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Investigating the Removal of Stormwater Pollutants in Small-Scale, Constructed Treatment Wetlands

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Abstract

Eutrophication of US surface waters is a growing problem due to nitrogen and phosphorus runoff in stormwater. In natural ecosystems, wetlands can absorb and remove a variety of water pollutants, including nutrients. Wetlands also provide flood control and wildlife habitat. Mimicking natural systems, constructed treatment wetlands can remove stormwater pollutants, are economic to build and maintain, provide a bionetwork for a wide range of plants and animals, and can be used for educational purposes.

While constructed treatment wetlands can remove stormwater pollutants such as total suspended solids, organic carbon, and nitrates, a significant reduction in phosphate concentrations has not been observed using plant and soil media alone. Calcium carbonate was shown to reduce phosphate concentrations when added to soil media, but its effectiveness has not been tested in a wetland system. To further remove these pollutants, longer detention times were expected to decrease pollutant concentrations.

The ability of constructed treatment wetlands to remove phosphate from artificial stormwater was tested using two laboratory-scale, constructed treatment wetlands composed of three basins each. Water quality parameters including pH, turbidity, nitrate, and phosphate were monitored at each basin outlet. The final wetland basins were amended with two sizes of calcium carbonate in the form of limestone: 1.18-9.5mm pebbles removed 4-7% of phosphate, and fines removed a 20 – 22.5% of phosphate. The addition of recycle lines doubled the detention time of the wetlands systems from 3.46 ± 0.21 hr to 7.33 ± 0.18 hr, however, the recycle lines did not improve the removal of phosphate, nitrate, or turbidity, and worsened overall water quality.

To further optimize phosphate removal, follow up studies should include testing the removal efficiency of different concentrations of limestone fines in the soil.

Background

Natural Wetlands

Wetlands are widely used for removing the pollutants found in stormwater. (1,2,3,4,5,6,) They are often used to reduce concentration of suspended solids, different forms of nitrogen, phosphorus, biological oxygen demand levels (BOD), and maintain neutral pH levels. (2) Wetlands can do this through filtering stormwater through plant and soil media. They are able to improve the quality of water in a natural way with less maintenance burden and lower capital cost when compared to other treatment processes. (1) There are two types of wetland setups: free water flow and subsurface flow. A free water flow wetland is comprised of rooting media for the aquatic plants, and shallow open water that is covered with vegetation. (1) These types of constructed wetlands can achieve a high removal of suspended solids and moderate removal of pathogens, nutrients and other pollutants, such as heavy metals. (3) Therefore, it is appropriate for filtering low-strength wastewater. (3) Subsurface flow wetlands consist of a layer of rock or gravel, rhizome network, and vegetation. (1) SSF wetlands have a high reduction of BOD, total suspended solids and pathogens but low nutrient removal. (3) It is a good treatment for communities that have primary treatment, such as septic tanks or compost filters, but are looking to achieve a higher quality water. (3)

Phosphorus

Sedimentary rocks contain large quantities of inorganic phosphorus. Theses rocks are eventually eroded away, and the phosphorus is released in the water for the plants to soak up the nutrient. It will cycle from these plants to the animals that consume it back into the soils after digestion until the phosphorus is able to find its way into a body of water. (8) The amount of phosphorus in bodies of surface water are not usually a problem unless it is in excess. (9) The EPA defines healthy lakes and reservoirs as having a total phosphorus concentration of 0.0375 mg/L and healthy rivers and streams as having a concentration of 0.07625 mg/L in the Corn Belt and Northern Great Plains Ecoregions. (13) With the creation of synthetic fertilizer there is much more phosphorus in the water than there should be. These fertilizers contain an abundance of phosphorus which is used to help crops flourish. When water exposed to fertilizer drains into the surrounding bodies of water eutrophication can occur. Eutrophication causes algae to grow at a rapid rate that the ecosystem is unable to handle. When these algae die, bacteria must break it down. In the process of breaking down the algae, bacteria use a significant amount of the dissolved oxygen in the water. This causes fish to become ill or die because there is not enough oxygen to sustain their needs as well. This process causes the water to look and smell bad, can irritate a swimmer's skin, and can cause poisoning. (5)

Many studies have varied in the amount of phosphorus that they were able to remove over the course of their experiment. (3,5,6,7,9) There has been a range of a 10 to 90 % removal rate depending on the material used in the process. The materials used in these experiments include tree bark, alum, fly ashes, pumice, limestone, and zeolites. The phosphorus loading rate of each material, availability and percent of phosphorus removed were the main guidelines to determine how well each material performed. The phosphorus loading (p-loading) potential is the amount of phosphorus a material can remove before it becomes ineffective and the p-loading rate is how quickly it reaches this potential. Tree bark was effective in removing a moderate amount of phosphorus but would need to be replaced often due to its low phosphorus loading rate. (6) Alum and fly ash performed well due to their high phosphorus removal, but they may have negative effects on the wetland due to high metal content and may harm some of the biological components. (6) Limestone was able to moderately remove phosphorus in lab tests, had a high p-loading rate, and was readily available. (6) Limestone is composed of calcium carbonate, which has been indicated to be able to sorb phosphorus. Limestone is abundant in the state of Indiana and makes up a large portion of the bedrock geology. In gardening soils, it is regularly used to regulate the pH levels. It can be useful for both amending soil and filtering water to remove phosphorus; in addition, the limestone would still be beneficial to use after the experiment when it has reached its full p-loading potential. (6) The limestone could be used as a base for roads, combined with shale to become cement, and landscaping. Other studies have not given a finite time frame of when it becomes ineffective but previous work demonstrated use for 90 days without showing a trend in their data indicating that it has reached full p-loading potential. (7) A previous study looked at the removal of total phosphorus using reagent grade calcium carbonate. Zurayk's studies showed that the most amount of phosphorus was removed in the first six hours of contact. They also used crushed limestone and obtained similar results to those found with reagent grade calcium carbonate, but data values were not specified in their study. To evaluate the ability of limestone to remove phosphate in a field setting, additional testing with field conditions is needed in order to see if limestone is an adequate material for removing phosphorus.

Increased Retention Time

The removal efficiency of pollutants is dependent on variables such as hydraulic loading rate, hydraulic retention time, and depth of the water in the system. (15) All of these variables effect the amount of time the water is in contact with the soil media in the wetland systems. Hydraulic retention time is the amount of time the water takes to make it through the wetland system. In one horizontal subsurface flow constructed wetland, three different hydraulic retention times were tested. (14) The largest amount of total nitrogen and phosphorus was reduced with a retention time of 120 hours followed by 72 hours and the least amount of total nitrogen and phosphate concentrations reduced with a 9-hour retention time. (14) Other studies had reintroduced water back into the wetland system once it had been passed through, in order to increase the hydraulic retention time. (10) They also tested how the amount of recycled water effected the reduction of pollutants. (10) The more amount of water that was reintroduced into the system the more the concentration of total nitrogen was reduced. (10,14)

Methods

Artificial Stormwater

In order to effectively replicate a wetland in the lab, stormwater would be used during the tests. Due to unpredictable weather, there was no reliable source to collect stormwater runoff. Creating artificial stormwater using tap water, crushed ZIPP soil, potassium nitrate, and sodium phosphate allowed tests to be run without being dependent on the weather. Adding these to the tap water allowed for very little variability in the initial turbidity, nitrate, and phosphate concentrations.

