Testing the Waters: An Analysis of Recent Nutrient Levels in Westhampton Lake and Their Implications for Water Quality Management

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Abstract

This investigation was undertaken to understand recent nutrient levels of Westhampton Lake and determine the implications of its water quality relative to the sustenance of aquatic life on campus at the University of Richmond. Nutrient data was obtained from the documentation of ongoing monthly sampling by a research team from Virginia Commonwealth University and consisted in the evaluation of total nitrogen, total phosphorus, ammonia, nitrogen oxides, chlorides, and the bacteria, *Escherichia coli* between November 20, 2018, and December 9, 2021. Analysis of each individual nutrient included the comparison of its minimum, maximum, and mean level relative to recommended criteria provided by the Virginia Department of Environmental Quality and local experts, with healthy levels being defined as those that support aquatic life. In addition, nutrients were analyzed spatially and temporally, applying recommended criteria to the sample site and sample date of a nutrient. Apart from total nitrogen, all average nutrient levels surpassed criteria; however, chlorides were unable to be evaluated due to nonexistent criteria. Findings indicated the need for the adoption of standardized criteria for all nutrients sampled, modification of sites being used for sampling to discern on-campus from off-campus sources, and consideration of additional features that could be added to the lake to combat excess nutrients.

Introduction

Regarded as a centerpiece of campus life for people and biota alike, the University of Richmond's Westhampton Lake attracts students, neighbors, and visitors as well as residential and migratory aquatic and terrestrial animals. While Westhampton Lake was once open to recreational use by university members and visitors, effective in 1976, swimming was banned by university authorities, and other leisure activities later followed (Ahnell et al., 2014). The lake is connected on either end to Little Westham Creek, and both are components of the James River System. Little Westham Creek feeds into Westhampton Lake which feeds into the restored continuation of Little Westham Creek which eventually meets the Kanawha Canal and James River (Figure 1 and Figure 2). Therefore, the nutrient content of the lake and its watershed drains into the James River Watershed and the larger Chesapeake Bay Watershed, a watershed that spans over 168,000 km^2 of land (Jantz et. al., 2005). In comparison, the drainage basin of Westhampton Lake occupies approximately 6.6 km^2 of land (Ahnell et al., 2014). Unfortunately, due to climate change and urbanization, the Chesapeake Bay Watershed is suffering detrimental losses in riparian biomes that are responsible for serving as buffer areas to nonpoint-source pollutants contributing phosphorus, nitrogen, and other nutrients contained in sediment (Gilliam, 1994; Lowrance et al., 1997; Ahnell et. al., 2014; Chesapeake Bay Foundation, n.d.).

Impervious Surfaces and Runoff

It is known that the construction of impervious surfaces in urban development further facilitates the ease with which non-point source pollutants can enter freshwater bodies in the form of runoff (Schueler, 2000; Zhou et al, 2016; Hamilton et al., 2020). The United States Environmental Protection Agency (US EPA) reports that an impervious surface the size of one city block can produce over five times the amount of runoff as a natural woodland area of the same size (United States Environmental Protection Agency, 2003). Furthermore, the National Water Quality Inventory reports runoff from urbanized areas to be the leading cause of water quality impairments to surveyed lakes (United States Environmental Protection Agency, 2003). The University of Richmond's campus has a high percentage of impervious surfaces that take the form of academic buildings, dormitories, parking lots, roads, and walking paths (Figure 3). The 2011 Campus Master Plan for the University of Richmond acknowledges water quality issues in the form of the construction of development (such as residential areas and shopping centers) on higher elevations upstream of campus, changes in sewage drainage patterns that have increased drainage into swales and increased flooding issues, and more frequent, high-flow rainfall events that have increased soil erosion along the banks of feeding streams (University of Richmond, 2011). The 2011 Campus Master Plan also notes particular harm to water quality caused by development that occurred prior to the introduction of regulations requiring the maintenance of a Resource Protection Area (RPA) (University of Richmond, 2011). As the university battles seasonal blooms of duckweed and algae in addition to low dissolved oxygen contents within the lake, it has installed 13-14 bubblers to aerate water and flashing lights to prevent geese from spending the night on the banks of the lake, both of which can be found in the lake today.

Small Lakes Theory

With substantial concern devoted to the aesthetic appearance of the water of Westhampton Lake for the university as a site of attraction for visitors and prospective students there exists the need to foster physically and chemically desirable water quality. Westhampton Lake is estimated to be no more than 8-10 feet deep and 14 acres in size (Ahnell et al., 2014). Small water bodies like Westhampton Lake serve as a refuge for species that have disappeared from larger, disturbed freshwater bodies, helping mediate virtually all water-related ecosystem services (Biggs et al., 2017). Further, shallow lakes like Westhampton Lake are defined by two distinct alternative equilibrium states: a "clear-water state" denoted by the presence of aquatic vegetation, and a "turbid water state" characterized by algal growth (Scheffer et al., 1997). The balancing act of these two states for a single water body compose what is known as the shallow lakes theory (Scheffer et al., 1997). A high loading of nutrients into a freshwater body is sufficient to cause a shift from a clear-water state to a turbid state, and once a turbid state has been reached, it can be very time-consuming and complex to reverse (Scheffer et al., 1997). Equally detrimental is any direct harm caused to the plant community needed for stabilization of the clear-water state, as can occur through mechanical and chemical damage and grazing (Phillips et al., 2016). Shallow lakes allow for more sunlight to penetrate the lake's bottom, promoting the growth of submerged macrophytes over algae and thereby preventing sudden transitions to eutrophic states (Phillips et al., 2016). Accordingly, the critical nutrient level required for Westhampton Lake to become turbid is higher than that required by a larger, deeper lake (Scheffer and van Nes, 2007). However, smaller, shallower lakes are more prone to sudden temperature changes which are also capable of prompting transitions from one state to the other, with the introduction of earlier growing seasons for vegetation (linked to global warming) favoring conditions for macrophyte establishment over algae (Rooney and Kalff, 2000).

Objectives

Considering the shallow lakes theory and its implications for the dynamics of Westhampton Lake, my investigation sought to unveil which nutrients within the lake are of greatest concern based on criteria conducive to the health of aquatic flora and fauna, as set by the US EPA and local, specialized recommendations. I simultaneously attempted to discern the temporal trends of nutrients, based on sampling dates, and their spatial trends, based on sample site locations. Additionally, modifications to current sampling strategies as well as options for the introduction of constructed water quality treatment strategies were considered. Beginning in 1997, the University of Richmond partnered with Virginia Commonwealth University (VCU) and a team of professionals from their Environmental Department, spearheaded by faculty member, Dr. Paul Bukaveckas. The VCU team surveys nutrient concentrations within Westhampton Lake, utilizing four sample sites and documenting various nutrient levels, each of the sample sites, and indvidual sampling dates in a publicly accessible "Master_FacilitiesWaterQualityData" Excel spreadsheet. Recognizing the significance of this data, I chose to investigate concentrations of ammonia, total nitrogen, total phosphorus, nitrogen oxides, chlorides, and *Escherichia coli* as a part of the most recently avaialble data, from 2018-2021.

