

Low Cost Vertical Flow Constructed Wetland Wastewater Treatment System for Small Wineries

Final Report
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Table of Content

Introduction	1
Problem Statement	1
Objectives and Hypotheses	2
Literature Review	2
Methods	3
Studies and Phases	3
Adsorption Media	4
Experimental Design	5
Testing	7
Results and Discussion	9
Column Study	10
Start Up Study	28
PO4Sponge Study	35
Wetland Modeling	37
Conclusions	39
Appendix A: Column Study Data	40
Appendix B: Start Up Study Data	53
Appendix C: PO4Sponge Study Data	55

Introduction

Problem Statement

In 2018, there were nearly 150 wineries that produced more than 2.7 million gallons of wine in Michigan, resulting in this industry being the fifth largest in the United States.¹ Further, Michigan wineries are popular tourist destinations with more than 1.7 million visitors each year.¹

More than 7 gallons of wastewater results from producing 1 gallon of wine.² Because this wastewater is considered high strength and most Michigan wineries are on small plots of land, traditional onsite wastewater treatment may be difficult. Meeting the recently established EGLE (previously the Michigan Department of Environmental Quality) loading rate of 50 lb BOD/acre/day requires a significant amount of land that may reduce that available for vineyards and negatively impact profitability. Alternatives have been examined but the periodic nature of wine production and the likelihood of substantial flows in late autumn add to the challenge of finding effective and affordable wastewater treatment options. Small wineries showcase Michigan's beauty and tourism industry resulting in the urgent need to provide guidance on effective and affordable alternative wastewater treatment options.

The vertical flow constructed wetland (VFCW) is a proven technology for treating diverse, high strength wastewater. VFCWs treat wastewater biologically in three sub-surface gravel cells. A layer of soil above the VFCW prevents freezing conditions. All microbial processes occur within the lined cells preventing any chance of metal mobilization resulting when the soil becomes anaerobic from the application of high BOD wastewater.³ Wastewater is only discharged into drain fields or filter strips or used for irrigation after treatment. This type of wetland has previously been researched for its utility in treating high strength milking facility wastewater⁴ and is now the basis for a NRCS standard (Michigan Gravel Contactor for Treating Milking Center Wastewater).

The intermittent nature of winery wastewater production and its wide variety of characteristics offers further challenges and the performance of the VFCW is unclear. Recent research out of the Department of Civil and Environmental Engineering at the University of South Florida has shown promising results for this type of wastewater for the sorption of ammonia using clinoptilolite and nitrate using tire chips as the microbiology builds up and becomes adequate to completely treat the nitrogen. Additionally, oyster shells are added to provide pH buffering. All of these materials are inexpensive and do not leach harmful byproducts. In this research, a modest amount of each sorbent was investigated for immediate removal of nitrogen once winery wastewater resumes flow after extended no flow periods.

Phosphorus is another parameter that must be considered to achieve complete wastewater treatment and is especially important if subsurface discharge is into groundwater that rapidly progresses to surface water. This is common in the vicinity of lakes. MetaMateria Technologies

¹ Michigan grape and wine industry council. 2019. Fast Facts. Michigan Grape and Wine Industry Council. <https://www.michiganwines.com/fast-facts>.

² Turner, L. 2010. Fennville winery gets new wastewater system: State officials seek to protect groundwater from potentially toxic substances. Kalamazoo Gazette, Kalamazoo, MI. http://www.mlive.com/news/kalamazoo/index.ssf/2010/06/fennville_winery_gets_new_wast.html.

³ Safferman, S. I., Fernandez-Torres, I., Pfiffner, S. M., Larson, R. A., and Mokma, D. L. 2011. Strategy for Land Application of Wastewater using Soil Environment Sensor Monitoring and Microbial Community Analyses." *Journal of Environmental Engineering*, 137(2), 97-107.

⁴ Campbell, E. L., Safferman, S. I. 2015. Design criteria for the treatment of milking facility wastewater in a cold weather vertical flow wetland. *Transaction of the ASABE*, 58(6)1509-1519.

manufactures an engineered media, PO4Sponge, that uptakes phosphorus that can then be regenerated and reused or directly applied as a fertilizer.

Objectives and Hypotheses

It was hypothesized that a VFCW combined with adsorption media to remove/recover phosphorus and nitrogen, after idle periods before the microbial community is fully active, will effectively and efficiently treat winery wastewater so that it can be discharged without impact to the environment. Consequently, the objective of this project was to conduct a bench-scale evaluation of this integrated system and used the collected data to develop design criteria for the Michigan winery industry. Further, a mathematical model of the system was examined.

Literature Review

Wine production is a seasonal process with peak productivity from late September through January.⁵ During peak season, wineries are harvesting, crushing, and fermenting grapes as part of wine production. Much of the wastewater produced results from washing equipment.⁶ The volume and characteristic of winery wastewater can vary greatly. During the off-season, wastewater production is intermittent and flow rates are approximately one third of the maximum peak season flow.⁵ Table 1 shows data collection from five Michigan wineries.

Table 1. Winery Wastewater Composition

Parameter (mg/L)	Five Michigan wineries ⁵		
	Average	Minimum	Maximum
Chemical Oxygen Demand (COD)	3,236	493	5,722
Biochemical Oxygen Demand (BOD ₅)	2,046	336	3,578
pH	6.2	5.5	6.8
Sodium	279	28	792
Total Phosphorus (TP)	5.26	1.29	9.19
Total Nitrogen (TN)	7.60	2.63	18.5

Due to the wide variety of flows and loads^{5,6,7,8} conventional treatment systems are challenging.^{9,10} Therefore, land treatment system technology has been developed and is commonly used in the winery industry. However, surface land application is challenging in the

⁵ Lakeshore Environmental, Inc. (2015). "A Study on the Effectiveness of Onsite Wastewater Treatment Systems for Michigan Wineries," Final Performance Report to Michigan Department of Agriculture & Rural Development. Grand Rapids, MI, n.p

⁶ Serrano, L., De la Varga, D., Ruiz, I., & Soto, M. (2011). Winery wastewater treatment in a hybrid constructed wetland. *Ecological Engineering*, 37(5), 744-753.

⁷ De la Varga, D., Ruiz, I. and Soto, M., 2013. Winery wastewater treatment in subsurface constructed wetlands with different bed depths. *Water, Air, & Soil Pollution*, 224(4)1485.