To achieve a nitrate concentration of 3 mg/L, 1.21 g of KNO_3 was added to 25 gallons of tap water (Table 1). In order to have a turbidity of 3.5 NTU, 8.04 g of pulverized ZIPP was added to the 25 gallons of tap water (Table 1). To achieve a phosphate concentration of 5.0 mg/L, 0.98 g of Na_2HPO_4 was added to the water.

A 1000 ml sample of nitrogen and zipp tap water mixture was used to scale the amount of phosphate that would be needed in the 25 gallons of artificial storm water. A phosphate concentration of 5.01 mg/L was obtained when 0.0104 grams of Na_2HPO_4 was added. Using the ratio of Na_2HPO_4 in the sample, the desired amount of Na_2HPO_4 to be added for the 25 gallons of water was able to be calculated (Equation 1).

$$\frac{3785.41178\,mL}{1\,gal} * \frac{0.0104\text{ g}}{1000\,mL} * 25\,gal = 0.9842\,g$$

Equation 1. Calculation for desired amount of Na_2HPO_4 in water

Table 1. Amount of additives needed for the Artificial Stormwater recipe to obtain a certain concentration

Additive	Desired concentration	Tap water (gal)	Amount added (g)
KNO_3	3.0 mg/L	25	1.21 g
Zipp	3.5 NTU	25	8.04
Na_2HPO_4	5.0 mg/L	25	0.98

Wetland System Testing

Freshly prepared artificial stormwater was used for each test and was pumped into the system (Figures 1-2) within 10 minutes of mixing to decrease the amount off settling that could possibly occur with the Zipp soil and so the nitrate did not change forms. The pumps in the reservoirs were opened enough to not flood the first basin, but still provide an adequate amount of water to the systems. After the pumps were started the valves between each basin were opened to the indicated tick mark and gravity flow was initiated. The valve following the first basin was opened 20 minutes after the pump was started, the second and third valves were opened at the first sign of water flowing from the second basin in the SSF system or at an hour and a half after the pump was initially started. The detention time of one flow through was 3.46 ± 0.21 hours; the systems were damp before the water was pumped through. After one flow through, the water was collected in the second reservoir, and pumped back to the first reservoir to be cycled through the system again. Including the recycle line, the retention time was 7.33 ± 0.18 hours.

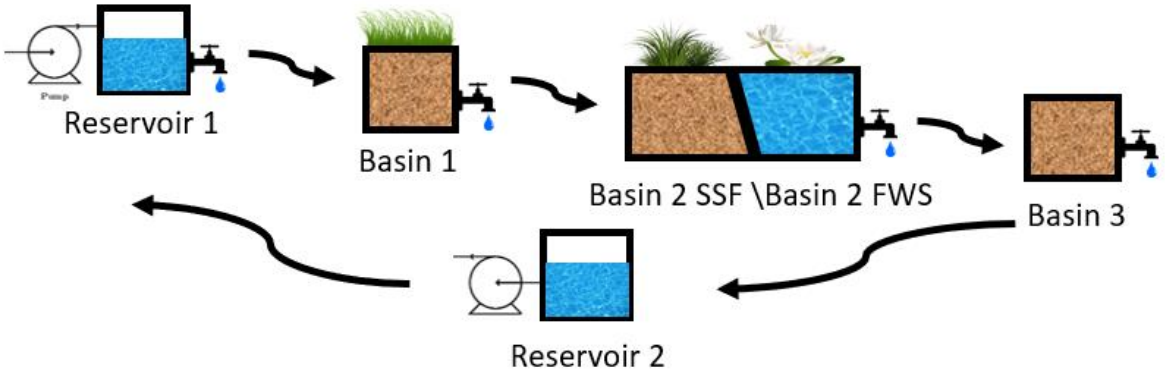


Figure 1: Basin configuration and flow pattern of artificial stormwater

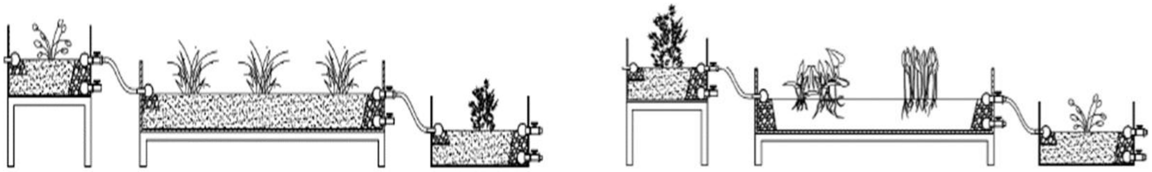


Figure 2: Subsurface (SSF) wetland system (left) and free water surface (FWS) wetland system (right) (Mueller Price, 2015)

Soil amendment

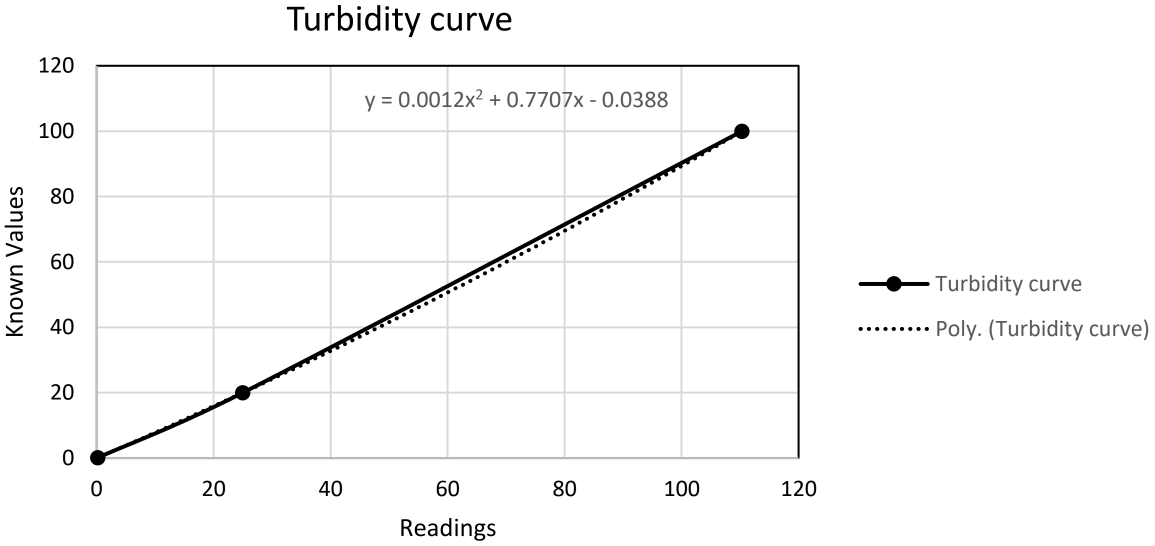
The soil composition of the two wetland systems was identical except for the soil in the second basins (Table 2). In the FWS wetland, the second basin was made up of 1152 cubic inches of soil along the bottom and aquatic plants including white water lilies and water knotweed (Cardno). Water levels fluctuated throughout testing. The SSF wetland was not designed to have standing water and was completely full of soil with June Grass and Prairie Dropseed plants (Cardno). The soil of the third basins in both wetland systems was amended twice during the research period. The first amendment added 1.18-9.5mm sized limestone. The limestone used was sieved through a ½ in, 3/8 in, and No.16 sieve in the sieve shaker for 3-5 minutes. The limestone used in the first soil amendment was the pebbles that passed through the ½ in, but that were retained by both the 3/8 in and the No.16 sieve. Roughly half of the sand was replaced with new soil without added phosphate, and three June grasses (Cardno) were planted. After the sixth flow-through test, basin 3 was amended a second time with 316.71 g of fine limestone powder to increase the surface area and concentration of the limestone in the systems. The fine limestone used was sifted through a No. 200 sieve before being put into basin 3.

