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Analyzing a Small-Scale, Constructed Wetland for Stormwater Treatment

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Abstract:

Stormwater treatment by means of constructed wetlands has the ability to effectively remove pollutants such as total suspended solids, nitrite, nitrate, and ammonia. Utilizing two small, lab-scale constructed wetlands, one free water flow system and one subsurface flow system, our research team analyzed the levels of these pollutants at different locations in the wetland. Our team of two Civil and Environmental Engineering undergraduate students tested a variety of different water samples including tap water, stormwater, and a high nitrate solution. A consistent decrease in nitrate and nitrite was observed throughout the systems. While there was not an overall decrease in ammonia, there were decreases between individual basins. This research demonstrates the potential impact of implementing constructed wetlands as a lower cost, environmentally friendlier alternative to reduce combined sewer overflows, or treatment via traditional wastewater treatment plants.

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1.0 Introduction:

Wetlands are areas where water covers the soil, or is present either at or near the surface of the soil year-round, or for varying periods of time during the year, including during the growing season (1). Wetlands differ from region to region due to changes in climate, soil type, vegetation, and precipitation. Constructed wetlands are man-made treatment systems that use vegetation, soils, and natural processes in order to improve overall water quality. Constructed wetlands are a prime application of biomimicry, the science of studying nature's models and systems, and adapting their designs and processes to fit our needs (9). Building off of the wetlands' natural ability to purify water, we can further adapt its design to maximize its efficiency. In addition to meeting human needs, wetlands provide an ecosystem beneficial to a variety of animals and insects.

There are two distinct varieties of constructed wetlands: free water flow (FWS) and subsurface flow (SSF). A SSF system consists of layers of rock, soil, water, and air (17). There are three basins for testing purposes; the middle acts as the main subsurface flow component. Subsurface flow systems allow for year-round operation, and cut down on insects which would otherwise be a factor. However, these factors are less concerning in the field (2). A typical FWS constructed wetland with emergent macrophytes is a shallow sealed basin or sequence of basins, containing 20–30 cm of rooting soil, and a water depth of 20–40 cm. Dense emergent vegetation covers a significant fraction of the surface, usually upwards of 50% (12). Besides planted macrophytes, naturally occurring species may be present. The benefits of FWS systems include the capability of fixing the system with locally available materials, omitting the use of electricity and chemicals for wastewater treatment, and lowering construction and operation costs (2).

The development of two small-scale wetlands, one FWS and one SSF, by a research team made up of students and a professor in the Civil and Environmental Engineering Department at Rose-Hulman Institute of Technology in 2014 gave us the opportunity to further explore pollutant removal in constructed wetlands. Comparing the effectiveness of the FWS and the SSF systems allows us to better gauge the removal of nitrate, nitrite, and ammonia throughout the two CW systems.

2.0 Background:

The various advantages of using wetlands to treat wastewaters can be outlined by the three pillars of sustainability (social, economical and environmental). Environmental and social benefits of using a CW include erosion and flood control, natural stormwater filtration, habitat creation for a wide range of species, and possibilities for educational use. Economically, constructed wetlands have the potential to financially friendly alternative to conventional systems, which cost between 50% and 90% more to construct.

Before we see constructed wetlands being more widely used as a means for water purification, lingering issues need to be sorted out. One such concern is the potential cost of maintaining the wetlands, particularly in cases of natural disasters and obstacles. For instance, insect problems can range from an inexpensive task such as mosquito control, to costly tasks such as infestation eradication. An imbalance in the ecosystem, potentially due to littering or pollution, can greatly affect the effectiveness of the process (2). Furthermore, constructed wetlands take up more total land than a conventional system, which could drastically reduce plausibility in highly populated areas, and regions where land prices are at a premium, such as near coastlines. There is currently not enough information about constructed wetlands for them to be used to treat all wastewater.