⁸ Grismer, M.E., Carr, M.A. and Shepherd, H.L., 2003. Evaluation of constructed wetland treatment performance for winery wastewater. *Water environment research*, 75(5), 412-421.

⁹ Mosteo, R., Ormad, P., Mozas, E., Sarasa, J., Ovelleiro, J.L. 2006. Factorial experimental design of winery wastewaters treatment by heterogeneous photo-Fenton process. *Water Res.* 40, 1561–1568.

¹⁰ Petruccioli, M., Duarte, J.C., Eusebio, A., Federici, F., 2002. Aerobic treatment of winery wastewater using a jet-loop activated sludge reactor. *Process Biochem.* 37(8)821–829.

winter when the soil surface freezes. Subsurface passive aeration system can be effective in reducing organic material but not nitrogen. Both can cause metal mobilization¹¹ and following the EGLE 50 lb BOD/acre/day requires a large footprint. A constructed wetland may provide many benefits, especially for small wineries such as a small footprint and low capital and operational costs.

Methods

Studies and Phases

This project consisted of three separate studies. The long-term column study (Column Study) investigated the use of a VFCW to treat winery wastewater under various conditions. A short-term column study (Start Up Study) evaluated the performance of the VFCW after a period of no-flow of wastewater. Lastly, the use of PO4Sponge to remove total phosphorus from treated effluent was assessed (PO4Sponge Study). Each study used process wastewater collected from a local winery. Samples from the experimental treatment systems were collected and tested two to three times per week. Experimental treatment systems and flow rates through the systems were maintained and monitored weekly. In the Column Study, each column was inoculated one week prior to operation with secondary effluent wastewater to establish a microbial community within the columns. In the Start Up Study, columns were not inoculated prior to operation, simulating a new system that was not inoculated or one that had been ideal for an extended time period.

Different operating conditions, called phases, were tested in the Column Study. The first phase was considered to be normal operating conditions. This phase was at room temperature (70° F) and wastewater was distributed into the VFCWs four times a day at 8 am, 11 am, 2 pm, and 5 pm. This schedule was chosen to simulate the frequency of wastewater production at a winery. Wastewater was distributed at a loading rate of 1.06E-2 lb chemical oxygen demand (COD)/ft²/d mL/d, resulting in a flow rate of 20 ml/min for 2.1 minutes per loading. This loading rate was previously determined to be optimum for a VFCW.¹² The second phase maintained the temperature and loading rate of Phase 1 but the distribution of wastewater was changed to even, 6-hour increments throughout the day. The third phase maintained the loading frequency and rate of Phase 2 but reduced the temperature of the wetland to 50°F. The Start-Up Study used the same operating conditions as Phase 2 and the PO4Sponge Study was performed at room temperature with the same daily loading and frequency as the Start-Up Study. These studies and phases are summarized in Table 2.

¹¹ Brian, T., Poll, J. and Buist, E. 2012. Passive soil aeration for the treatment of food processing wastewater. Final performance report, https://www.michigan.gov/documents/mdard/Smeltzer_Passive_Aeration_Study_FINAL_REPORT_-Summarized_384809_7.pdf.

¹² Campbell, E. L., Safferman, S. I. 2015. Design criteria for the treatment of milking facility wastewater in a cold weather vertical flow wetland. *Transaction of the ASABE*, 58(6)1509-1519.

Table 2. Project Studies and Phases

Study	Description	Phase	Operating Conditions
Column Study	Evaluation of wetland performance on various loading conditions	Phase 1: Normal operating conditions	Room temperature, uneven loading frequencies, loading rate of 1.06E-2 lb COD/ft ² /d Columns inoculated with domestic secondary effluent wastewater prior to operation
		Phase 2: Even loading frequency	Room temperature, even loading frequencies, loading rate of 1.06E-2 lb COD/ft ² /d
		Phase 3: Reduced temperatures	Reduced temperatures, even loading frequencies, loading rate of 1.06E-2 lb COD/ft ² /d
Start Up Study	Evaluation of wetland performance after no-flow of wastewater	N/A	Room temperature, even loading frequencies, loading rate of 1.06E-2 lb COD/ft ² /d Columns not inoculated prior to operation
PO4Sponge Study	Evaluation of PO4Sponge performance in phosphorus removal from winery wastewater	N/A	Room temperature, even loading frequencies, flow rate of 3 mL/min for 13.92 min 4 times per day

Adsorption Media

The utility of nitrogen adsorption media was investigated in the Column and Start Up Studies and phosphorus adsorption media was investigated in the PO4Sponge Study. Nitrogen adsorption media selected for this study was clinoptilolite and a combination of tire chips and crushed oyster shells. The phosphorus adsorption media selected for this study was PO4Sponge.

Clinoptilolite, a natural zeolite material that has been previously shown to effectively remove ammonium from domestic wastewater. This adsorption media is negatively charged and attracts positively charged NH_4^+ .¹³ Many researchers have studied the effectiveness of clinoptilolite and have found the adsorption capacity to range from 11.69 mg NH_4^+ -N/g to 32.5 mg NH_4^+ -N/g.^{14,15,16,17,18} A low cost and robust denitrification treatment system to complement the wetland during the winter and after idle periods is the tire-sulfur hybrid adsorption denitrification (T-SHAD) process. This process uses a combination of scrap tire chips and crushed oyster shells to remove nitrate.¹⁹ Krayzelova et al. (2014) found that the T-SHAD

¹³ Cooney, E.L., Booker, N.A., Shallcross, D.C., Stevens, G.W. 1999. Ammonia removal from wastewaters using natural Australian zeolite. II. Pilot-scale study using continuous packed column process. *Separation Science and Technology*, 34(14)2741-2760.

¹⁴ Rodriguez-Gonzalez, L. C., (2017). "Advanced Treatment Technologies for Mitigation of Nitrogen and Off-flavor Compounds in Onsite Wastewater Treatment and Recirculating Aquaculture Systems" Graduate Theses and Dissertations. <http://scholarcommons.usf.edu/etd/6941>

¹⁵ Huang, G., Liu, F., Yang, Y., Deng, W., Li, S., Huang, Y., Kong, X. 2015. Removal of ammonium-nitrogen from groundwater using a fully passive permeable reactive barrier with oxygen-releasing compound and clinoptilolite. *J. Environ. Manag.* 154(2015)1-7.