Methods and Materials

The primary source of data for this investigation was derived from the sampling efforts of the VCU team utilizing their most recent compilation of data that spans from November 20, 2018, until December 9, 2021. In conjunction with their work sampling Little Westham Creek, the VCU team collects monthly data from four sites within Westhampton Lake, taking one to two samples of a nutrient per month for total nitrogen, total phosphorus, nitrogen oxides, ammonia, phosphate, chlorides, and the bacteria, *Escherichia coli*. Sample Site A resides closest to the largest inflowing stream, Little Westham Creek, which channels through Henrico County, a nearby shopping center, and residential areas prior to reaching Westhampton Lake (Figure 4). Sample Site B is located near a secondary source of incoming nutrients from a smaller stream that passes through residential areas and parts of campus before entering the lake. Sample Site C is positioned at the mid-way point of the lake on its northern bank, downslope of the hill leading to Lakeview Hall. Sample Site D is located closest to the spillway located behind Tyler Haynes Commons, where water exits the lake and enters the restored continuation of Little Westham Creek that flows through the Eco-Corridor to eventually meet the James River.

Nutrients Evaluated

Total nitrogen (TN) includes nitrogen oxides in addition to ammonia and organic nitrogen dissolved in water and stored within proteins and amino acids, released in the form of urea and uric acid (Scott, n.d.). Standards set by the US EPA recommend that freshwater bodies contain less than 2 milligrams of TN per liter of water (< 2 mg/L) to be considered capable of supporting aquatic life (United States Environmental Protection Agency, 1986). Similarly, total phosphorus (TP) accounts for all forms of dissolved and organic phosphorus, including forms that are attached to soil particles and/or within living and decaying matter, including animal waste (Georgian Bay Biosphere Reserve, 2022). Water with a content of TP falling below 0.012 mg/L is considered oligotrophic; water containing 0.012-.0024 mg TP/L is considered mesotrophic; water with 0.025-0.096 mg TP/L is considered eutrophic; and water with a content of TP that exceeds 0.096 mg/L is hypereutrophic (Noyes and Niesel, 2021). The standard for mesotrophic water is targeted as being ideal for Westhampton Lake with phosphorus and nitrogen together constituting two limiting nutrients that can enhance the growth of algae and prompt eutrophic conditions in freshwater environments. Ammonia (NH_3) causes direct toxic effects on aquatic biota and is derived from commercial fertilizers, organic waste matter, and the natural process of nitrogen fixation (United States Environmental Protection Agency, n.d.). Recommended levels of ammonia for freshwater bodies are less than 0.1 mg/L. Nitrogen oxides (NO_x) include nitrate, nitrite, and nitrogen dioxide as a function of total nitrogen, and are largely sourced from vehicle emissions. When found in excess, nitrogen oxides may cause acidification of water, prompt eutrophication, and/or result in other toxic effects for aquatic life (United States Environmental Protection Agency, 1999). *Escherichia coli* (*E. coli*) is a bacteria found in feces and sewage that poses a significant threat to human health when ingested and is a comparable threat to aquatic life when found in concentrations above 126 colony forming units (cfu)/100 mL (Office of Water Quality and Standards & United States Environmental Protection Agency, 1986). Lastly, chlorides (Cl) can exist as calcium chloride, sodium chloride, and magnesium chloride, and predominantly enter freshwater bodies like Westhampton Lake from the application of road salts as deicers (Hunt et al., 2012). Chlorides can react readily with ammonia and other nitrogenous substances in addition to interfering with the osmoregulation of biota, especially amphibians (Hunt et al., 2012). No uniform standard exists for chlorides for freshwater bodies under the US EPA due to their transient nature.

Nutrient Criteria

Guidelines established by the US EPA supportive of freshwater aquatic life and the Virginia Department of Environmental Quality (VA DEQ) were referenced to determine thresholds for each nutrient. In addition, the expertise of Allison Moyer, Associate Director of Landscape Services with University Facilities, Paul Sandman, Integrated Pest Management Specialist with University Facilities, Bob Siegfried, Senior Project Manager with Resource Environmental Solutions (RES), and Dr. David Riedl, Technical Services Manager with SOLitude Lake Management, were used throughout this investigation as supplementary resources for the evaluation of nutrient content information. Excel was utilized as a tool for compiling and sorting desired data, calculating minimum, maximum, and mean values for each nutrient, and producing visuals to relate nutrient levels to each sample site and sample date (Figures 5 and 6, and Table 1). This permitted the visualization of spatial and temporal trends for each nutrient based on sample site location and sample date, respectively, and analysis of these trends in the context of the recommended levels of each nutrient.

Results

An analysis of the minimum, maximum, and mean values of all evaluated nutrients revealed that the mean values of TP, NO_x, NH_3, and *E. coli* from November 20, 2018-December 9, 2021 surpassed recommended criteria (Table 1). The maximum recorded value for TP exceeded seven times that of its standard; the maximum for NH_3 was over six times its standard, maximum *E. coli* was over 39 times its standard, and maximum NO_x was almost twice its median standard (Table 1). Due to the absence of a clear standard for chlorides in freshwater, TN was the sole nutrient that did not surpass its recommended threshold. Evaluation of nutrient levels based on their sample site led to the observation of particularly high levels of NO_x and *E. coli* for site A (Figure 5). Of all sites, Site A exhibited the three greatest spikes for *E. coli*, NO_x, and TN (Figure 5). Considering the seasonality of nutrients, an outlier peak in chlorides was noted to occur between the fall of 2018-winter of 2019, and *E. coli* similarly had a standalone peak within the winter of 2019-spring of 2019 (Figure 6). Comparably, NH_3, NO_x, and TP followed more cyclical seasonal patterns, generally peaking during in the summer months and declining in the winter, with values associated with these maximums and minimums for NO_x declining over the duration of the three years (Figure 6).