Table 2. Composition of the small-scale, constructed, modular wetlands (3* indicates the second time the third basin was amended)

Basin	Contaminant removed	Size (in x in)	Soil components (%)			
			Organic	Soil	Gravel	Limestone
1	TSS	20 x 20	5	45	50	0
2	BOD and Nitrate	24 x 60	50	40	10	0
3	Phosphate	24 x 24	15	60	5	20
3*	Phosphate	24 x 24	15	40	5	40

Water Quality Testing

To determine percent removal of pollutants, water quality parameters were measured for the initial artificial stormwater, after first cycle, and after the recycle. Turbidity, nitrate, temperature, pH, and phosphate were measured. One sample of at least 200 ml was taken after each cycle, stored in the dark at 20°C overnight, and were tested within twenty-four hours. The pH and temperature of the samples were measured with an IQ Scientific Instrument pH Meter. The pH meter was calibrated after every two runs which was normally once every week. Both nitrate and phosphate concentrations were tested using a Hach DR 2800 Spectrometer (product #DR2800-01B1). Before each test was performed the instrument was zeroed using the sampled water without the reaction powder in it. Using a syringe, 10 mL of the sample was transferred to square glass sample cells. Nitrate was measured using Hach Method 8039, cadmium reduction powder pillow method, high range test (0.3-30.0 mg/L NO_3^--N). This process was used again to measure phosphate using Method 8048 for mid-range phosphate concentrations. A Hach 2100 P Turbidimeter (product #4650000) was used to measure turbidity. The Turbidimeter was unable to calibrate correctly so an equation using known values and their corresponding readings was fit to account for this error. After placing samples into the 30 mL sample cells they were cleaned with a cloth and the water was gently mixed by rotating it by hand.



Shake Testing

To determine if the limestone was removing the phosphorus, a separate shake test was performed according to the study done by Zurayk et al. Representative samples of soil were taken from Basin 1 and Basin 3. Five grams of each type of soil was measured into a separate wide-mouthed container with 200 mL of the artificial stormwater. The containers were mixed in a New Brunswick Scientific Excella E24 Incubator Shaker Series at 175 rpm for three hours. Two separate tests were performed: one with the pebble-sized limestone and another with the pebble-sized limestone and additional fines from basin 3. After shaking, the samples settled for 30 min so 15 ml could be decanted into 1.5 ml microcentrifuge tubes. To further remove any particulates, the samples were centrifuged for 5 min at 10 rpm in an Eppendorf Centrifuge 5415D. The supernatant was subsequently tested for phosphate; three separate phosphate tests were performed for each sample.

Results

To determine the efficiency of the wetlands for removing stormwater pollutants, samples from each basin were collected for the first flow and recycle of an individual test. Each sample was tested twice for pH, Turbidity, Nitrate and Phosphate.

pH

The pH levels remained fairly constant throughout the entire system, only fluctuating by 0.34 pH units. The pH levels remained between 7.84 and 7.42 indicating that the wetland remined slightly basic throughout the system. Basin 2 increased the pH levels both times the water passed through.

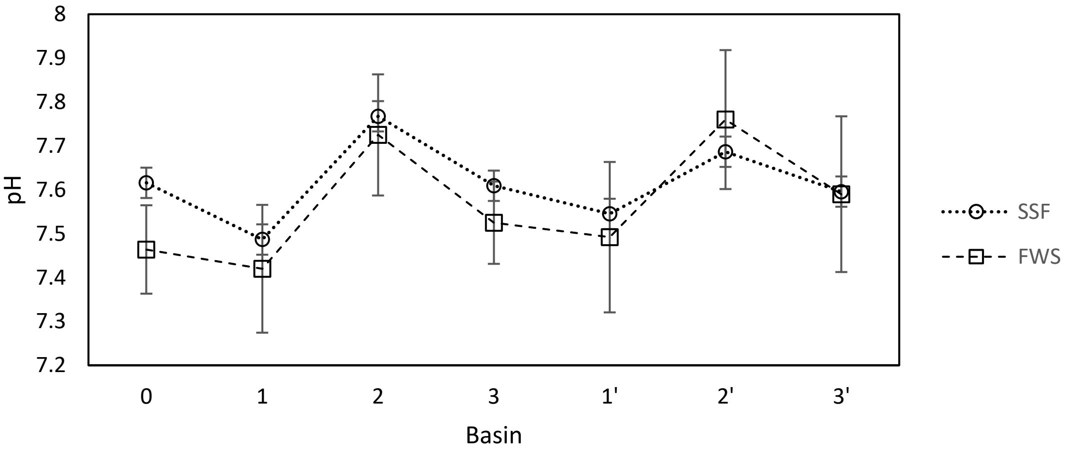


Figure 4. pH levels (error bars are from 12 measurements; 0 indicates measurements from the reservoir, 1-3 are data from the first cycle through, and 1'-3' are data from the recycle)

Turbidity

During the first cycle, both systems had similar levels of turbidity. Turbidity remained constant through basins 1-2, but turbidity was introduced into the system in basin 3. After the recycle, overall turbidity was not reduced. Percent turbidity increased substantially as a result of basin 3 before and after the recycle. By the end of the recycle the SSF wetland system had an average turbidity of 13.62 ± 4.74 NTU and the FWS wetland system had an average turbidity of 41.49 ±26.84 NTU. Turbidity in the SSF wetland system increased by a total of 217% and the FWS wetland system increased by 1037% when comparing the final values with the artificial stormwater that was initially mixed. In the third basin of the FWS system there was a large amount of variance in the measurements that were taken, potentially due to the limestone amendments in the third basins.