¹⁶ Karadag, D., Akkaya, E., Demir, A., Saral, A., Turan, M., Ozturk, M. 2008. Ammonium removal from municipal landfill leachate by clinoptilolite bed columns: breakthrough modeling and error analysis. *Ind. Eng. Chem. Res.* 47(23)9552-9557.

¹⁷ Mazeikiene, A., Valentukeviciene, M., Rimeika, M. 2008. Removal of nitrates and ammonium ions from water using natural sorbent zeolite (clinoptilolite). *J. Environ. Eng. Landsc. Manag.* 16(1)38-44.

¹⁸ Siljeg, M., Foglar, L., Kukucka, M. 2010. The ground water ammonium sorption onto Croatian and Serbian clinoptilolite. *J. Hazard. Mater.* 178(1-3)572-577.

¹⁹ Krayzelova, L., Lynn, T.J., Banihani, Q., Bartacek, J., Jenicek, P., Ergas, S.J. 2014. A tire-sulfur hybrid adsorption denitrification (T-SHAD) process for decentralized wastewater treatment. *Water research*, 61(2014)191-199.

process achieved 89% of NO₃-N removal under highly variable loading conditions, resulting in an adsorption capacity of 0.658 mg NO₃-N/g.¹⁹

Previous research has demonstrated that PO₄Sponge, a granular engineered adsorption media, can reduce total phosphorus from concentrations of 1 mg/L to less than 0.3 mg/L.²⁰ This study is unique from prior studies because wastewater was distributed into a column of PO₄Sponge from the top rather than filling the column from the bottom. The quantity of PO₄Sponge was determined following the manufacturer recommendation for empty bed contact time (a function of the amount of adsorption media and the flow rate of wastewater through the adsorption media) for the specific influent concentration of total phosphorus.

Experimental Design

Four parallel bench-scale wetland systems, each with three columns, were used in the Column Study. Each wetland system simulated a VFCW and each column represented a cell. Only the surface area was scaled down, resulting in 4-foot tall columns with the inlet of wastewater 1.5 feet below the top of the column (representing ground level). The diameter of the columns was scaled down to a 4-inches; research has shown that columns should have a diameter that is diameter of the largest particle size in order to minimize wall effects.²⁰ The columns were constructed of polyvinyl chloride (PVC) tubing, placed vertically, and sealed at the bottom with a PVC cap. A hose barb fixed into the PVC cap served as the outlet for effluent wastewater in Columns 1 and 3, and as the inlet for wastewater in Column 2.

Masterflex norprene tubing was used to convey flow of wastewater through the system. Influent wastewater was introduced into the first column of each system through an inlet barb, 1.5 feet below the top of the column, and flowed top-down to promote aerobic conditions. Effluent wastewater from the first column was then either pumped back into the top of the first column (recycled) or into the bottom of the second column. The recycling ratio was maintained at 3:1 with three times as much wastewater going into the first column as the second. Filling the second column from the bottom resulted in water saturation and an anoxic environment within the second column. Effluent wastewater from the second column was then pumped to the top of the third column, which served as a polishing column and had aerobic conditions. Treated effluent wastewater flowed out of the bottom of the third column into a collection bottle. A single wetland system is shown in Figure 1.

¹⁹Safferman, S. I., Dong, Y., & Thelen, J. (2015). SP Removal from Domestic Wastewater Using Engineered Nano-Media, presented at the Onsite Wastewater Mega-Conference, Virginia Beach, November 3-6, 2016. Virginia: National Onsite Wastewater Recycling Association

²⁰ Radolinski, J, Wu, J, Xia, K, Stewart, R, 2018. Transport of a Neonicotinoid Pesticide, Thiamethoxam, from Artificial Seed Coatings. Science of the Total Environment, 618, 561-568.

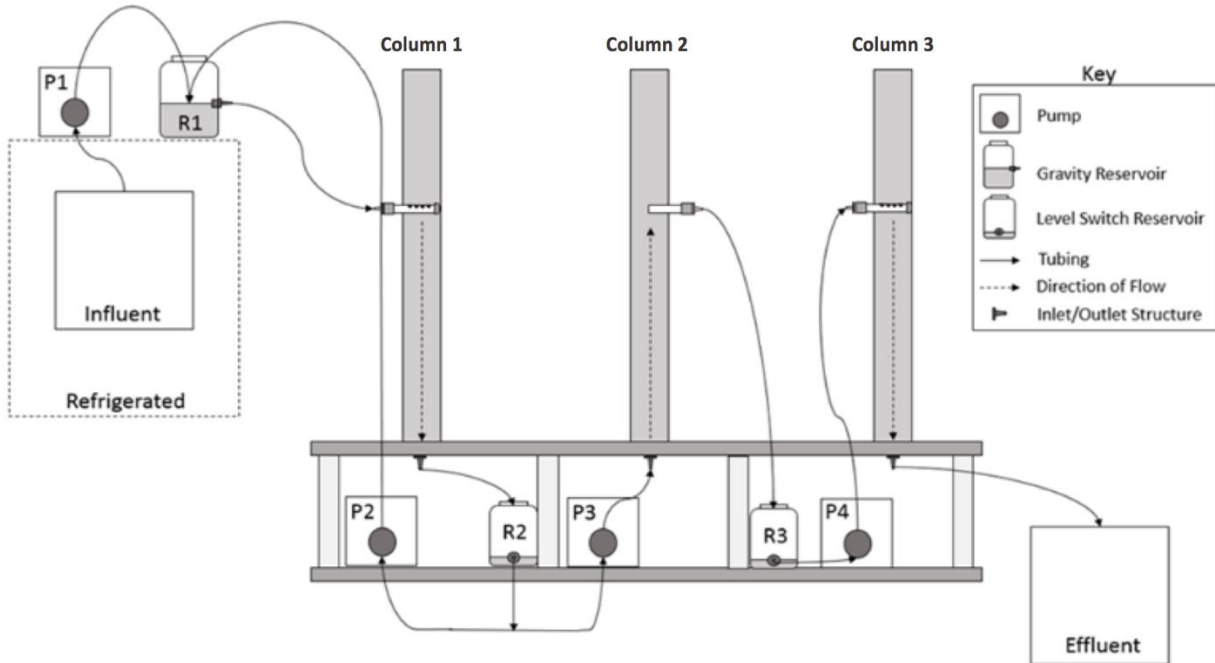


Figure 1. Bench-Scale Experimental Wetland ²¹

All of the columns were filled with gravel and the test columns had adsorption media. Gravel was 0.25-inch in diameter and cleaned prior to being used. The quantity of adsorption media was calculated based on the capacity of the adsorption capacities (11.69 NH₄⁺-N/g and 0.658 mg NO₃-N/g), winery wastewater characteristics from literature (118 mg/L total nitrogen) ²², and the maximum hydraulic loading that a VFCW would ever receive (0.504 gal/ft²/d).²¹

System 1 served as the control and contained only gravel. System 2 had clinoptilolite and gravel mixed into the first column and only gravel in the second column. In Systems 3 and 4, the first column of the test systems included clinoptilolite and gravel and the second column of the test systems included tire chips, oyster shells, and gravel. The third column of each system was a polishing column with only gravel present. A 1.5-inch layer of river rock, 0.75-inches in diameter, at the bottom of each column kept the gravel from blocking the bottom inlet/effluent hose barb. Media in each system and column is summarized in Table 3.