Discussion

Bob Siegfried (RES) provided insight into the indications and potential sources of each nutrient. Although on average TN stayed below its threshold compared to other nutrients, Siegfried reported that results over 1.0 mg/L TN "are pretty stressful on [a] system" and are "high even for urban systems" (Figure 6). Dr. David Riedl (SOLitude Lake Management) noted the need for concern with spikes in TP levels stating that while nitrogen can be removed from a system with sufficient aeration and bacteria levels within a lake, phosphorus is more complex to work with and prone to accumulation over time from soil that enters the lake as it ages. Siegfried commented on a consistent cycle of high nitrate (NO_3) in the late fall to early spring, followed by a drop-off that he linked to the use of nitrate by algae during their growing season in the summer (Figure 6). This could indicate that nitrogen levels are consistently high all year long within the lake as NO_3 and ammonium, NH_4, as well as in the form of particulate organic nitrogen (PON) as algae tissue. Additionally, Siegfried linked spikes in NH_3 that occurred during the winter and during the months of June to either an input, like sewage, or low oxygen concentrations, and spikes in chlorides during the summer of 2018 with the use of the toxic disinfectant, chloramine (chlorine and ammonia), to clean out drinking water pipelines (Figure 6). Siegfried encouraged consideration of the history of drinking water pipeline breaks on campus, or swimming pools and/or water fountains that have been pumped out in the spring to be cleaned for the summer, explaining that these are major locations for "misconnections" where the overflow or backwash water is released into the stormwater system as opposed to the public sewer system, ultimately reaching the lake. Regarding the extremely high peak in *E. coli* at Site A on January 16th, 2020, although sewage systems could be to blame, Siegfried suggested that an unknown misconnection within sewer pipelines would result in a continual source of a pollutant and not the occasional spike (Figure 5). Further investigation is necessary.

If the university is to consider reopening the lake for recreational use, many of the nutrients considered in this study and their sources will have to be reevaluated in more depth. Overall, it is recommended to make changes to the current sample sites to permit discernment of nutrients entering the lake from on-campus versus off-campus sources. Specifically, the adoption of an upstream, potentially off-campus site (a portion of Little Westham Creek residing in Henrico County) would be beneficial to identify those nutrients arriving from off-campus prior to their entry into the lake. A downstream site located beyond the spillway of THC, within Little

Westham Creek, could also be beneficial to sample to evaluate what nutrients are exiting the lake. Finally, the testing of stormwater at select manhole covers located far enough upstream of the lake to contain purely on-campus runoff are suggested for future sampling procedures (Figure 7). Accordingly, there exists the need to develop and implement a university-wide stormwater management program to monitor outfalls following heavy precipitation events. It would also be advantageous to include supplementary records of the weather conditions (such as temperature or recent precipitation events) along with field notes and the testing of other variables such as dissolved oxygen content, pH, and turbidity of the water – two measurements that are included within the sampling procedure of Little Westham Creek but excluded from that of the lake – when sampling occurs at the proposed modified site locations. Another factor worthy of consideration that influences the duration of the presence of certain nutrients within Westhampton Lake is the residence time of its water, a quality that can take the form of a few hours to a few years, via the determination of the flow rate of the water of the lake (Shaw, 2004; Sage, 2014).

Equally vital is the need to adopt consistent, standardized criteria for the evaluation of appropriate levels of nutrients/pollutants for Westhampton Lake. While US EPA standards apply country-wide and were used for the purpose of this investigation, the VCU team and the University of Richmond do not acknowledge specific criteria values to be referenced when considering the documented data. Even amongst experts, recommendations of nutrient contents for freshwaters vary. For example, Riedl stated that levels above 2 mg/L NO_x for freshwaters were unadvisable whereas Siegfried did not recommend surpassing 1 mg/L for the same nutrient. To complicate things further, the Water Watch Partnership through the University of Massachusetts at Amherst states that NO_x levels that exceed 0.3 mg/L are capable of supporting summer algal blooms (UMass Amherst Massachusetts Water Watch Partnership, 2016). Lack of clarity can lead to misinterpreted decisions and ineffective or potentially harmful attempts at implementing solutions.

The organization and maintenance of data within the master spreadsheet and ensuing reports could also be improved. Within the latest report used for this investigation, the sample collection for phosphate was included for the lake but it was incomplete, with values nonexistent for sampling between December 4, 2019, and December 9, 2021. Further, details pertaining to some nutrients were vague/unclear. For example, ammonia (NH_3) was listed on the report sheet while ammonium (NH_4) was listed on the actual data sheet, and the representation of “Cl” as all forms of dissolved chlorides as opposed to chlorine was not made explicitly known.

One additional alternative that could be considered to assist with removal of excess nutrients from the lake is the construction of a floating treatment wetland (FTW) or a retaining wall within the lake or along its banks, respectively. FTWs or floating wetland systems (FWS) are a form of a constructed wetland (CW) that can be used to absorb excess nutrients in a nondiscriminatory way from nutrient-rich freshwater water bodies (Díaz et al., 2012). Within these systems, plants absorb nutrients through their roots and shoots, with most nutrient storage occurring in the latter area (Garcia et al., 2019). FTWs must take into account the style of flow of a water body, water evapotranspiration processes, characteristics of vegetation, and residency time of water in the process of their design (Díaz et al., 2012). Recognizing the direction of flow from Westhampton Lake and the initial entry of nutrients near sites A and B, the introduction of a FTW would be most effective in proximity to these two sites. Plants composing FTWs are able to help reduce TN and TP concentrations from the water, especially during their initial rapid growth stage when introduced to the water (Chua et al., 2012). The Lewis Ginter Botanical Garden, a local botanical garden in Richmond, Virginia, has successfully constructed and maintained a FTW in the past (Holland, 2013) (Figure 8). Alternatively, a retaining wall could be constructed along the northern bank of Westhampton Lake at the base of Boatwright Hill and along Campus Drive to directly block nutrients linked to surface runoff from these features and other higher elevation sources from the Richmond College side of campus (Figure 9). A plan for the introduction of a retaining wall complete with biofilters was proposed to the university in 2012 by 3north, a design firm of landscape architects and interior designers (3north, 2012; Figure 10). Here again stormwater surveillance of drainpipes located beneath manhole covers around campus would be necessary to determine the relative contribution of nutrients arriving from off-campus or on-campus drainage and thus the effectivity of biofilters within this design concept. A retaining wall could also potentially deter the lingering of Canadian geese and their production of waste along the bank of the lake, a particular nuisance species on campus. Comparing the two constructed methods, a FTW would require more long-term maintenance than a retaining wall, with a retaining wall likely having more expensive up-front costs.

In conclusion, small lakes like Westhampton Lake are not only recognized for the dynamic biotic communities that compose them and the ecosystem services that they provide but also for their important role in the sustenance of high values of biodiversity on a regional scale, in support of beta diversity (Biggs et al., 2017). While nutrient testing conducted by the VCU team is expensive, equating to an estimated annual cost of $14,000 to the University of Richmond (according to Allison Moyer, University Facilities), there exists the need to continue monitoring efforts in order to maintain the health of Westhampton Lake to sustain aquatic life, catch potential issues early-on through routine discussion of findings, gain a better understanding of the sources of problematic nutrients that find their way into the lake, and increase collaboration with neighboring counties in protection of the larger James River and Chesapeake Bay watersheds.