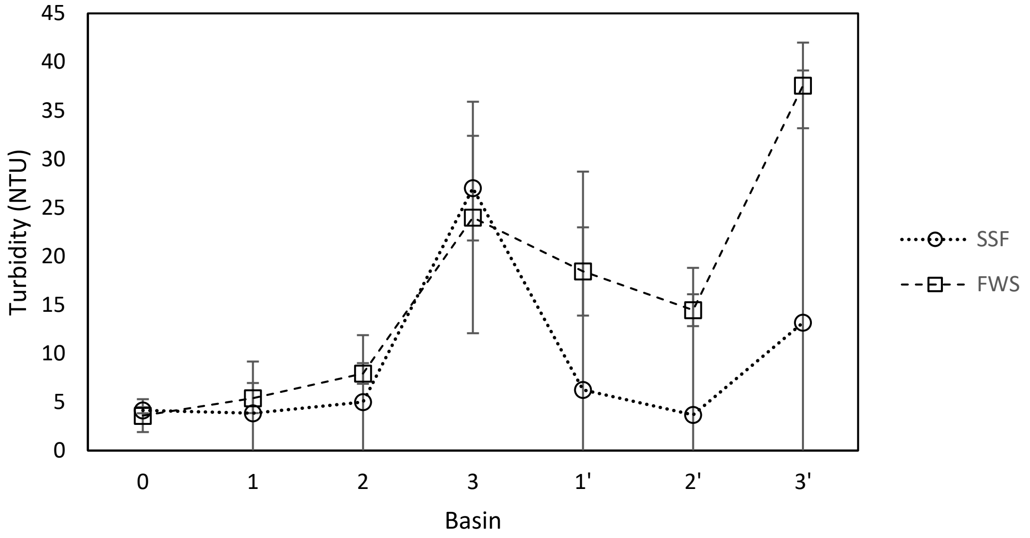


Figure 5. Turbidity Levels (error bars are from 12 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1'-3' are from the recycle)

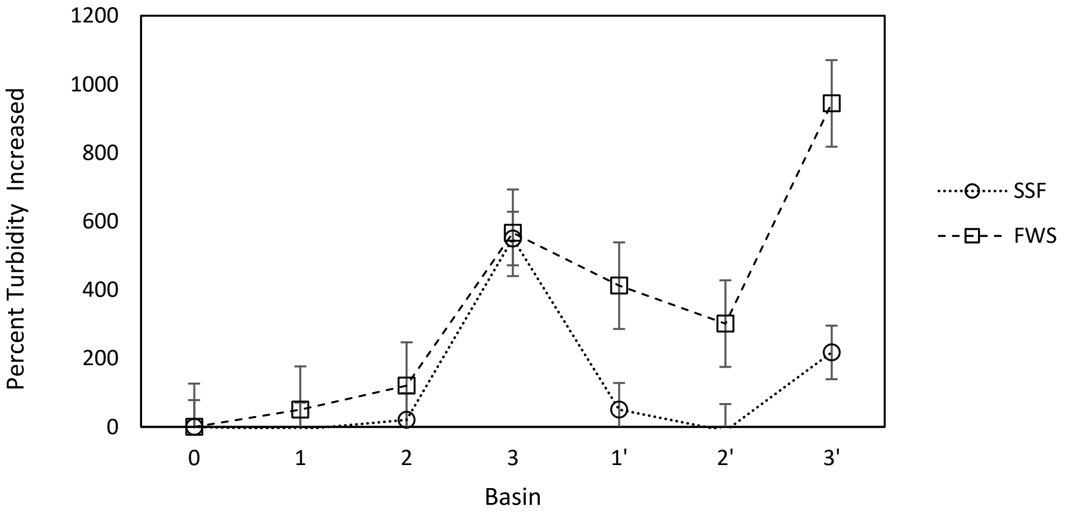


Figure 6. Percent Increase in Turbidity (0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1'-3' are from the recycle; increase based on average initial artificial stormwater values)

Nitrate

The first cycle removed 94.0% of nitrate in the SSF wetland (0.17 ± 0.72 mg/L compared to initial value of 2.87 ± 0.79 mg/L) and removed 98.9% in the FWS wetland (concentration of 0.02 ± 0.74 mg/L compared to initial value of 2.15 ± 0.66 mg/L). . Nitrate was reintroduced into the system after the water was recycled. After the recycle, nearly all nitrate was removed again in the FWS wetland with an 85.81% decrease in concentration (0.31 ± 0.60 mg/L compared to the initial value of 2.15 ± 0.66 mg/L). But, the SSF did not perform as well in the recycle. The nitrogen concentration stayed constant once nitrate was reintroduced when recycled, and only 26.66% was removed by the final outlet (2.10 ± 0.14 mg/L when compared to the initial value of 2.87 ± 0.79 mg/L).

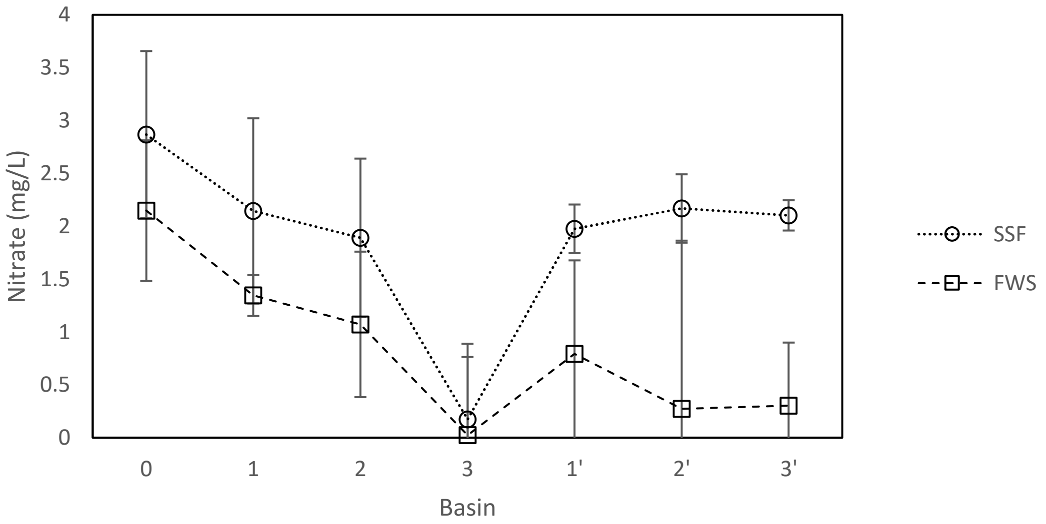


Figure 7. Nitrate Concentration Levels (error bars are from 10 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle)

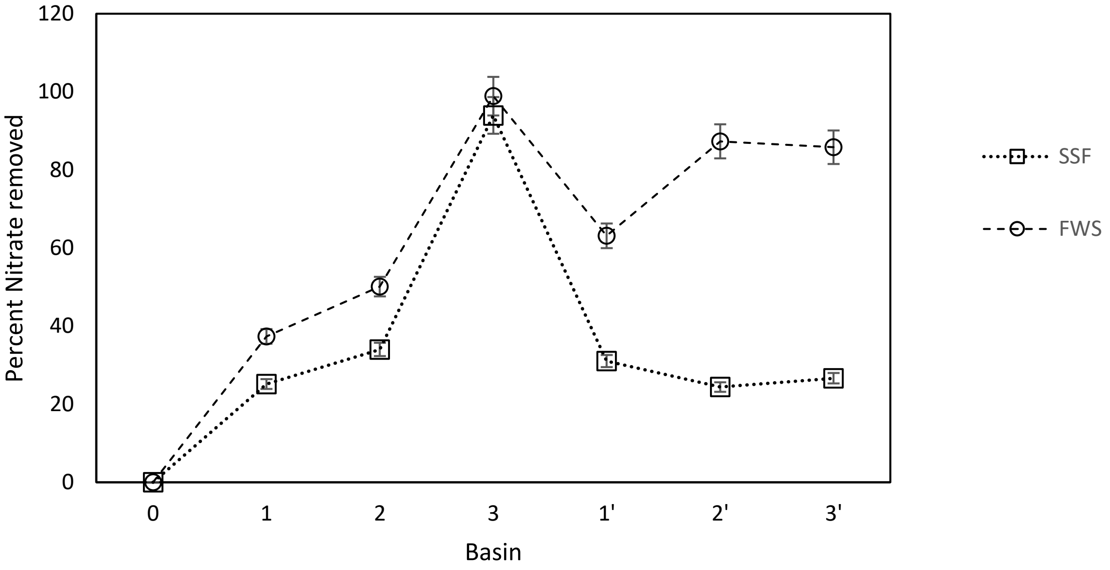


Figure 8. Percent Removal of Nitrate (0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle; decrease based on average initial artificial stormwater values)