Nitrogen plays a crucial role in the lives of all living organisms, N_2 making up nearly 80% of the atmosphere, though it is in a form that is not useful to humans due to its unreactive state (3). The process in which nitrogen is converted chemically throughout the atmosphere is known as the nitrogen cycle. There are five main processes of the cycle: nitrification, denitrification, nitrogen fixation, ammonification, and assimilation, which ultimately produce ammonia, nitrite and nitrate.

Nitrogen fixation is a process by which molecular nitrogen is converted to a more-reactive form (ammonia, nitrates and nitrites). Simply put, this is when nitrogen is turned into useful forms. It can be written as $N_2 + 8H^+ + 8e^- + 16ATP \rightarrow 2NH_3 + H_2^+ + 16ADP + 16P_i$ (6).

Ammonification is the process in which the organically bound nitrogen of microbial, plant, and animal biomass is turned into ammonium by bacteria breaking down organic matter (7). This process happens more rapidly than nitrification, which ultimately allows for increasing ammonia concentrations along a flow path of a wetland (15). The rate at which the process takes place is dependent on pH levels and temperature in the soil. Ideally, the pH level would range from 6.5 to 8.5.

Ammonia is a large source of nutrition for many organisms, especially plants which absorb the chemical to help increase their rate of growth (7). A common farming practice is to inject the soil with premade ammonia, which acts as a catalyst to make natural processes occur more quickly. Though ammonia is highly hazardous when inhaled by a human, it does not last long in the atmosphere before being absorbed (7).

Nitrification is a microbial process by which reduced nitrogen compounds, primarily ammonia, are sequentially oxidized to nitrite and nitrate (4). The process follows the following chemical equations:

1. $NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$ (ammonia to nitrite)
2. $NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$ (nitrite to nitrate)

There are potential issues with high quality water from nitrification. These issues include reduction in pH levels, bacterial growth or regrowth, and dissolved oxygen depletion (4). These can be harmful to humans and animals when they are exposed to waterborne pathogens by drinking the water.

Assimilation is the process by which plants and animals use the nitrites, nitrates, and ammonia formed through the previous processes of nitrogen fixation and nitrification (8). They serve as nutrients and proteins to plants and other organisms.

During denitrification, nitrate is reduced to produce molecular nitrogen written as N_2. The progress can be written as $2NO^{3-} + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O$ (14). It is important that this process occur in order to regulate the chemicals involved in the process, nitric oxide, and nitrous oxide, as they are greenhouse gases that can be harmful in massive amounts in the atmosphere.

In practice, denitrification can be used to remove nitrogen from sewage and municipal wastewater (5).

3.0 Methods

Our research team concentrated on the removal of nitrate, nitrite, and ammonia occurring during the natural purification process of the water flowing through the constructed wetlands. Past research conducted by a Rose-Hulman research team indicated that the nitrogen removal cycle may be a major benefit of constructed wetlands.

3.1 Wetland Setup

The constructed wetland is a collection of basins set up in the Cook Laboratory for Bioscience Research at Rose-Hulman Institute of Technology. The purpose of the constructed wetlands is to imitate the functions and natural processes of larger scale constructed wetlands. Our system is composed of two separate configurations, one FWS and one SSF, each operating independently from the other. Water is pumped into each configuration from a reservoir, and subsequently flows through three basins, each connected through its own valve-controlled hose.

Every basin has a unique primary function. The first basin, filled with soil and plants, is designed to filter out suspended solids. The second compares different methods of nutrient absorption. The SSF has water run below the surface of the soil, passing through the roots of surface plants. In contrast, the FWS has the water flow freely above the soil, and contains water-based plants floating above the water surface. The third and final basin serves to filter out smaller particles not picked up in the other basins.