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Figure 1: A map of the landscape of Richmond displaying the interconnectivity of Little Westham Creek, Westhampton Lake within the University of Richmond, and the James River and Kanawha Canal (obtained from the "Stormwater" map within the public "GIS_water_data" ArcGIS Project File: \\hemisphere\geopower\PUBLIC\DATA\CampusData\Water_Quality\GIS_water_data).

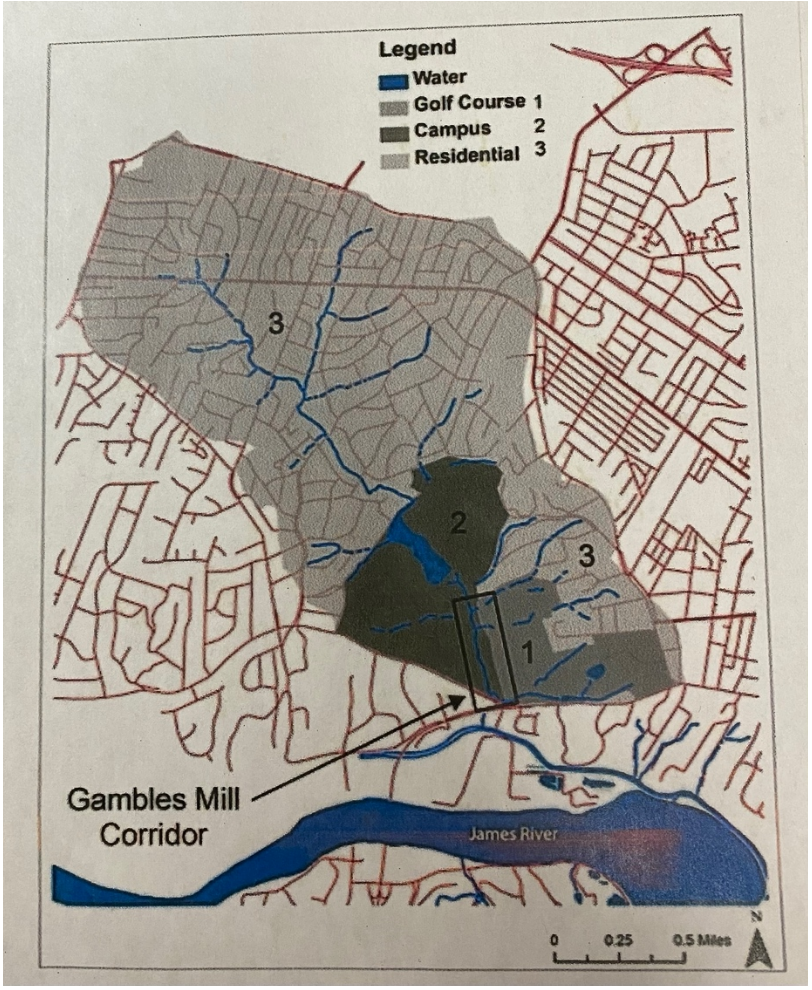


Figure 2: The shared watershed between the campus of the University of Richmond, residences, and the Country Club of Virginia's Westhampton Course.

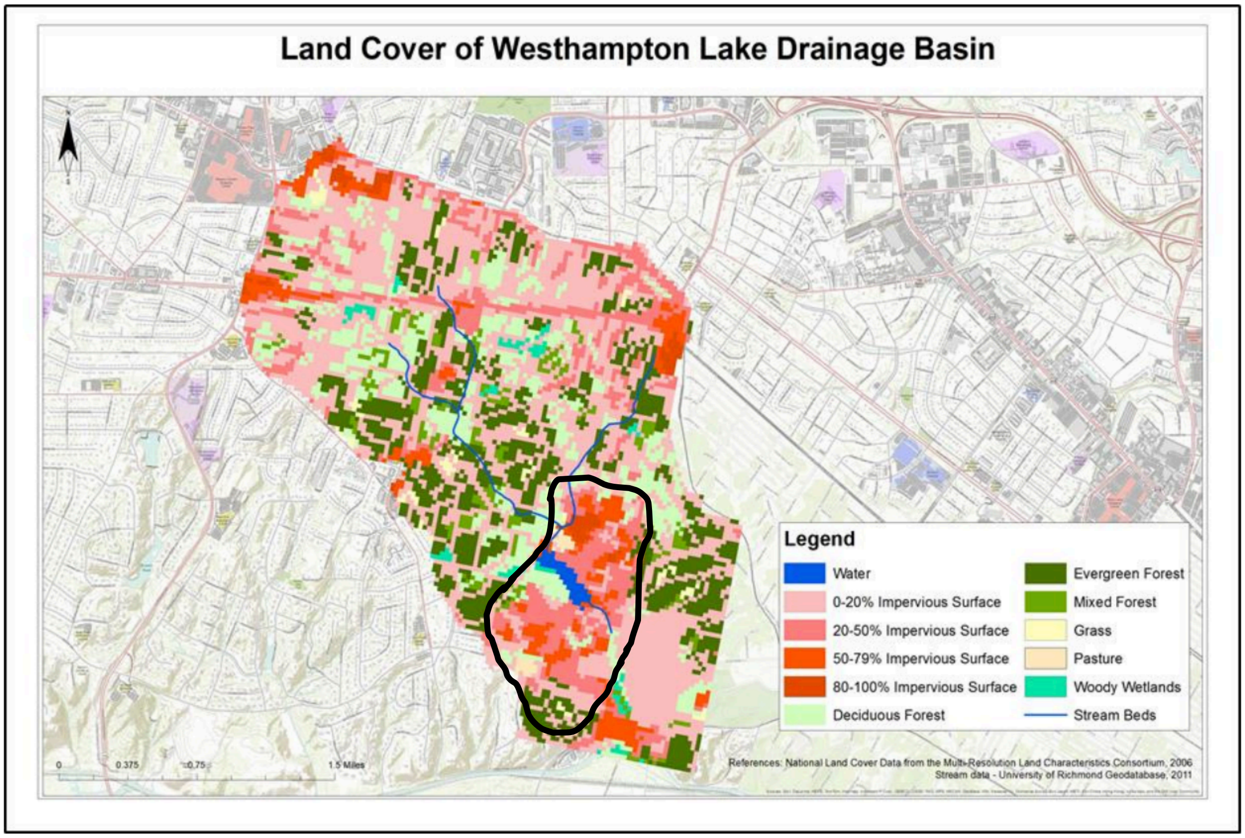
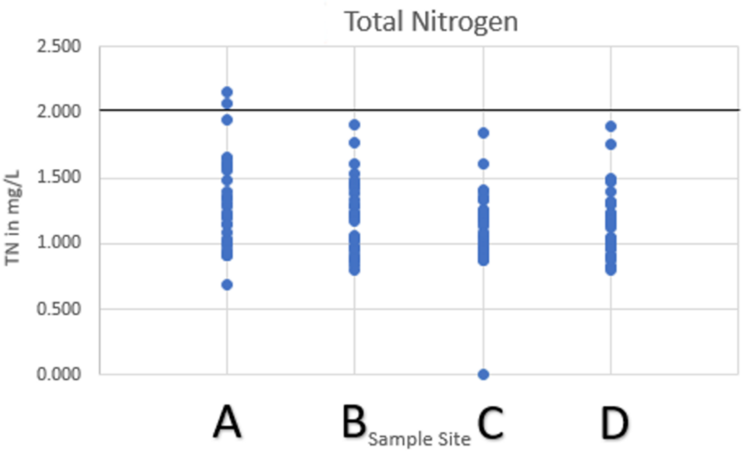
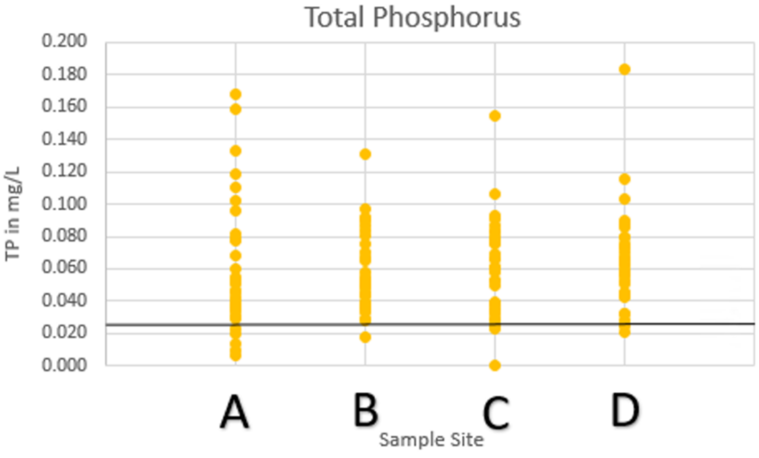
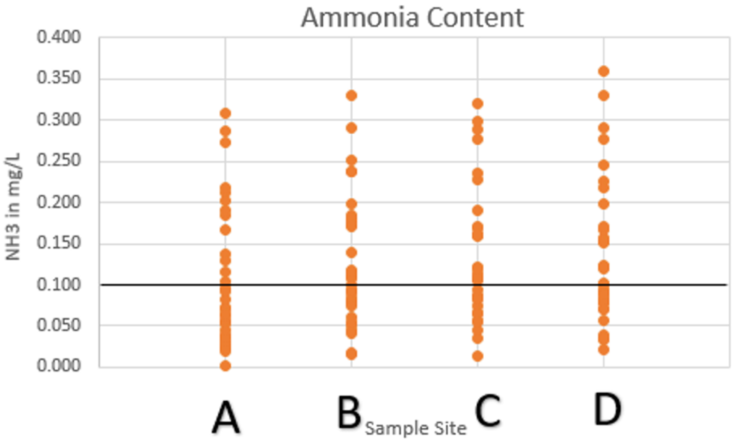