Table 3. Media in each Column

System	Column 1	Column 2	Column 3
System 1	Gravel	Gravel	Gravel
System 2	Gravel, clinoptilolite	Gravel	Gravel
System 3	Gravel, clinoptilolite	Gravel, tire chips, oyster shells	Gravel
System 4	Gravel, clinoptilolite	Gravel, tire chips, oyster shells	Gravel

²¹ Campbell, E. L., Safferman, S. I. 2015. Design criteria for the treatment of milking facility wastewater in a cold weather vertical flow wetland. *Transaction of the ASABE*, 58(6)1509-1519.

²² Ioannou, L. A., Puma, G. L., & Fatta-Kassinos, D. (2015). Treatment of winery wastewater by physicochemical, biological and advanced processes: A review. *Journal of Hazardous Materials*, 286, 343–368. doi.org/10.1016/j.jhazmat.2014.12.043

Plants were not investigated in this project as nutrients are not continuously up taken in Michigan during winter. Additionally, the subsurface application of the wastewater in a VFCW is below the root zone of most wetland-style plants. As such, it was determined that excluding plants would result in a more conservative experimental design.

The Start Up Study used four columns with the same configuration as Column 1 in the column study; two columns were filled with gravel only (Control 1 and Control 2) and two columns were filled with gravel and clinoptilolite (Treatment 1 and Treatment 2). Operation was the same as in the Column Study, Phase 2.

The PO4Sponge Study used 1.5-inch diameter PVC columns sealed at the bottom with a PVC cap to contain the PO4Sponge. A 1-inch layer of gravel at the bottom of the columns prevented washout of the media through the effluent hose barb, located at the bottom of the columns. One column served as the control and contained only the gravel layer (Control). Two columns contained the gravel layer and 90 mL of PO4Sponge (Test and Replicate). Effluent, treated wastewater from the Column Study was spiked with monopotassium phosphate to match the average phosphorus concentration of the untreated wastewater. This wastewater was pumped into the top of the columns and distributed directly onto the adsorption media (Figure 2).

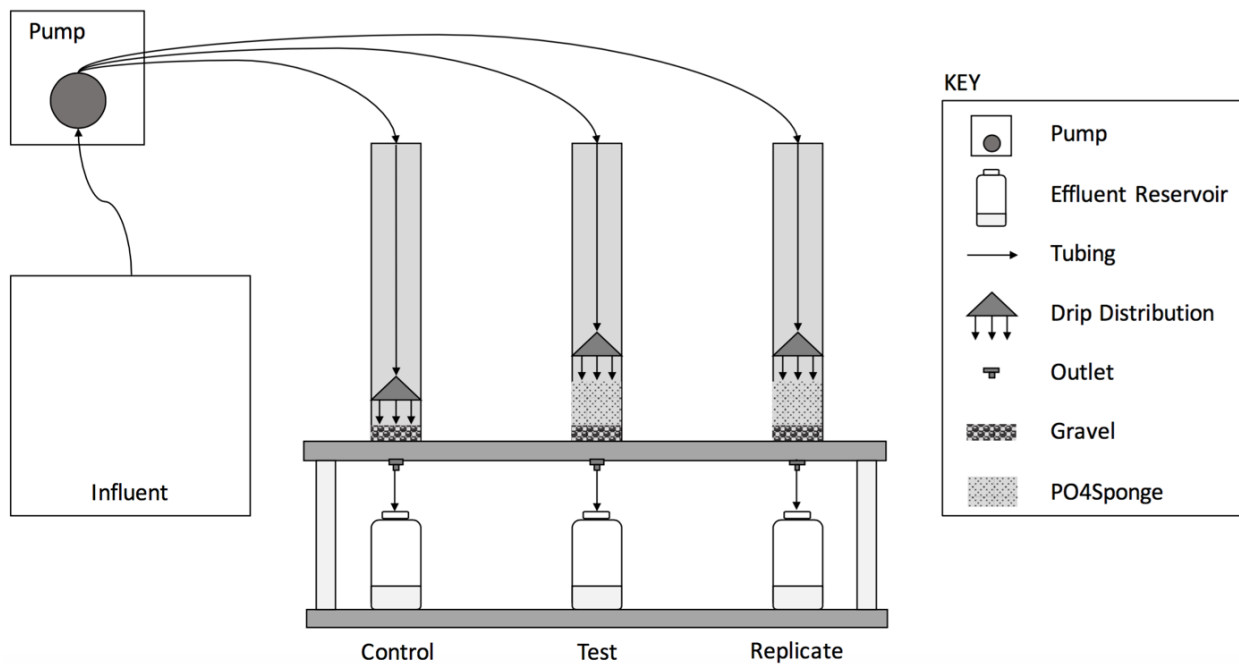


Figure 2. PO4Sponge Experimental Design

Testing

Grab samples for each study were collected immediately following wastewater loading into the treatment systems. Samples were then refrigerated or tested immediately. If a sample was not tested within 24 hours of collection, it was preserved with concentrated sulfuric acid and tested within 28 days of preservation. A preserved sample was first neutralized with 5 N sodium

hydroxide solution before testing. Testing followed HACH standard procedures, summarized in Table 4.