Phosphate

The Phosphate concentration remained fairly constant throughout the wetland systems and there was not a substantial amount of phosphate removal. By the end of the recycle, 7.65% of phosphate was removed from the SSF wetland system (final concentration of 4.79 ± 0.12 mg/L compared to the initial concentration of 5.19 ± 0.32 mg/L) and 4.53 % from the FWS wetland (final concentration of 4.97 ± 0.44 mg/L, with an initial value of 5.21 ± 0.35). The second basin in the FWS wetland had the highest percent removal of phosphate for both the first cycle (4.03±1.22 compared to 5.21 ± 0.35), and the recycle (4.54 ±1.35 compared to 5.21 ± 0.35).

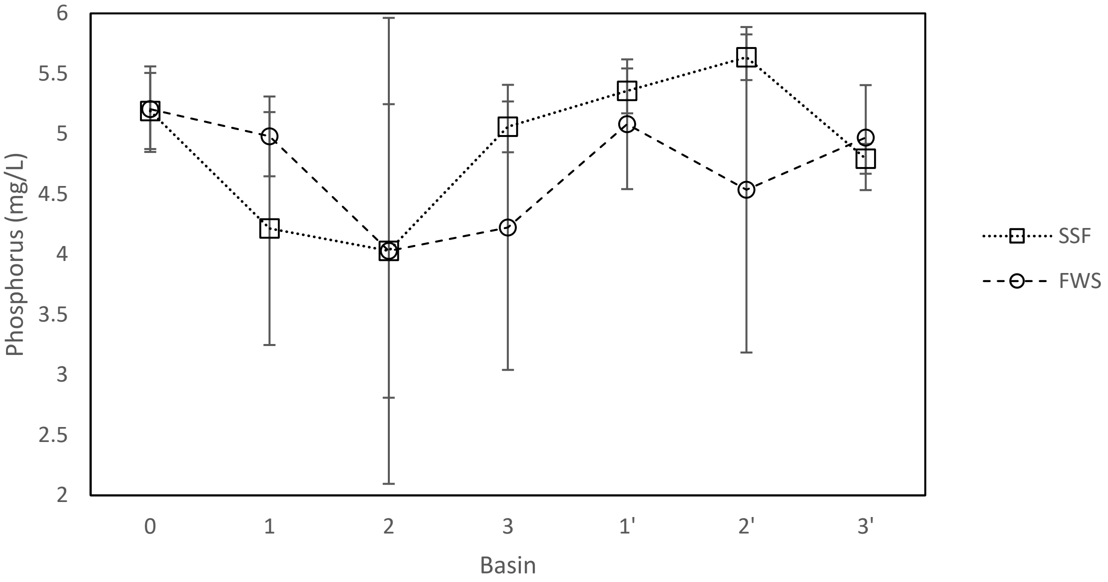


Figure 9. Phosphate Concentration levels (error bars are from 10 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle)

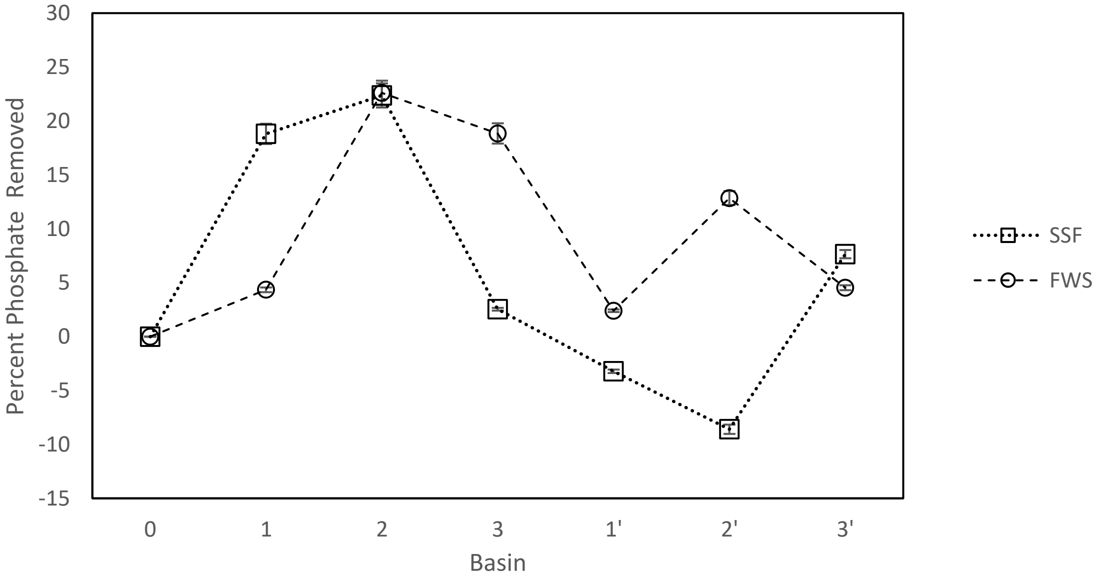


Figure 10. Percent Removal of Phosphate (0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle; decrease based on average initial artificial stormwater values)

To further examine the ability of limestone to remove phosphate, limestone fines were subsequently added to basin 3. The fines have a larger surface area compared to the 1.18-9.5mm limestone per unit volume. Separate water quality parameters were measured and displayed due to the distinct variation in results found after fines were amended into the third basin.

pH

While there were no significant changes, there was a decrease in the pH levels after the third basin. For the first cycle, the water in the third basin had a pH of 7.47 ± 0.09 in the SSF wetland, and 7.42 ± 0.07 in the FWS wetland. The pH levels decreased further after the recycle. The SSF wetland had a pH level of 7.29 ± 0.17 in the SSF wetland, and 7.17 ± 0.10 in the FWS wetland.