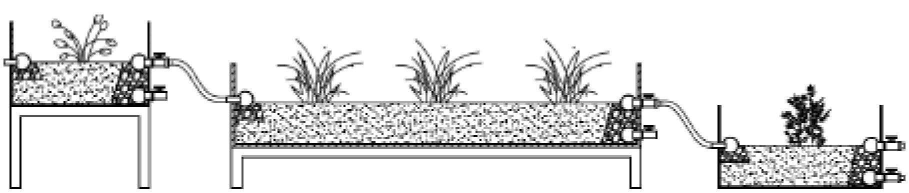

Figure 1: SSF (13)

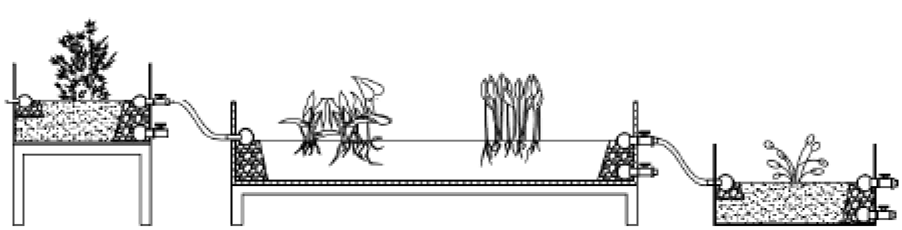

Figure 2: FWS (13)

	Rock	Gravel	Sand	Topsoil	Sandy Loam	Peat	Composted Waste
Basins 1/3	10%	20%	35%	35%	17.5%	8.75%	8.75%
Basin 2 (FWS)	50%	0%	0%	50%	25.0%	12.5%	12.5%
Basin 2(SSF)	10%	20%	20%	50%	25.0%	12.5%	12.5%

Table 1: Soil composition of each basin

Maintenance of the wetland required constant attention to the health of the wetland ecosystem, and the state of the basin structures and connectors. Although the wetland system had already been built by previous researches, minor repairs and installations were necessary to ensure functionality. The pump initially installed was significantly larger than needed for the scale of our wetland, so it was replaced by a PE-A series Little Giant pump, which had a more appropriate pumping rate for our purposes. Another problem was getting a consistent, gradual, flow of water running through the system. Due to leaking issues in the basins, silicone was reapplied to the hoses connecting the basins multiple times to effectively seal the connections. Once the system was in operation, routine maintenance was performed to keep it running. The greenhouse in which our research was conducted had an infestation of mealybugs, which contributed negatively to the health of our plants. We sprayed Neem Oil and Safer Soap on the plants and pruned them regularly in an attempt to control the infestation. The FWS had consistent buildup of algae, requiring regular cleaning of the basin. The FWS basin proved to be a difficult environment for the water-based plants to survive, presumably due to a combination of high temperatures and the mealybug problem.

3.2 Wetland Operation

The function of the system is to pump source water through three separate, interconnected, basins in order to purify stormwater. The source water is stored in a 50 gallon reservoir, and subsequently pumped by the pump into the first basin of either the FWS system, the SSF system, or both. After the water flows into the first basin, gravity continues the flow of water through the system. As water makes its way through the wetland, plants absorb the target pollutants during the purification process.

In our tests, we allow the source water to flow through both the FWS system and SSF system at a flow rate of 80 gallons per hour for approximately 6.5 hours. The hydraulic retention time (HRT) was found by dividing volume by flow rate.

The first tests ran used tap water in order to troubleshoot any functional problems in the system. Additionally, it provided data points on the effects of a wetland on previously purified water. After major rainfall, we were able to perform the same procedure using stormwater. We also ran tests with a high nitrate solution in order to better gauge nitrate and nitrite removal.

3.3 Chemical Testing

All chemical testing was taken within an 8 week period spanning between June, July and August. The order of testing was consistently nitrate, nitrite, ammonia, temperature, pH and total suspended solids. The samples had less than one hour between being taken from basins to being measured in the lab. During that time period the samples were stored in the fridge to limit any chemical reactions which may have occurred after collection.

Nitrate: The concentration of nitrate was measured using a Hach DR 2800 spectrometer (product #DR2800-01B1) and Hach Method 8171. A NitraVer 5 powder pillow (product #1403428) was poured into 10 mL of sample and shaken until dissolved. A blank sample was then created for testing. A five minute reaction time began and the measurement was taken afterwards in mg/L. This test was measured once with tap water, twice with stormwater, and three times with high nitrate water. Each test required three measurements be taken.