Table 4. Testing Methods

Test	Method	Range	HACH
Phosphorus, Total (HR)	Ascorbic Acid	0.5-5.0 mg/L PO ₄ -P	10209
Phosphorus, Total (ULR)	Ascorbic Acid	10-500 µg/L PO ₄ -P	10209
Chemical Oxygen Demand	Reactor Digestion	20-1,500 mg/L	8000
Nitrogen, Total	Persulfate Digestion	1-16 mg/L	10208
Nitrogen, Nitrate	Dimethylphenol	0.2-13.5 mg/L NO ₃ -N	10206
Nitrogen, Ammonia	Salicylate	1-12 mg/L NH ₃ -N	10205
Alkalinity	Sulfuric acid titration with digital titrator	10-4,000 mg/L	8203
pH	pH Probe	1-13	Calibrated Probe

A standard, replicate, and blank sample were included in testing for quality assurance and control at an approximate rate of 10%. Replicates were chosen randomly and dilutions were replicated as needed. The percent relative range between replicates is summarized in Table 5 and is separated by study and parameter. The percent recovery of the tested standards and their supposed value is summarized in Table 6 and is separated by study and parameter.

Table 5. Percent Relative Range

Parameter	Column Study	Start Up Study	PO4Sponge Study	Average
Total Phosphorus, HR	5.1	2.1	1.7	3.0
Total Phosphorus, ULR	N/A	N/A	4.9	4.9
COD	5.2	2.7	N/A	4.0
Nitrogen, Total	6.4	9.8	N/A	8.1
Nitrogen, Nitrate	6.5	8.5	N/A	7.5
Nitrogen, Ammonia	6.0	1.6	N/A	3.8
Average	5.8	4.9	3.3	

Table 6. Percent Recovery

Parameter	Column Study	Start Up Study	PO4Sponge Study	Average
Total Phosphorus, HR	92.1	93.9	97.4	94.5
Total Phosphorus, LR	N/A	N/A	94.3	94.3
COD	95.0	98.8	N/A	96.9
Nitrogen, Total	95.3	97.1	N/A	96.2
Nitrogen, Nitrate	99.9	101.5	N/A	100.7
Nitrogen, Ammonia	93.6	99.2	N/A	96.4
Average	95.2	98.1	95.9	

Results and Discussion

Results are divided by each study. First, data is shown followed by an analyses.

Column Study

Analytical results from the Column Study are presented graphically by parameter and by system (Figures 3 – 29). Each graph includes the influent concentration of wastewater and the effluent of each column within a system. Vertical lines on the graph indicate a new phase of the study. Total phosphorus is presented first, then COD, nitrogen, pH, and alkalinity. A discussion of each parameter is included following the results. Numerical results of the Column Study are included in Appendix A. Results from the Start Up Study are examined. These graphs are categorized by parameter and by control and treatment columns. Parameters are discussed in the same order as the Column Study. Numerical results of the Start Up Study are included in Appendix B. Results from the PO₄Sponge Study are presented and discussed. Numerical results of the PO₄Sponge Study are included in Appendix C.