Figure 3: Land classification of the Westhampton Lake catchment area (Ahnell et al., 2014). The boundaries of the main campus of the University of Richmond are outlined in black.

Figure 4: Map of sample sites, originally assigned numbers, used by the VCU team for Westhampton Lake.


Total Nitrogen
2.500
2.000
1.500
1.000
0.500
0.000
TN in mg/L
A
B
Sample Site
C
D


Total Phosphorus
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
TP in mg/L
A
B
C
D
Sample Site


Ammonia Content
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
NH3 in mg/L
A
B
Sample Site
C
D

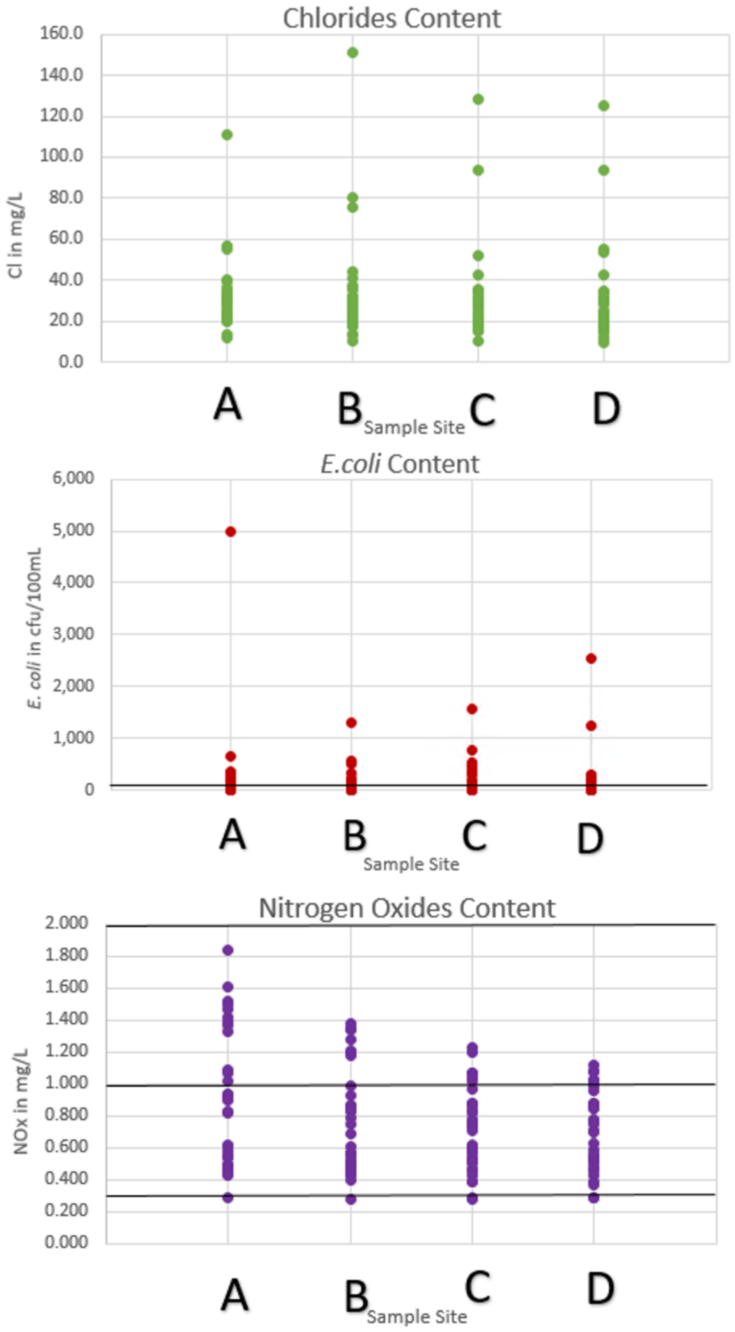
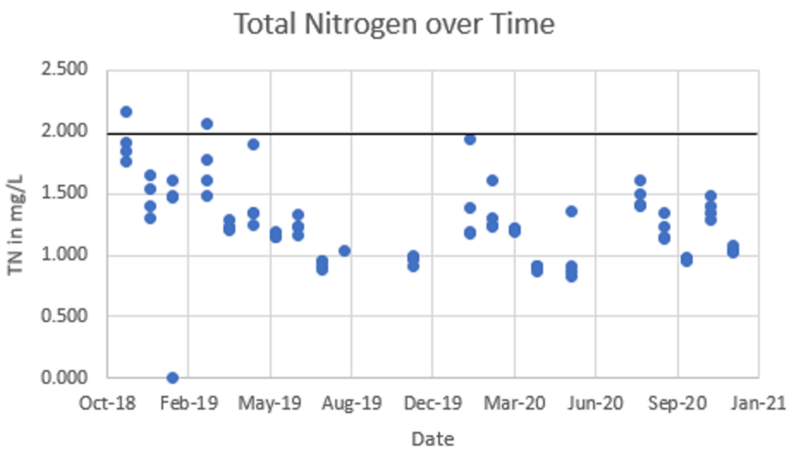
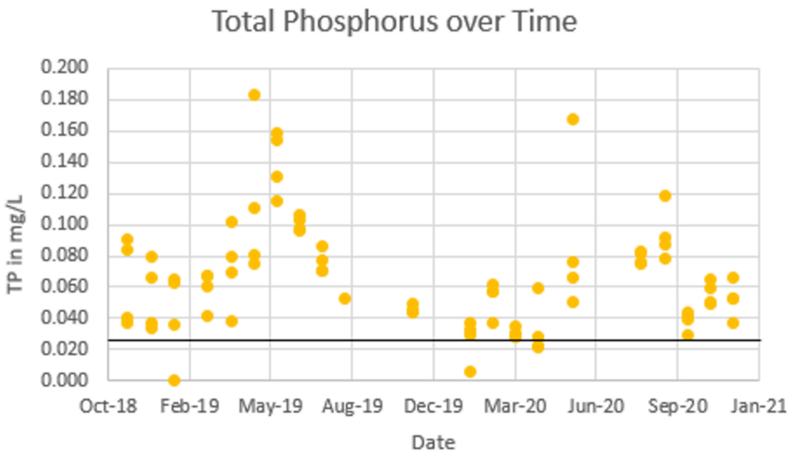
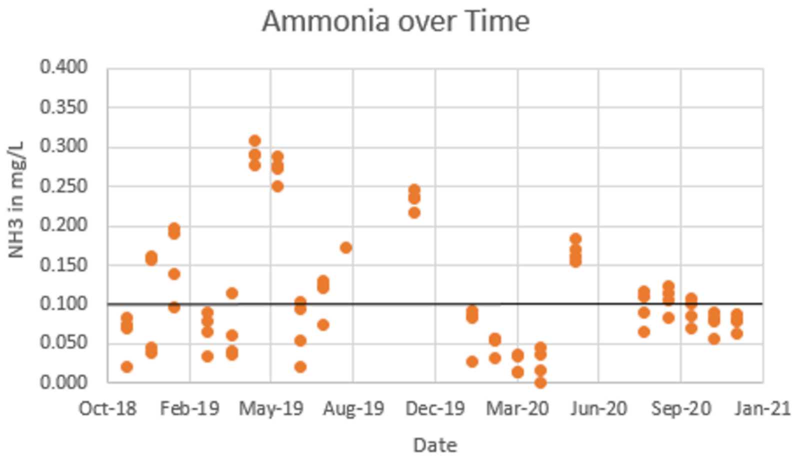


Figure 5: Spatial variation of nutrients from November 20th, 2018, until December 9th, 2021, based on sample site location. Black horizontal lines designate threshold levels for each nutrient based on the VA DEQ freshwater aquatic life acute toxicity standards and US EPA standards for freshwater bodies (*9VAC25-260-140*, 2019; United States Environmental Protection Agency, 1986). Three alternative criteria are presented for NO_x based on the recommendations of Bob Siegfried, David Riedl, and the University of Massachusetts at Amherst (UMass Amherst Massachusetts Water Watch Partnership, 2016).


Total Nitrogen over Time
TN in mg/L
2.500
2.000
1.500
1.000
0.500
0.000
Oct-18
Feb-19
May-19
Aug-19
Dec-19
Mar-20
Jun-20
Sep-20
Jan-21
Date


Total Phosphorus over Time
TP in mg/L
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
Oct-18
Feb-19
May-19
Aug-19
Dec-19
Mar-20
Jun-20
Sep-20
Jan-21
Date


Ammonia over Time
NH3 in mg/L
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
Oct-18
Feb-19
May-19
Aug-19
Dec-19
Mar-20
Jun-20
Sep-20
Jan-21
Date