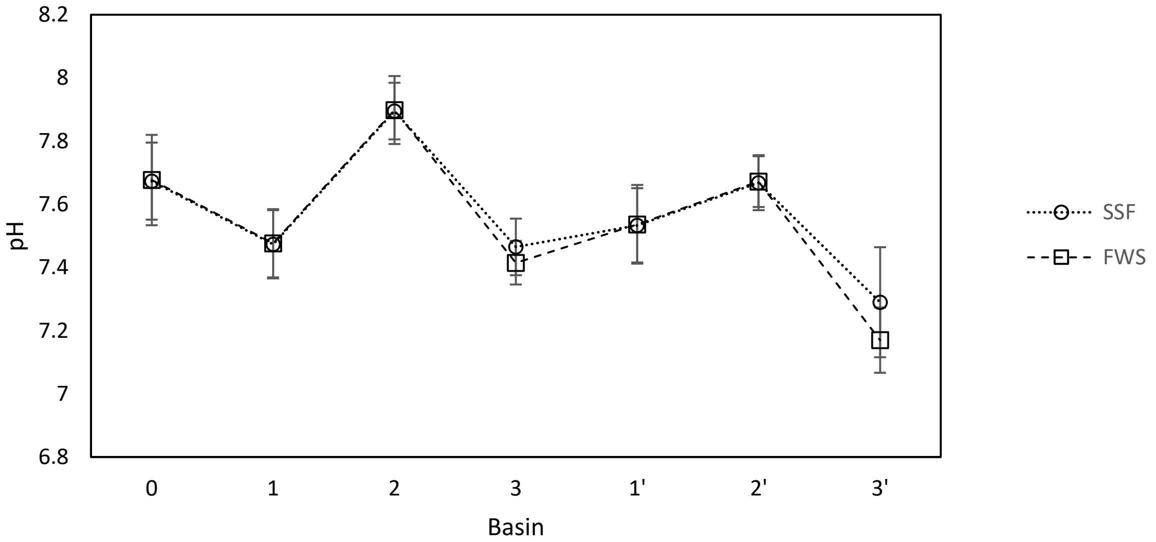


Figure 11. pH levels (error bars are from 6 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle)

Turbidity

Turbidity increased after the water passed through the third basin. The systems were able to get the turbidity back under control in the first and second basin when the water was recycled through but was unable to keep it at those levels when passing through the third basin for a second time. By the end of the recycle the FWS wetland system had an average turbidity of 35.01 ± 5.35 and the SSF wetland system had an average turbidity of 32.25 ± 7.09 NTU. Turbidity in the FWS wetland system increased by a total of 920.7% and the SSF wetland system increased by 792.8% when comparing the final values with the artificial stormwater that was initially mixed.

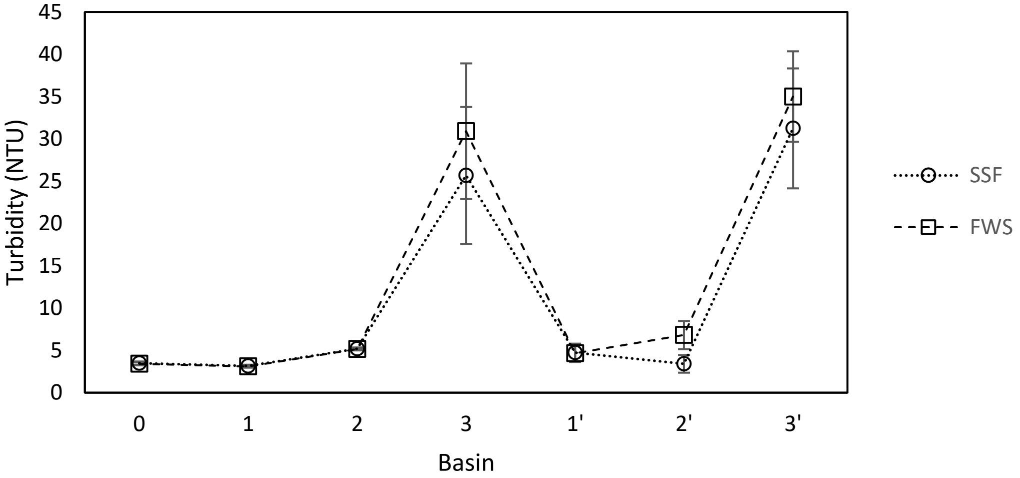


Figure 12. Turbidity Levels (error bars are from 6 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1'-3' are from the recycle)

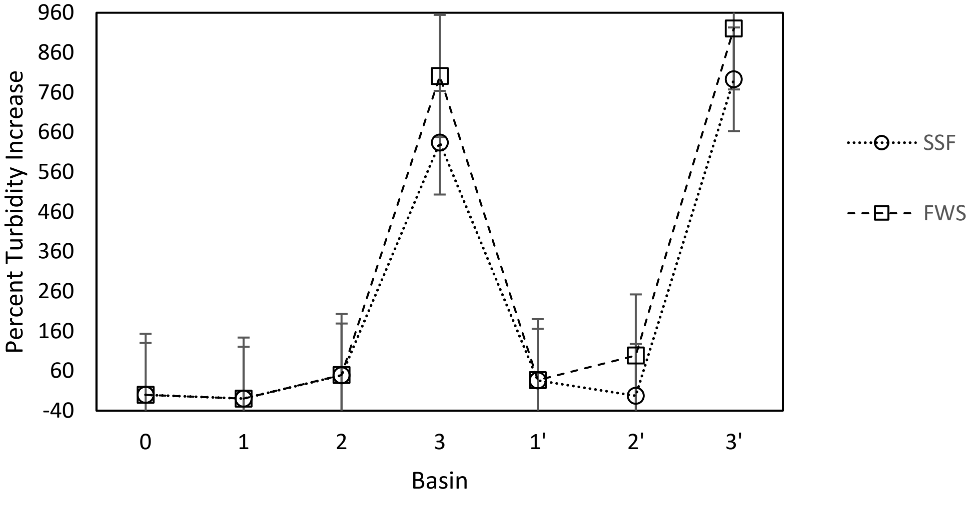


Figure 13. Percent Increase in Turbidity (0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1'-3' are from the recycle; increase based on average initial artificial stormwater values)

Nitrate

The addition of fine limestone may have impacted the reduction of nitrate concentrations slightly, compared to that of the pebble sized limestone. The FWS wetland removed nitrate more effectively compared to the SSF wetland. The first cycle removed 92.15% of nitrate in the SSF wetland (0.24 ± 0.16 mg/L compared to the initial value of 3.02 ± 0.17 mg/L), and 114.14%in the FWS wetland (less than 0 mg/L which is below detection limit, compared to the initial value of 3.09 ± 0.07 mg/L).