Total Phosphorus

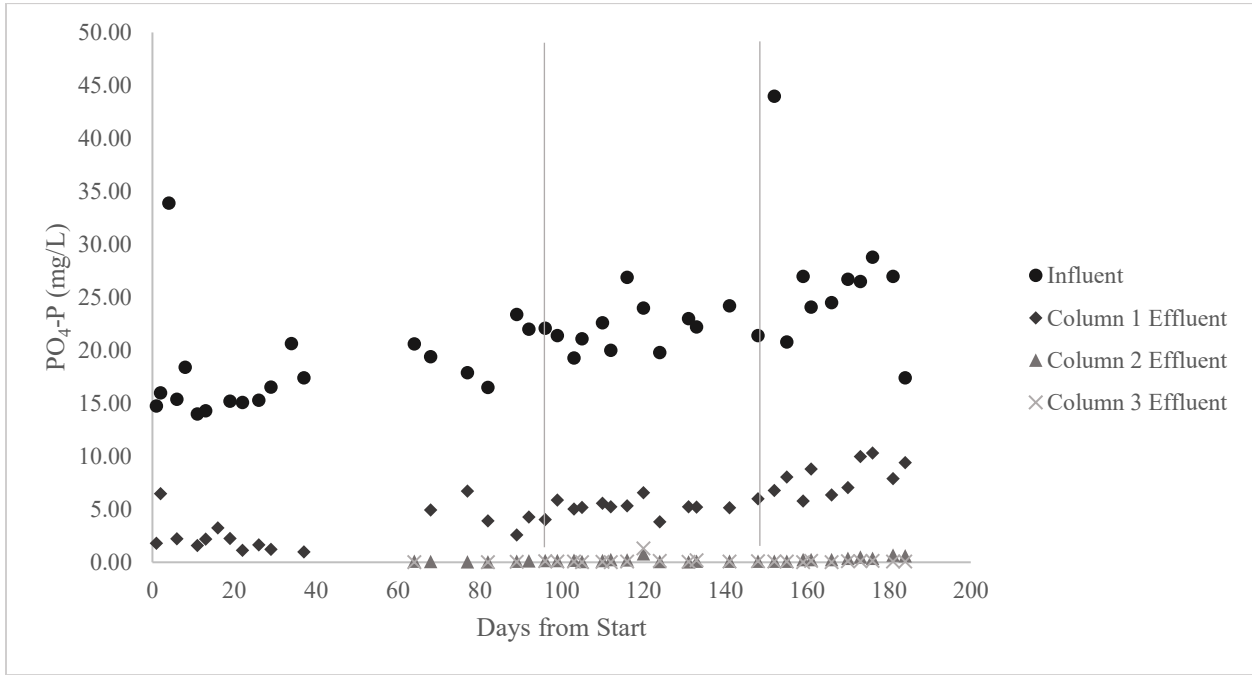


Figure 3. System 1, Total Phosphorus

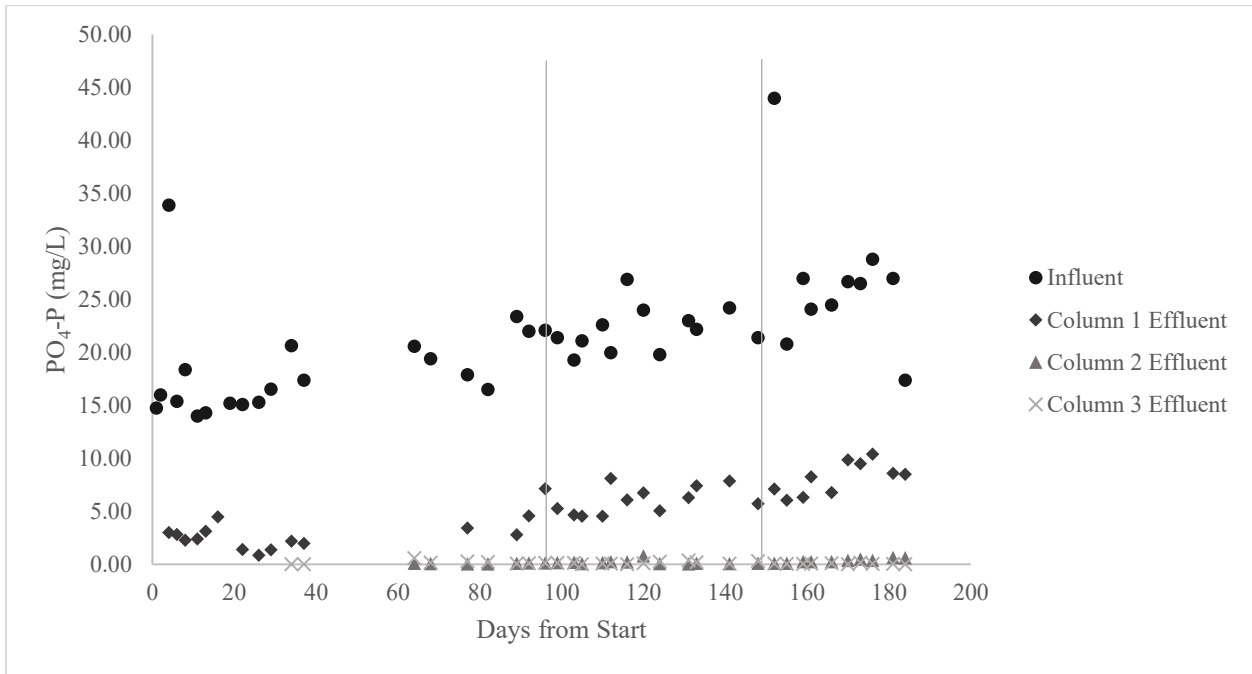


Figure 4. System 2, Total Phosphorus

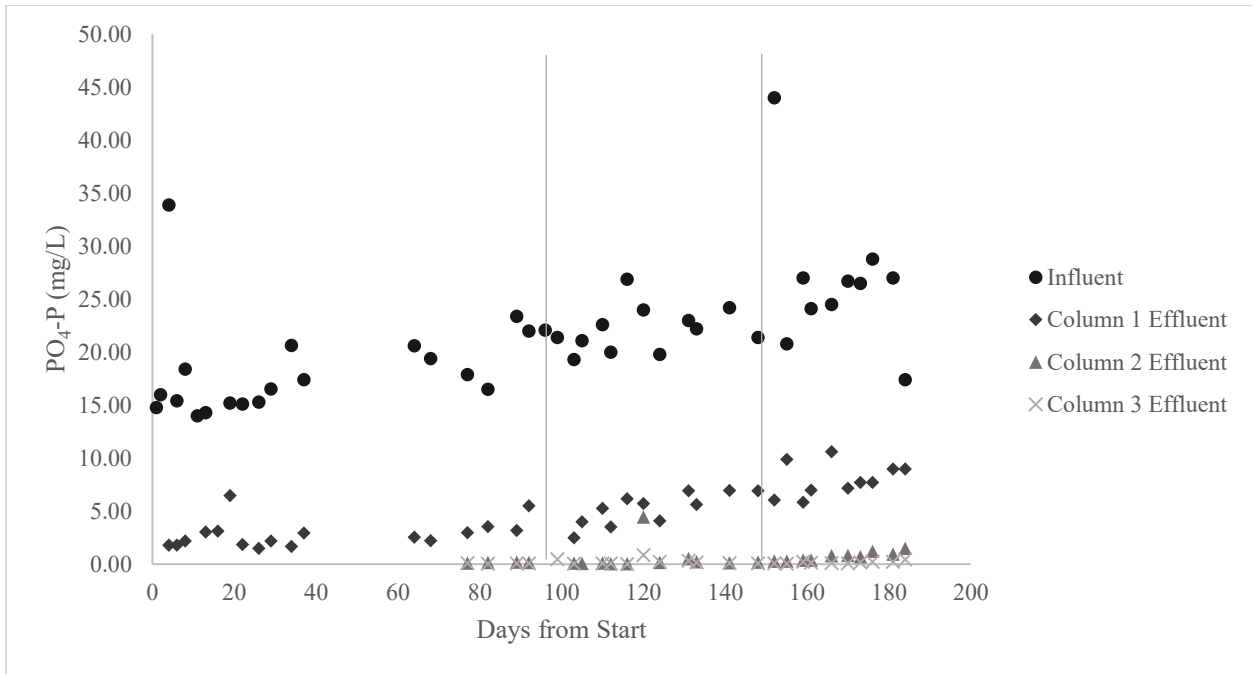