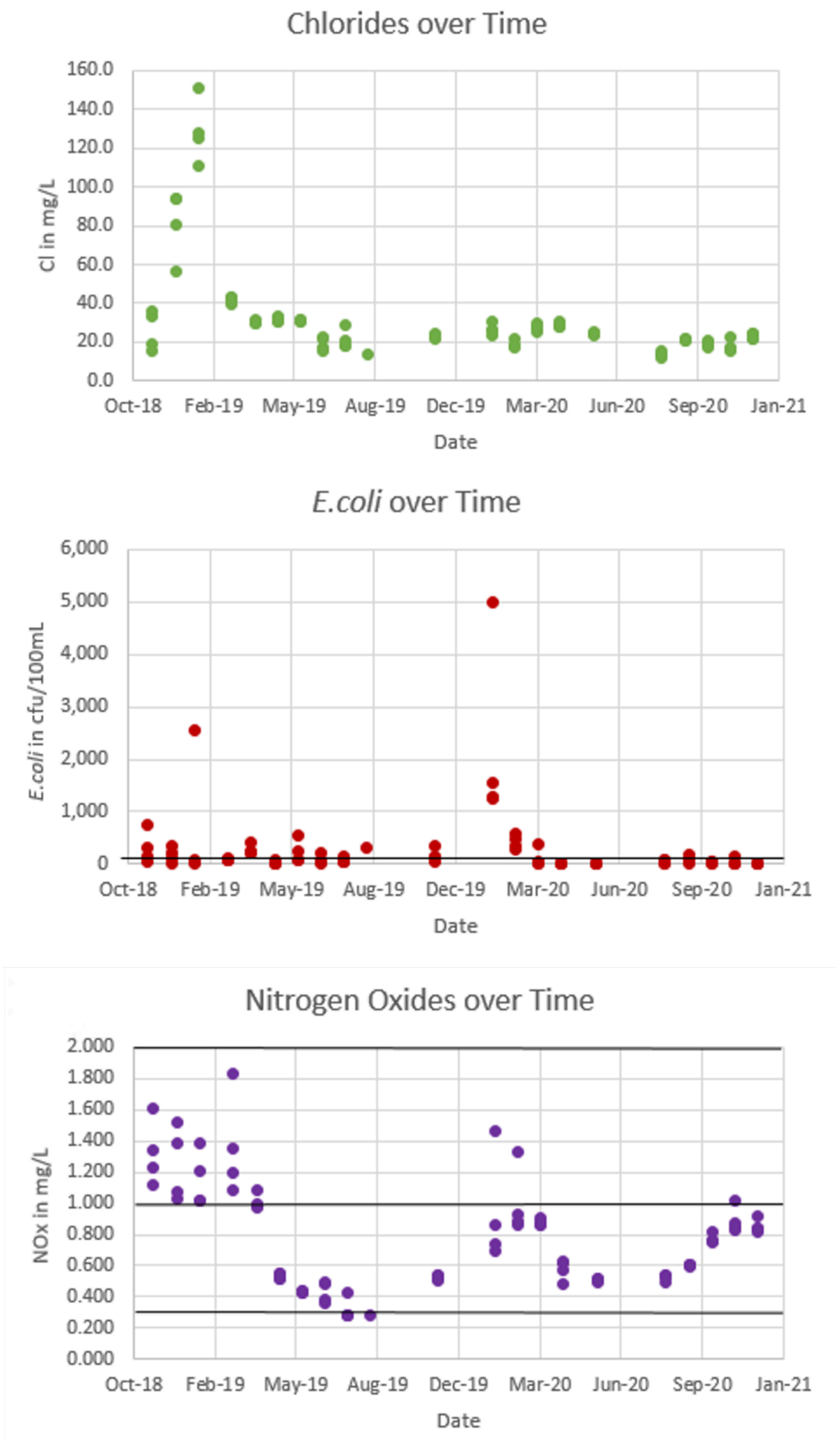


Figure 6: Temporal variation of nutrients from November 20th, 2018, until December 9th, 2021. Threshold levels have been maintained from the previous set of figures for each nutrient based on standards set by the VA DEQ, US EPA, and recommendations from local experts (*9VAC25-260-140*, 2019; United States Environmental Protection Agency, 1986). Three alternative criteria exist for NO_x based on the recommendations of Bob Siegfried, David Riedl, and the University of Massachusetts at Amherst (UMass Amherst Massachusetts Water Watch Partnership, 2016).

Table 1: Minimum, maximum, and mean values calculated for each nutrient, cumulatively, in comparison to the EPA-set standards appropriate for freshwater aquatic life. Alternative standards for NO_x are represented based on three different sources. No clear standards exist for chlorides.

	TN (mg/L)	**TP (mg/L)**	**NH_3 (mg/L)**	**Cl (mg/L)**	***E. coli*** **(cfu/100mL)**	**NO_x (mg/L)**
Minimum	0.65	0.006	0.001	9.6	0	0.008
Maximum	2.158	0.183	0.605	150.8	5000	1.837
Mean	1.141	0.061	0.143	29.3	214	0.658
Standards	<2	<0.024	<0.1		<126	<0.3 (UMass Amherst), <1 (Siegfried), <2 (Riedl)

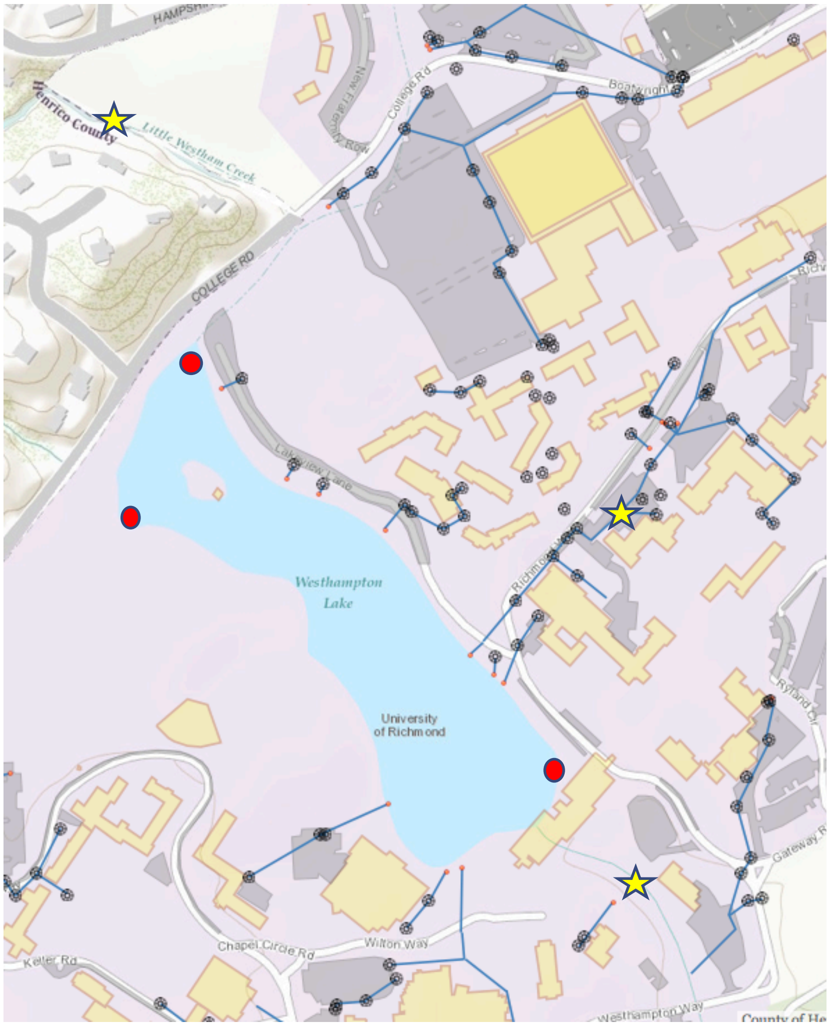


Figure 7: Map of the stormwater drainage system that exists on campus at the University of Richmond. Yellow stars have been added to denote two proposed new sampling sites to compliment those within the lake. Red circles denote current sampling sites that should remain.