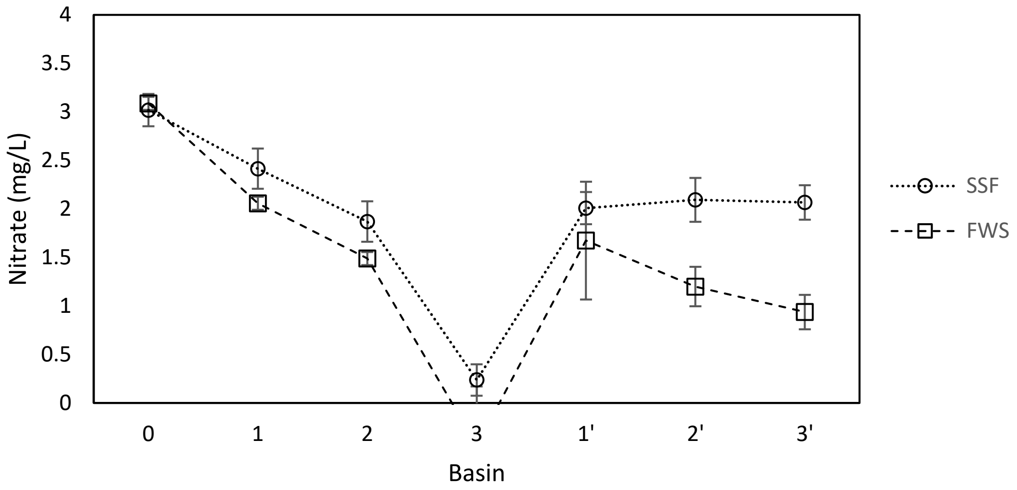


Figure 14. Nitrate Concentration Levels (error bars are from 6 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1'-3' are from the recycle)

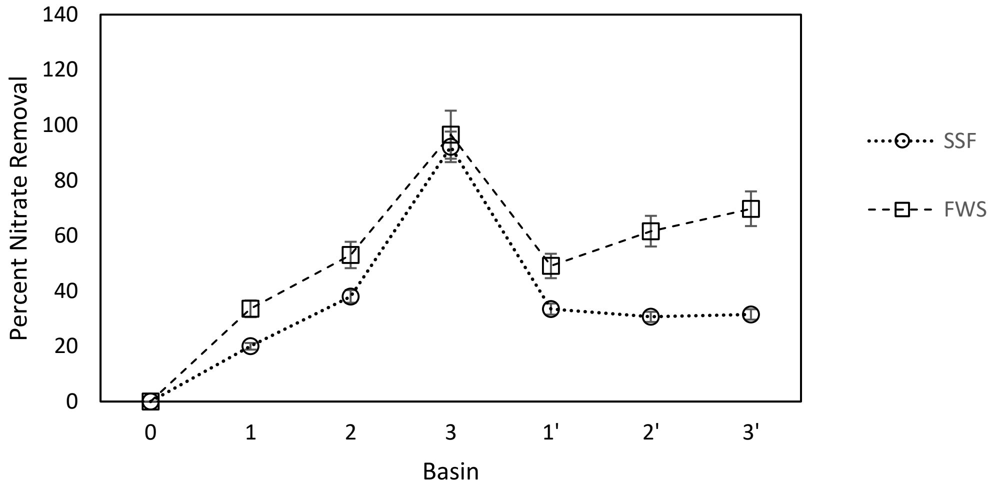


Figure 15. Percent Removal of Nitrate (0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle; decrease based on average initial artificial stormwater values) * below detection limit

Phosphate

The additional limestone added to the third basin removed more phosphate than the 1.18-9.5 mm limestone. The first cycle removed 18.48 % of nitrate in the SSF wetland (4.16 ± 0.10 mg/L compared to the initial value of 5.10 ± 0.05 mg/L), and 21.14 %in the FWS wetland (4.09 ± 0.05 mg/L, value below detection limit, compared to the initial value of 5.19 ± 0.10 mg/L). Phosphate removal was similar for both the FWS and SSF in the recycle. The recycle removed 19.85 % of nitrate in the SSF wetland (4.09 ± 0.09 mg/L compared to the initial value of 5.10 ± 0.05 mg/L), and 22.45 % in the FWS wetland (4.03 ± 0.06 compared to the initial value of 5.19 ± 0.10 mg/L).

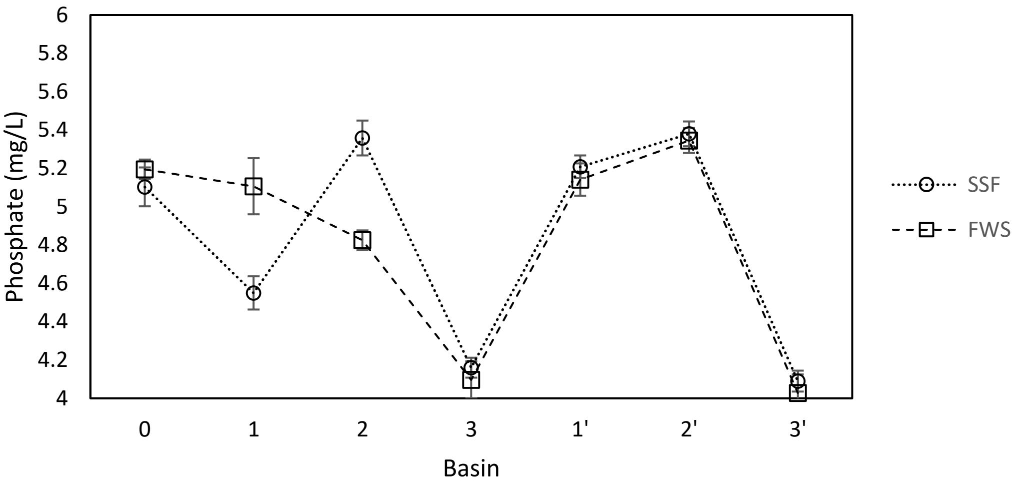


Figure 16. Phosphate Concentration Levels (error bars are from 6 measurements; 0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle)

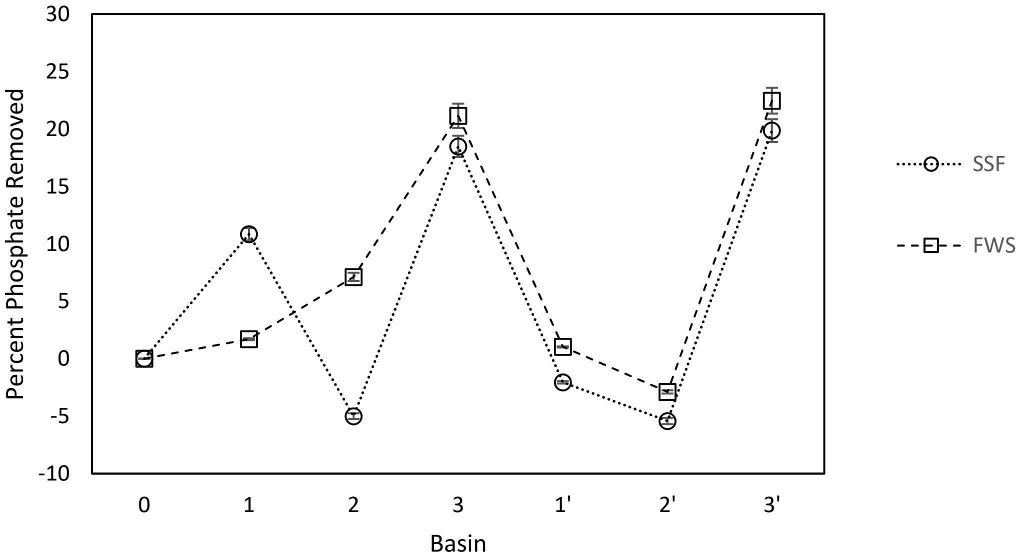


Figure 17. Percent Removal of Phosphate (0 indicates measurements from the reservoir, 1-3 are from the first cycle through, and 1’-3’ are from the recycle; decrease based on average initial artificial stormwater values)

Shake test

To test the ability of the limestone in a controlled laboratory setting, a shake test was performed. In the shake test, the addition of pebble sized limestone to the third basin decreased the phosphate concentration by 2.26 ± 4.98 % when compared to the initial value. The phosphate concentration was increased by 9.79 ± 1.96% in the first basin, which did not have any limestone in the soil.