Nitrite: The concentration of nitrite was measured using a Hach DR 2800 spectrometer (product #DR2800-01B1) and Hach Method 8507. A NitraVer 3 powder pillow (product #2107169) was poured into a 10 mL of sample and shaken until dissolved. A blank sample was then created for testing. The reaction was monitored for 20 minutes, and a measurement was taken afterwards in mg/L. This test was measured once with tap water, twice with stormwater, and three times with high nitrate water. Each sample was measured in triplicate.

Ammonia: The concentration of ammonia was measured using a Hach DR 2800 spectrometer (product #DR2800-01B1) and Hach Method 8155. An Ammonia Salicylate powder pillow (product #2653299) was poured into a 10 mL of sample and swirled to dissolve. After a three minute reaction period, a Ammonia Cyanurate Reagent powder pillow (product #2653199) was poured into the sample to dissolve. A blank sample was created for the testing process. After a twenty minute reaction period, the measurement was taken in mg/L. This test was measured once with tap water, twice with stormwater, and three times with high nitrate water. Each sample was measured in triplicate.

Total Suspended Solids: A Hach 2100P Portable Turbidimeter (product #4650000) was used to test turbidity of the samples. This test required the sample to be stirred, poured into the sample cell, and placed in the turbidimeter yielding a value in Nephelometric Turbidity Unit (NTU). This test was measured once with tap water, once with stormwater, and twice with high nitrate water.

Temperature and pH: A Beckman pH/Temp/mV/ISE Meter was used to determine the temperature and pH of each sample. After calibration, a probe was stuck into the sample and swirled around until a constant value was met. This test was run once initially, twice with stormwater, and three times with high nitrate water. Each test required three measurements be taken.

4.0 Results

Nitrite:

A consistent decrease in nitrite across the overall system was observed. For tap water testing, there was 50% increase in nitrite concentration in the SSF system Basins 1 and 2. However, this was followed by an 83.33% removal between Basins 2 and 3 (Figure 3). In the freeflow system, there was a 75% removal across all basins. For stormwater, there was a decrease among each basin for both the subsurface and freeflow systems. The subsurface concentrations varied from 0.0130 mg/L in the reservoir to 0.0020 mg/L in Basin 3, while the freeflow system ranged from 0.0130 mg/L to 0.0015 mg/L. High nitrate results showed a 91.66% removal for the subsurface system (Figure 3). However, there was an increase in concentration from Basin 1 to Basin 2 in the freeflow system of 27.3%. Overall, there was a 62.2% removal for the freeflow system and a 60% removal in the subsurface flow system for the high nitrate solution.

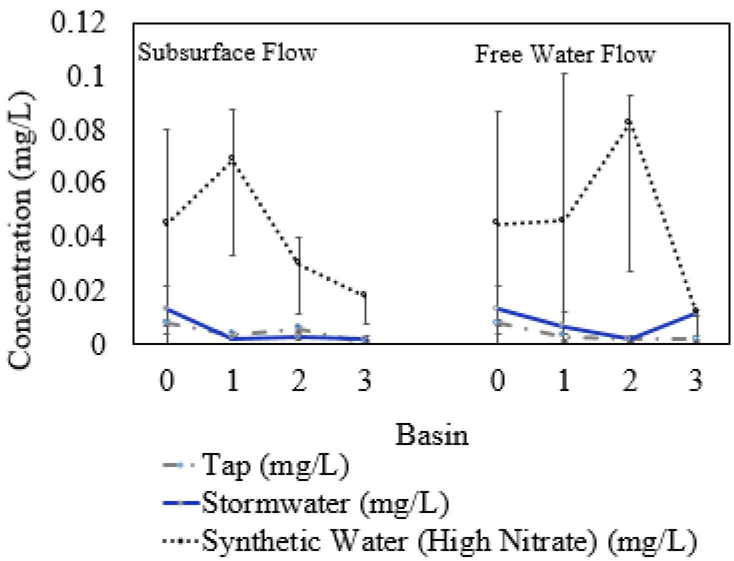

Figure 3: Nitrite concentrations from tap water, stormwater, and synthetic water testing