Figure 5. System 3, Total Phosphorus

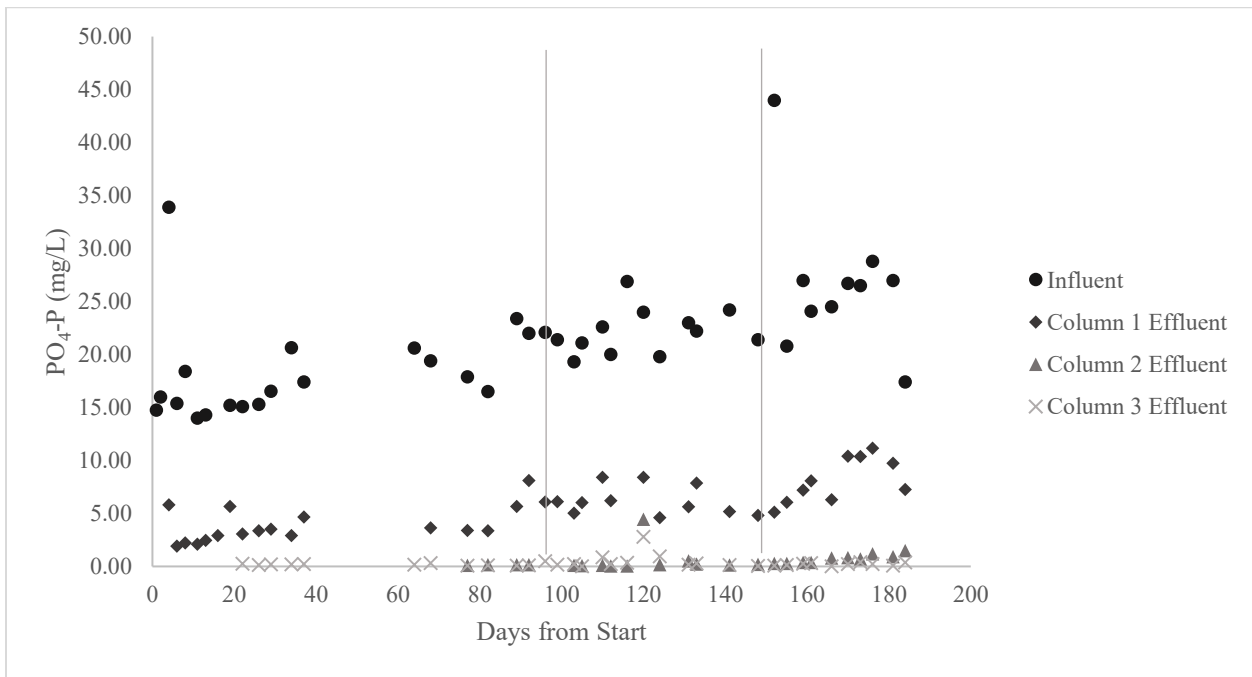


Figure 6. System 4, Total Phosphorus

Chemical Oxygen Demand

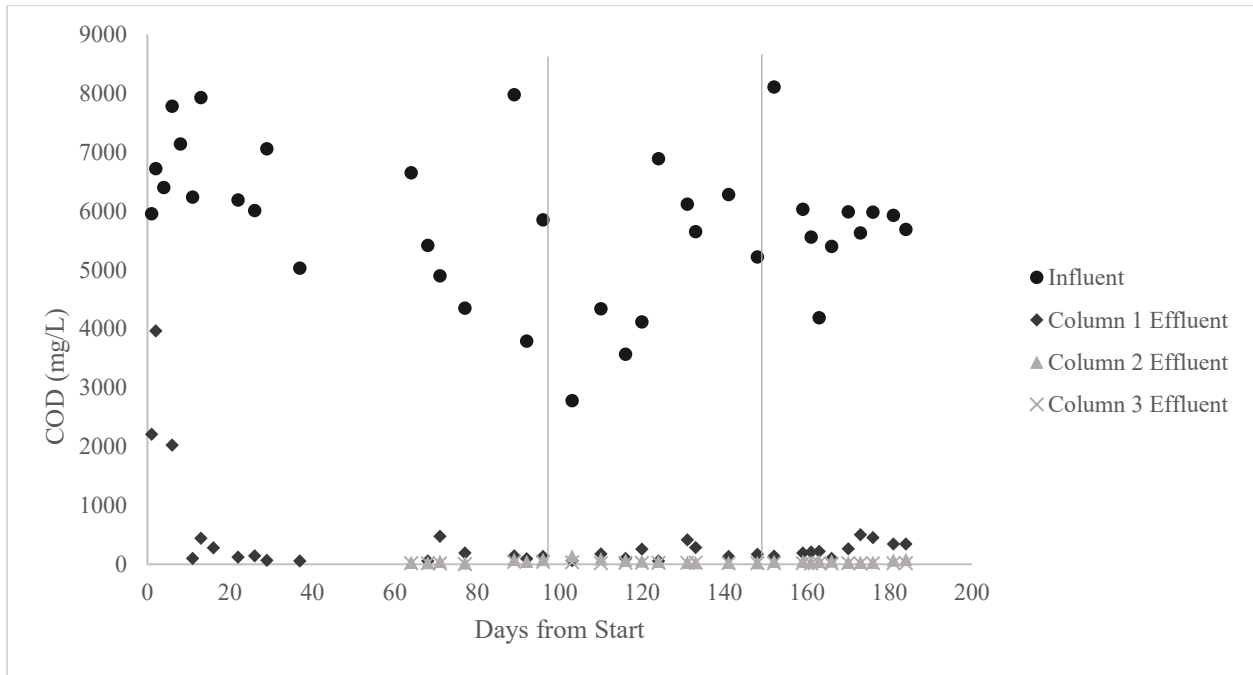


Figure 7. System 1, COD

