths until the end of the period when surface turbidity increased, and bottom turbidity decreased • Surface chlorophyll started with a diel signal and remained low • Bottom chlorophyll started lower than the surface but spiked and then

		increased to be greater than the surface
Runoff Event August 4	• Significant drop in air temperature and PAR • 2.2 (5.8 cm) rainfall	• Cooling throughout water column • Depths nearly mixed • DO and pH homogenized at times • SPC homogenized • Turbidity homogenized • Chlorophyll increased at surface and decreased at bottom
Stable Period 2 Aug 5 through Aug 15	• Air temperature and PAR slowly declined • Moderate periodic rainfall • Mixture of sunny and cloudy days	• Surface temperature rose as a step function with a diel signal • Bottom temperature remained low and constant • Surface DO rising and variable diel signal • Bottom DO at 0 with brief spikes • Surface pH rose but showed wide variation • Bottom pH showed a slight diel pulse but remained lower • SPC homogenized for much of the period • Bottom turbidity rose to be greater than the surface • Surface and bottom chlorophyll started with a diel pulse of similar values • Surface chlorophyll decreased and exhibited a diel pulse • Bottom chlorophyll greatly increased
Runoff Event August 16	• 1.4 in (3.64 cm) rainfall • Slight cooling of air temperature • Drop in PAR	• Surface temperature significantly declined • DO and pH exhibited wide variation and became nearly homogenized • SPC increased at bottom to become slightly greater than surface • Chlorophyll and turbidity decreased and homogenized between depths
Stable Period 3	• Air temperature rose and fell	• Surface temperature rose slowly and exhibited a diel pulse

August 17 through August 29	with a net decrease • PAR slowly decreased • Moderate periodic rainfall • Mixture of sunny and cloudy days	• Bottom temperature remained low and constant • Surface DO had some diel signal and showed a general decrease • Bottom DO rose at the beginning of the period but stayed at 0 with brief spikes • Surface pH showed some diel signal • Bottom pH remained low • SPC homogenized often • Turbidity was greater at the bottom than the surface for most of the period • Surface chlorophyll started with a diel pulse and decreased • Bottom chlorophyll started a diel pulse and rose to be greater than the surface

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