Nitrate:

There was a consistent decrease in concentrations of nitrate in both systems for tap water, storm water and high nitrate testing. Tap water had a high variability in concentrations, showing a 217% increase between Basin 1 to Basin 2 in the subsurface system, and a 57% removal from basin 2 to basin 3 in the freeflow system (Figure 4). There was an overall removal of 50% in the subsurface system and of 16.66% in the freeflow system. Stormwater yielded an overall percent removal of 46.82% in the subsurface system, and 43.48% in the freeflow system. For high nitrate testing, there was a vast difference in both systems between the reservoir, Basin 1 and Basin 2 compared to Basin 3 (Figure 5). Overall, there was a 43.47% removal in the freeflow system and a 47.82% removal in the subsurface flow system for the high nitrate solution.

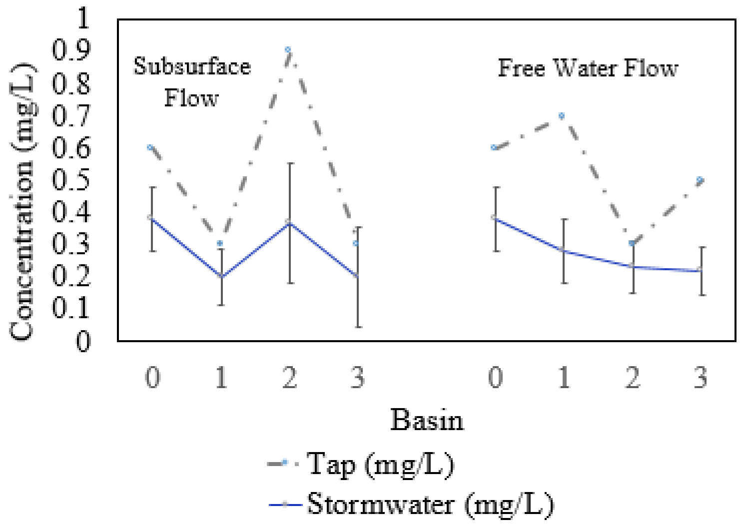

Figure 4: Nitrate concentrations from tap and stormwater testing

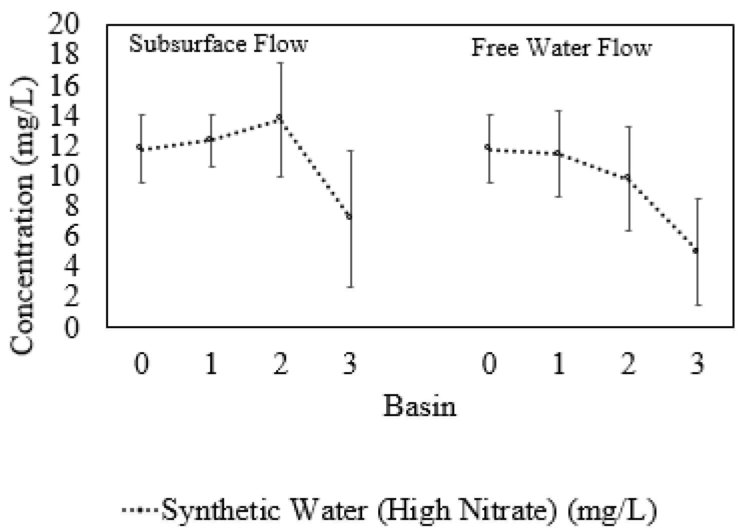

Figure 5: Nitrate concentrations from synthetic water testing

<u>Ammonia</u>:

Ammonia had the most variability in concentrations of all of the pollutants measured. Part of the variability stemmed from the amount of testing done compared to other tests (Section 3.3). Tap water testing showed an overall increase for both systems increasing levels 1200% in the subsurface system and 1600% in the free flow system (see figure 6). Stormwater removal rates varied greatly between the two systems. The subsurface system increased the concentration by 106.5%, whereas the freeflow system yielded a removal of 83%. High nitrate results show a 70% removal from the reservoir to Basin 1, but an increase 200% in the remaining basins in the subsurface system (Figure 6). In the freeflow system, there was a decrease of 60% from the reservoir to Basin 1, but an increase of 75% between Basin 1 and Basin 3. Overall, the high nitrate solution showed increases of 8.96% in the freeflow system, and 11.94% in the subsurface system.

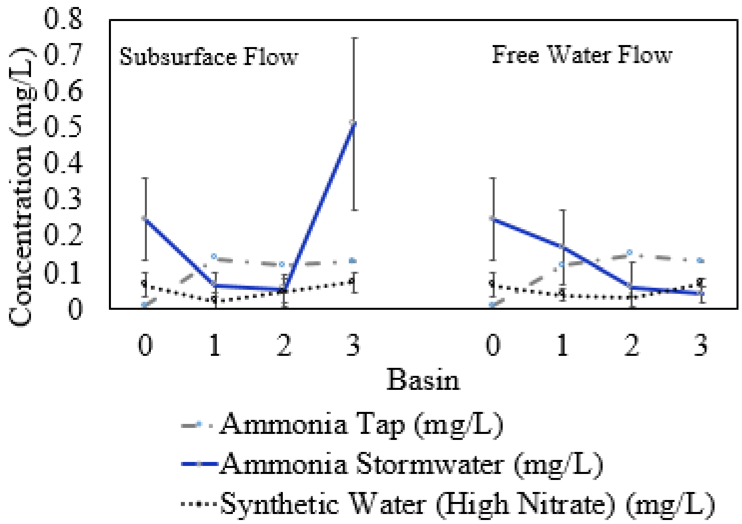

Figure 6: Ammonia concentrations from tap water, stormwater, and synthetic water testing

Turbidity:

An overall increase in total suspended solids was observed in the tests run, but removal in basin 3 varied by system. There was an overall percent removal of 49.8% in the subsurface system and of 14.6% in the freeflow system. However, there were points of increase between basins. In the subsurface system for stormwater there was a large decrease of 84.16% observed between the reservoir and Basin 2, but a 136% increase from Basin 2 to Basin 3. This resulted in an overall increase of TSS in the subsurface system. Unlike the subsurface system, the freeflow system consistently decreased levels in all basins, resulting in a 63.8% removal. For high nitrate testing, there was a considerable difference between each system (Figure 7). In the subsurface system, there was an overall decrease of 22.7%. In contrast, in the freeflow system there was an overall increase of 51%, with a 17.15% removal being observed between Basins 1 and 2. Overall, there was a 63.8% removal in the freeflow system and 15.2% removal in the subsurface flow system for the high nitrate solution.