Table 5. Shake test results when basin 3 included 1.18-9.5 mm limestone

Basin 3 with 1.18-9.5mm CaCo3	Initial Value (mg/L)	Basin 1 (mg/L)	Basin 3 (mg/L)
Test 1	5.24	5.86	5.42
Test 2	5.17	5.58	4.72
Test 3	5.22	5.72	5.14

The additional fines added to the third basin decreased the phosphate concentration by 36.40 ± 1.28% when compared to the initial value. The phosphate concentration increased by of 9.00 ± 1.16% in the first basin.

Table 6. Shake test results when basin 3 included 1.18-9.5 mm limestone and fine limestone

Basin 3 with fine CaCo3	Initial Value (mg/L)	Basin 1 (mg/L)	Basin 3 (mg/L)
Test 1	5.04	5.49	3.13
Test 2	5.09	5.49	3.32
Test 3	5.01	5.52	3.18

Discussion

Before the amendment of the fines in basin 3, the second basin removed more phosphate in both systems in the first cycle. With plant media being more abundant in basin 2 it acted as a filter and could be a possible explanation as to why this decrease was seen. With the addition of the fine limestone in basin 3, it was able to remove 20-22.5% of phosphate concentrations when compared to the initial amount put into the system. The increased reduction rate compared to that of the pebble sized limestone concluded that the concentration of limestone in the soil is not as important as the size of the particles in the soil. The third basin performed as expected after the amendment of the fines and removed the highest concentration out of all three basins. The increased surface area of the fines allowed the stormwater to be in contact and sorb more with the limestone.

Under certain circumstances, previous work observed much greater removal rates of phosphate with calcium carbonate than without the calcium carbonate. Comparing to the results obtained from the tests from both wetland systems and the shake test, previous work had higher rates of concentration removal. Previous studies used carbonate free sand in their shake tests that allowed for the effects of the additional calcium carbonate to be isolated (7). Reagent grade calcium carbonate was also used to perform these tests. Therefore, the calcium carbonate was in a much purer form compared to the calcium carbonate in the form of limestone used in our tests. The shake test performed by Zurayk resulted in a 90% reduction of phosphate concentration (21% calcium carbonate concentration) and a 93% reduction of phosphate concentration (38% calcium carbonate concentration) (7). Comparisons between the test performed by Zurayk and the data collected throughout this study shows how variables in each test effected the percent phosphate removal (Table 7 and 8). Having a variety of soil in our soil sample, locally sourced limestone, lower initial phosphate concentrations and different time durations, such as the 6 hours Zurayk et al. (7) shake tested for compared to our 3-hour shake test, could have resulted in the variation in results between the two shake tests performed.

Seeing as the constructed treatment wetland it is mimicking a natural system, many variables may impact results. The actual wetland systems had more variability in the results obtained when compared to previous studies and the shake test performed. New plant media being added to the basins, the fertilizer used to support the new plant media in transportation being added to the system, and the previous basins dictating the phosphate concentration present at the time the stormwater contacts the soil in basin three are all variables that were not considered in other studies.

Table 7. Comparisons of phosphate removal with 20% calcium carbonate concentrations in previous and current studies (7).

Test	Percent concentration	Phosphate Concentration (mg/L)	Time Elapsed (hours)	Percent Phosphate removed
Zurayk et al.	21	200	6	90
Shake Test	20	5.21 ± 0.03	3	2.27 ± 4.98
FWS	20	5.21 ± 0.35	7.33 ± 0.18	4.53 ± 0.37
SSF	20	5.19 ± 0.32	7.33 ± 0.18	7.65 ± 0.40

Table 8. Comparisons of phosphate removal with 40% calcium carbonate concentrations in previous and current studies (7).

Test	Percent concentration Limestone	Phosphate Concentration (mg/L)	Time Elapsed (hours)	Percent Phosphate removed
Zurayk et al.	38	200	6	93
Shake Test	40	5.04 ± 0.03	3	36.40 ± 1.28
FWS	40	5.19 ± 0.10	7.33 ± 0.18	22.36 ± 0.02
SSF	40	5.10 ± 0.05	7.33 ± 0.18	19.86 ± 0.12

The recycle line did not improve the overall quality of water. With the increased retention time, nitrate concentrations were expected to decrease. The nitrate concentrations we observed remained constant after being recycled through the system. Additionally, turbidity concentrations increased as a result of the recycle. The increase in turbidity was likely due to the amendments made in basin 3 where the fines in the soil were made mobile after it had been disturbed to add both the pebble and fine sized limestone to the soil. After the phosphate concentrations were reduced in the first cycle, they were observed to go back to initial levels in the recycle. This rebound in phosphate concentrations was from the presence of phosphate in Basins 1 and 2 since they did not have calcium carbonate soil amendments to reduce phosphate introduced from the first cycle. Previous work observed a reduction of 56% of total nitrogen when no water was recycled in a vertical flow constructed wetland made up of a sedimentation tank, two vertical flow beds, and pumping equipment to manage recycle volumes (16). This wetland system also observed a 9% increase in reduction rated when 50% of the water was recycled (16). This was similar to the rate we observed after the recycle in the FWS system. With 2/3 of the water available to be recycled, and the other 1/3 absorbed into the wetland soil, the FWS system removed 70% of nitrate. The SSF system also retained 50% of the water initially cycled through the system but the recycle reduced the nitrogen concentrations by only 31%. The reduction rate observed in the FWS and SSF in the current study was nearly double that of Brix when the water had not been recycled through the system.

Table 9. Comparisons of nitrate removal with 0% water recycled in previous and current studies (16).

Test	Nitrogen Concentration (mg/L)	Percent water recycled	Percent Total Nitrogen removed
Brix et al.	54	0	56
FWS	3.02 ± 0.17	0	96.56
SSF	3.10 ± 0.06	0	92.16

Table 10. Comparisons of nitrate removal with various percent water recycled in previous and current studies (16).

Test	Nitrogen Concentration (mg/L)	Percent water recycled	Percent Total Nitrogen removed
Brix et al.	54	50	65
FWS	3.02 ± 0.17	33	69.77
SSF	3.10 ± 0.06	75	31.53

Conclusions

The research done using two laboratory-scale, constructed treatment wetlands showed that the addition of fine limestone to the wetland soil reduced the phosphate concentrations by 20-22.5 % due to the increased surface area of the fines compared to the pebble-sized limestone (0.95-0.18 mm). Also, increasing the retention time with the addition of the recycle line did not further reduce phosphate concentration, nor did it improve the overall water quality. When comparing the two wetland systems, a substantial difference in their abilities to remove pollutants was not observed.

Future Work

- To optimize phosphate removal from stormwater, different concentrations of the fine limestone in the soil should be tested.
- To further reduce phosphate, nitrate, and turbidity from the system, the order of the basins should be changed. Turbidity was reduced in basin 1, but was increased in basin 3. However, phosphate and nitrate were reduced in basin 3, but remained constant in the other two basins. Because of these observations, the order of basins 1 and 3 should be switched.

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