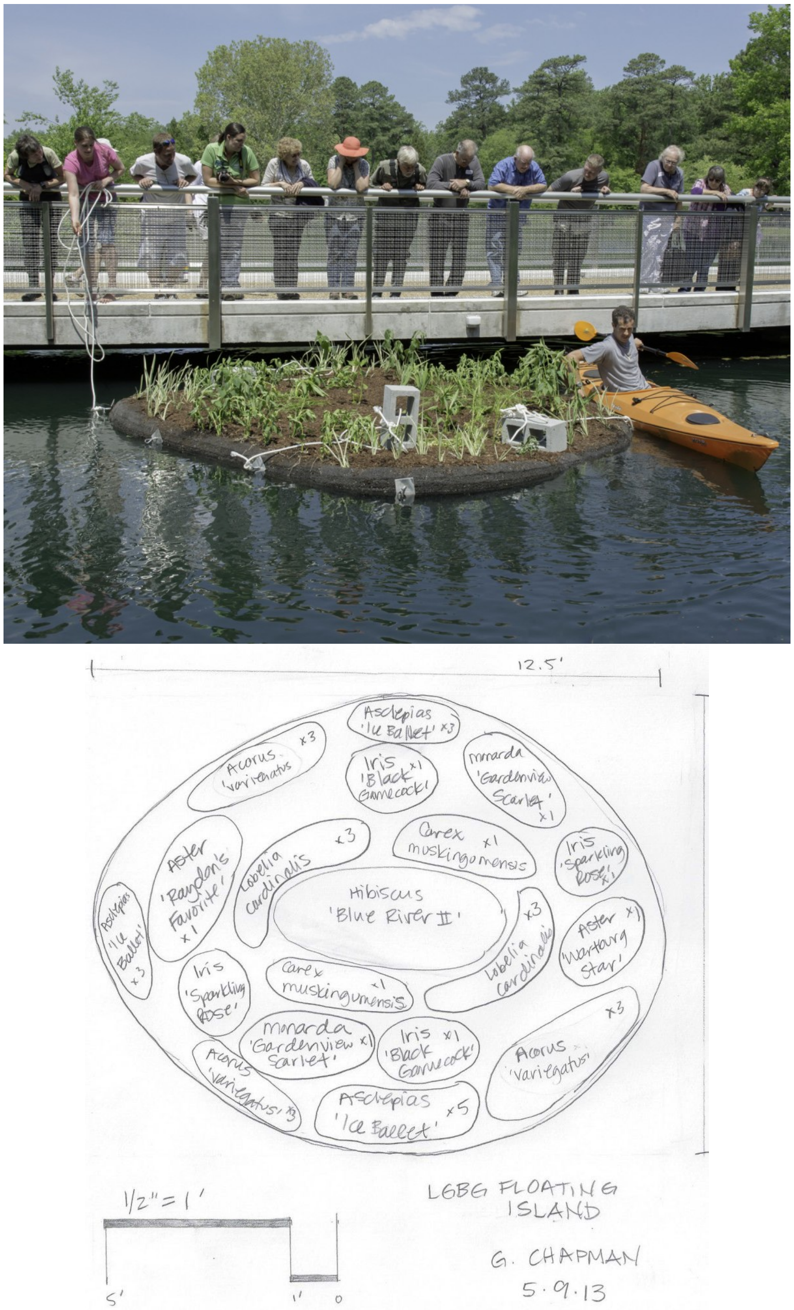


Figure 8: The floating treatment wetland ("floating island") introduced to Lewis Ginter Botanical Garden (Holland, 2013).

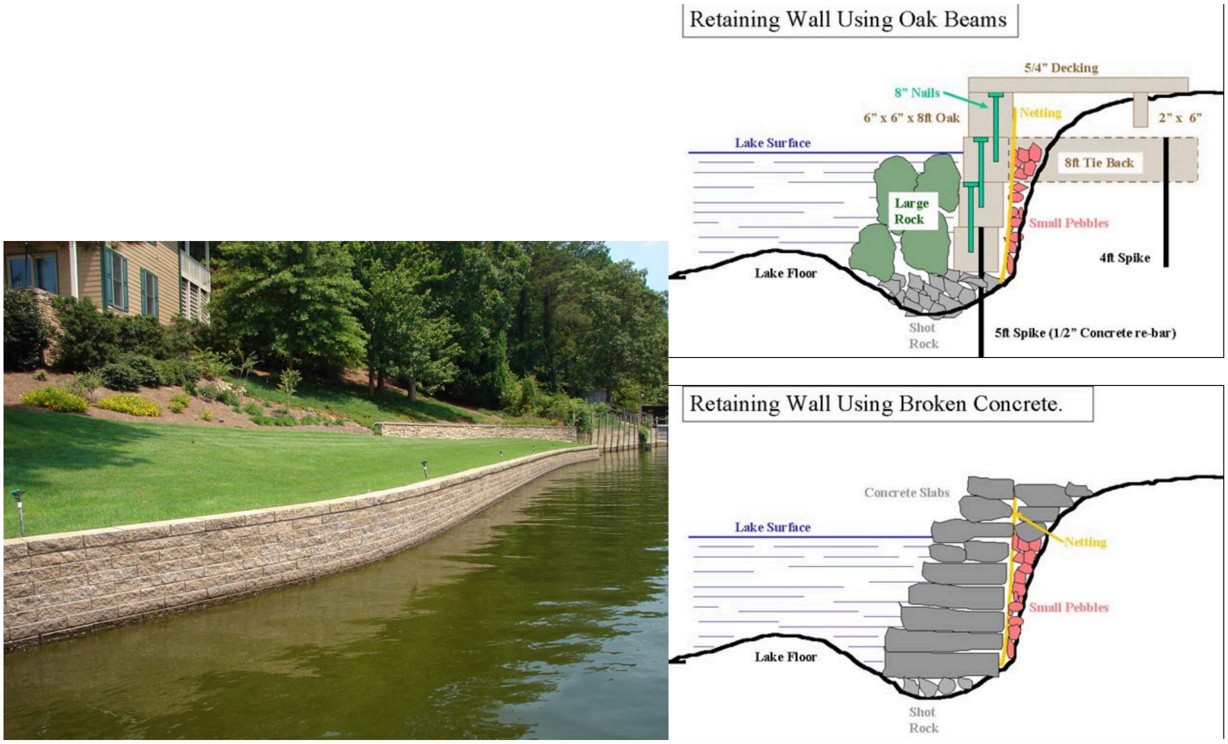


Figure 9: A hypothetical example of a retaining wall and its design methods that could similarly be constructed along the bank of Westhampton Lake (Seawall, n.d.; *There are 3 ways to build a retaining wall*, n.d.).

Figure 10: 3north's design for a retaining wall with biofilters to be constructed along the lake (3north, 2012).