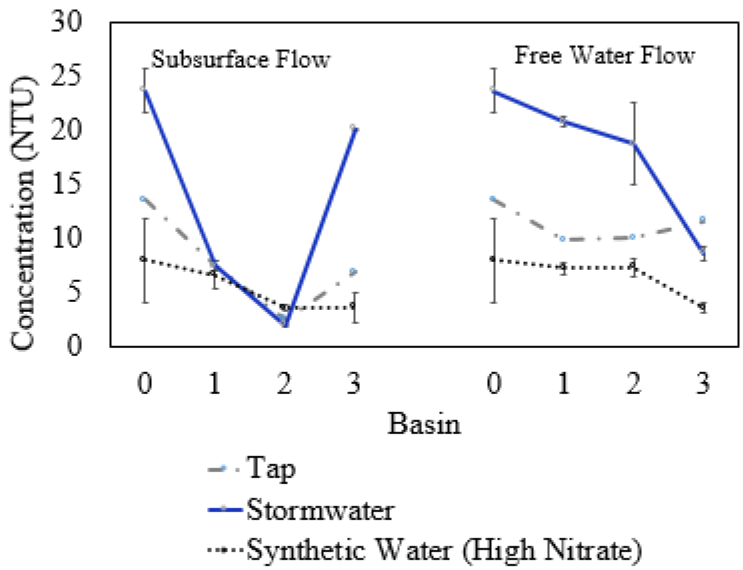

Figure 7: Total Suspended Solids concentrations from tap water, stormwater, and synthetic water testing

pH:

The measured pH levels were consistently between 6.5-7.5, which is in an acceptable range between 6.5-8.5. This shows a nearly neutral, 7.0, pH value over the measured times. Due to this, the wetland is considered to be healthy and operating normally.

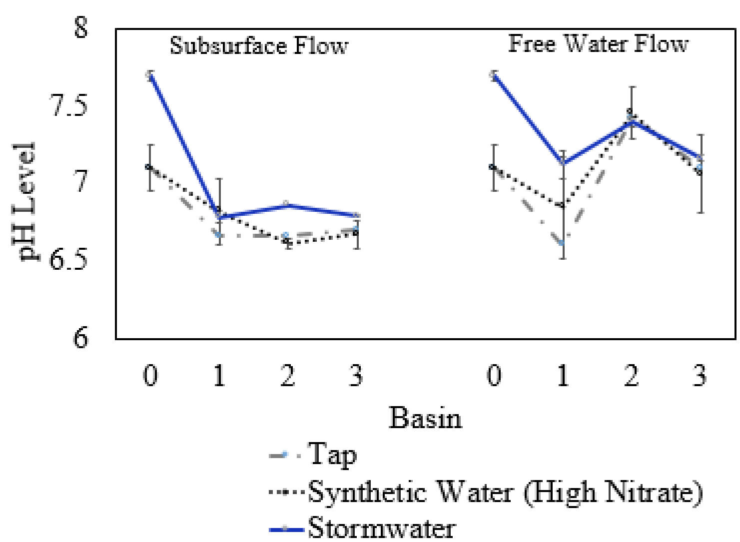

Figure 8: pH levels from tap, stormwater and high nitrate testing

Temperature:

The measured temperatures varied from approximately 25.8°C to 27.9°C. There was the capability of vast changes in temperature depending on weather and time of day. However, considering the low 2.1°C difference from all of the basins, we consider soil temperatures to be normal. The greatest gap in temperatures was shown in the high nitrate test from subsurface Basin 1 to subsurface Basin 3.

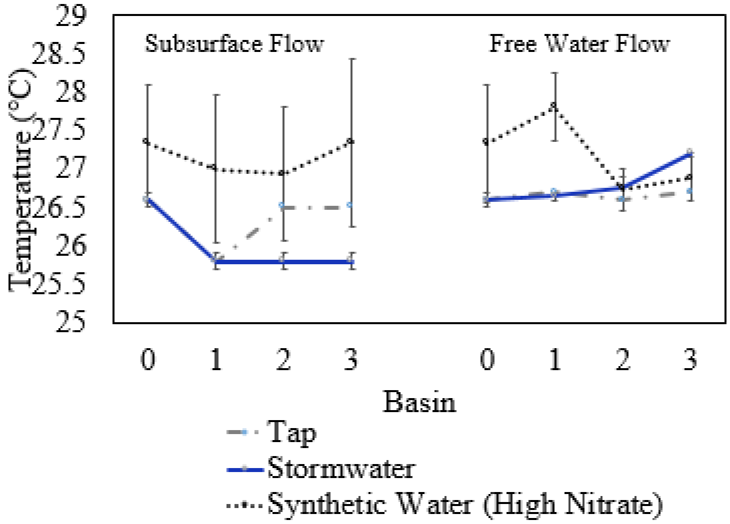

Figure 9: Temperatures across the system from tap, stormwater, and high nitrate testing

5.0 Discussion and Conclusion

Based on expected results derived from previous research using the wetland, the wetland system performed consistently with previous years. A sizable decrease in nitrate and nitrite concentration was observed in nearly every test. The stormwater is the only tested water that saw any decrease in ammonia, while the high nitrate solution stayed fairly consistent, and levels in the tap water noticeably increased. Total suspended solids (TSS) reduced in nearly every instance through Basin 2, but increased to its initial value after passing through the final basin. The subsurface flow system was particularly successful in the removal of TSS in the first two basins. Temperature and pH measurements were also taken to ensure the wetland system was performing up to standards.

The effectiveness of nitrite removal observed in the wetland contradicted past research done on the topic, which had indicated nitrite levels would increase. The subsurface and free flow systems produced opposing results in the second basin for the high nitrate test. While the subsurface flow system had a significant decrease in the second basin, the free flow system yielded a noticeable increase. This is likely the product of the varied methods of nutrient absorption the systems utilize. Nonetheless, Basin 3 made the largest impact in reducing nitrite concentration in both systems, indicating the importance of its presence for chemical removal.

The nitrate concentrations in the tests had a tendency to stay even until the final basin. The first two basins had very minimal impacts on the nitrate levels in both the subsurface flow and the free flow systems. There was an overall removal of 57.6% in the free water flow system and an overall removal of 39.3% in the subsurface flow system. The major reduction of nitrite and nitrate occurring in the third basin is extremely promising for the use of constructed wetlands for water purification.

Total suspended solids had a tendency to increase during the final basin, especially in the subsurface flow system. The first basin, however, drastically decreased TSS in nearly every case. This is consistent with the purpose on the first basin, which serves primarily to filter out suspended solids present in stormwater. The third basin then filters out small particles not removed in prior basins in the system. However, the third basin's tendency to reintroduce suspended solids into the water calls into question the effectiveness of the basin, at least in terms of filtering out solids. This could be a point of emphasis in further study of constructed wetlands.

Ammonia levels were dependent on the type of water tested. Tap water had very low levels of ammonia initially, but consistently increased as water flowed through the wetland, dropping only slightly from Basin 2 to Basin 3 in the subsurface flow system. In the case of the high nitrate synthetic water, although basin 1 effectively removed a fair amount of ammonia, the following two basins reintroduced ammonia, resulting in only minimal removal of ammonia. Removal of ammonia was most considerable in the storm water. Considering constructed wetlands would primarily deal with stormwater, this data positively reflects on wetlands as a plausible stormwater treatment option.

pH and temperature were recorded with the intent of maintaining quality control in our experimentation. pH levels were consistently in a satisfactory range between 6.5 and 7.5, which is standard for a constructed wetland. The temperature of the sampled water also fell into a reasonable range between 25.8°C and 27.9°C (11). Various factors may have played into temperature differences, such as time of day, outside temperature, and body heat transfer when handling samples. These minor inconsistencies should have had negligible consequences on the recorded data.

One factor that may have affected the data is the plants used in each basin. Some of the plants in Basins 1 and 2 of each system were replaced before testing due to their diseased condition. However, the plants were replaced with either the same type as previously or a plant of similar type. The type of plants being used may affect how much water and nutrients are being taken up and therefore further research should be conducted to find a balance of plants to use in each basin to best remove the nutrients being tested.

6.0 Recommendations

In the future, another basin could be added to attempt to remove phosphorus in the wetland. The basin could be located after Basin 3 as a fourth basin, and connect back to Basin 1. A fourth basin could aim to reduce TSS, since the third basin tended to reintroduce suspended solids into the water. Researching the correlation between TSS, and nitrate and nitrite presence can help determine how to minimize both without sacrificing one or the other. Also, additional plants can be added based on how they survive in the ecosystem. After more thorough research, nutrients can be monitored to discover how different plants affect nutrient removal.

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