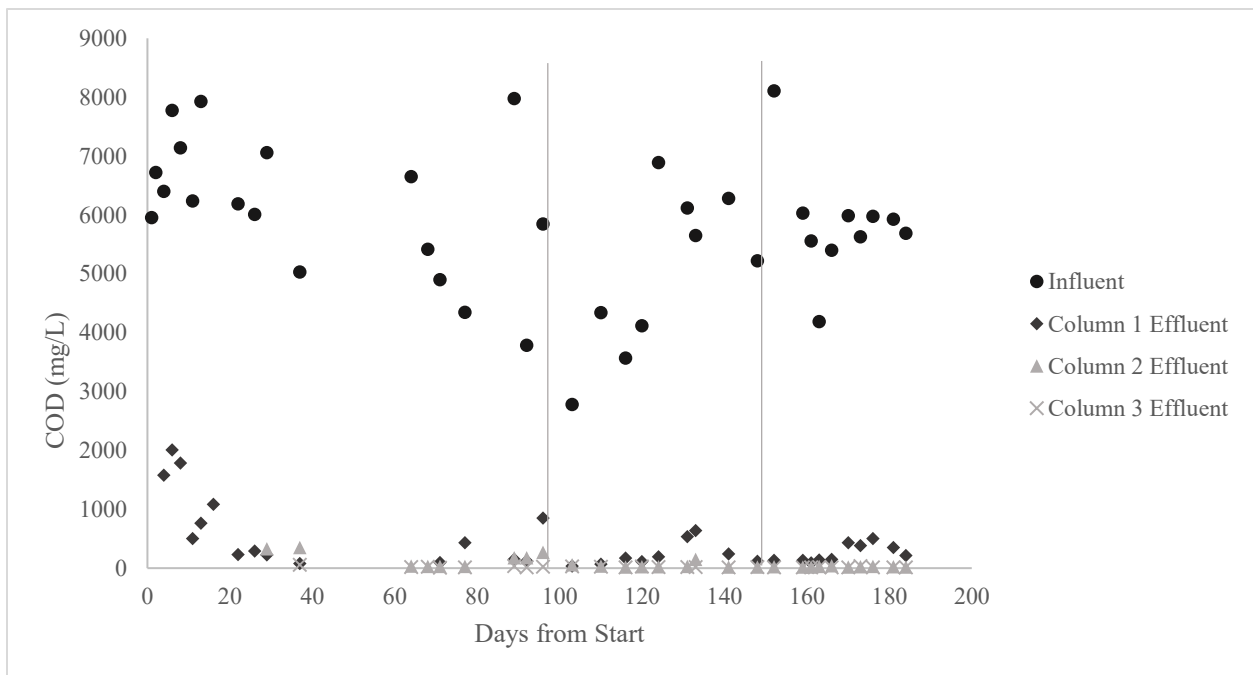


Figure 8. System 2, COD

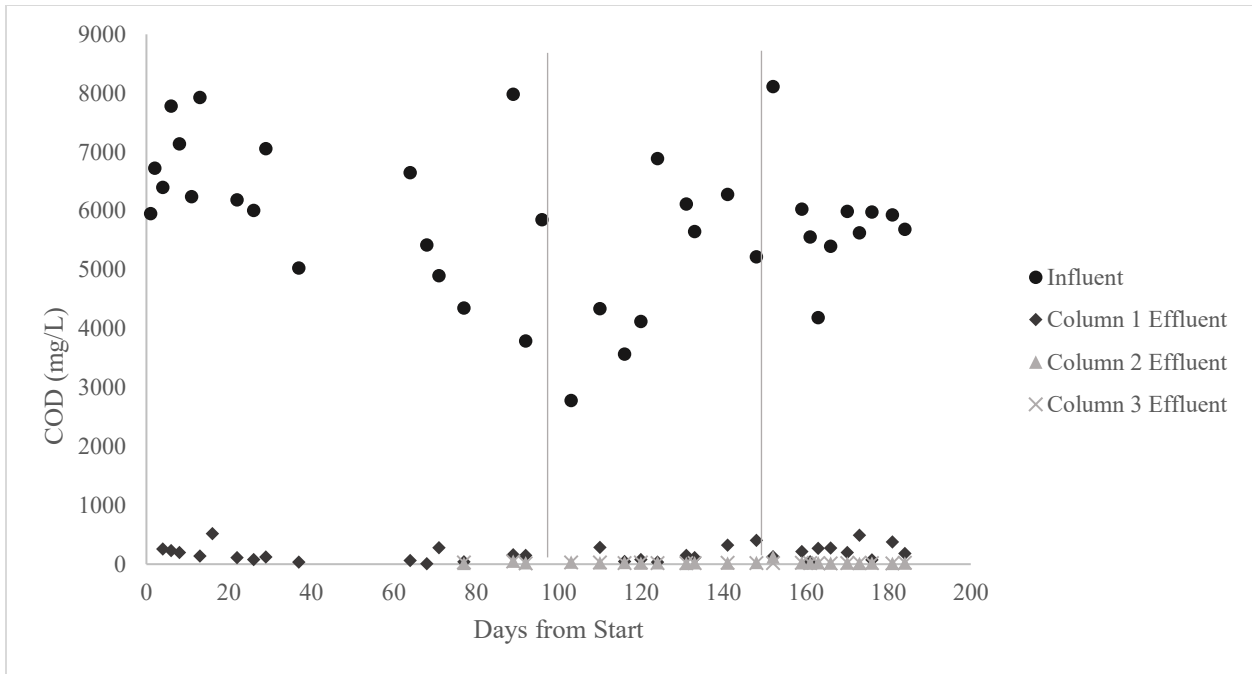


Figure 9. System 3, COD

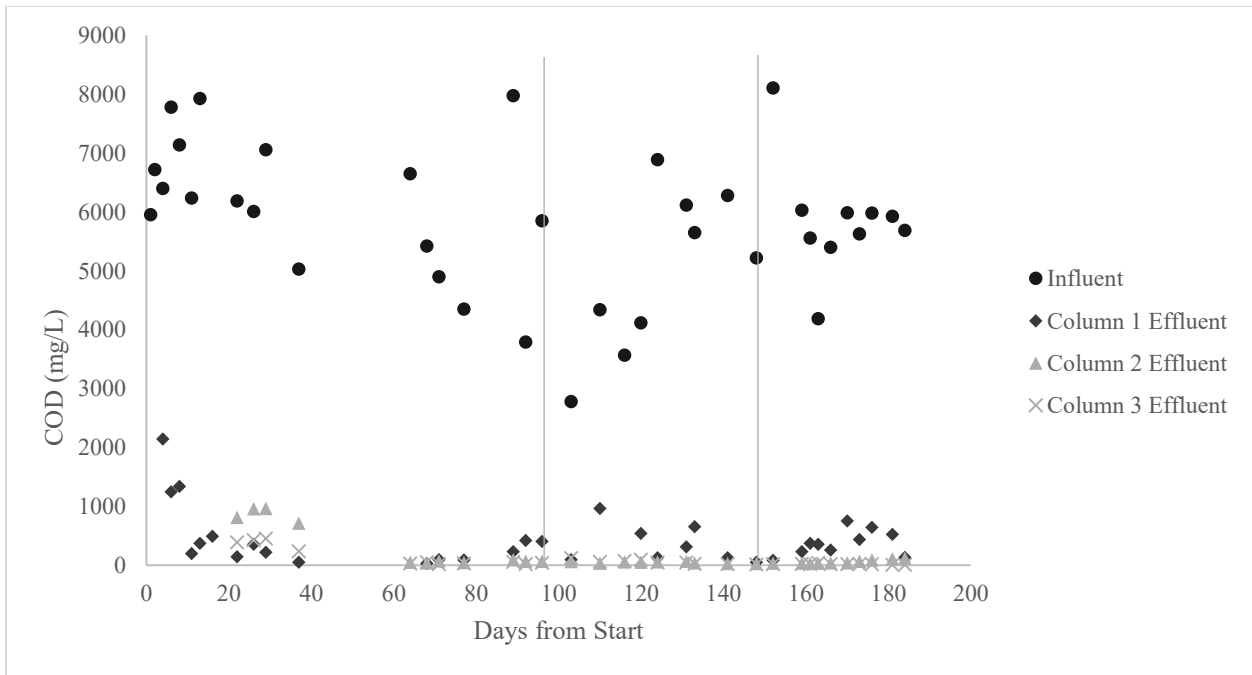


Figure 10. System 4, COD

Nitrogen, Total

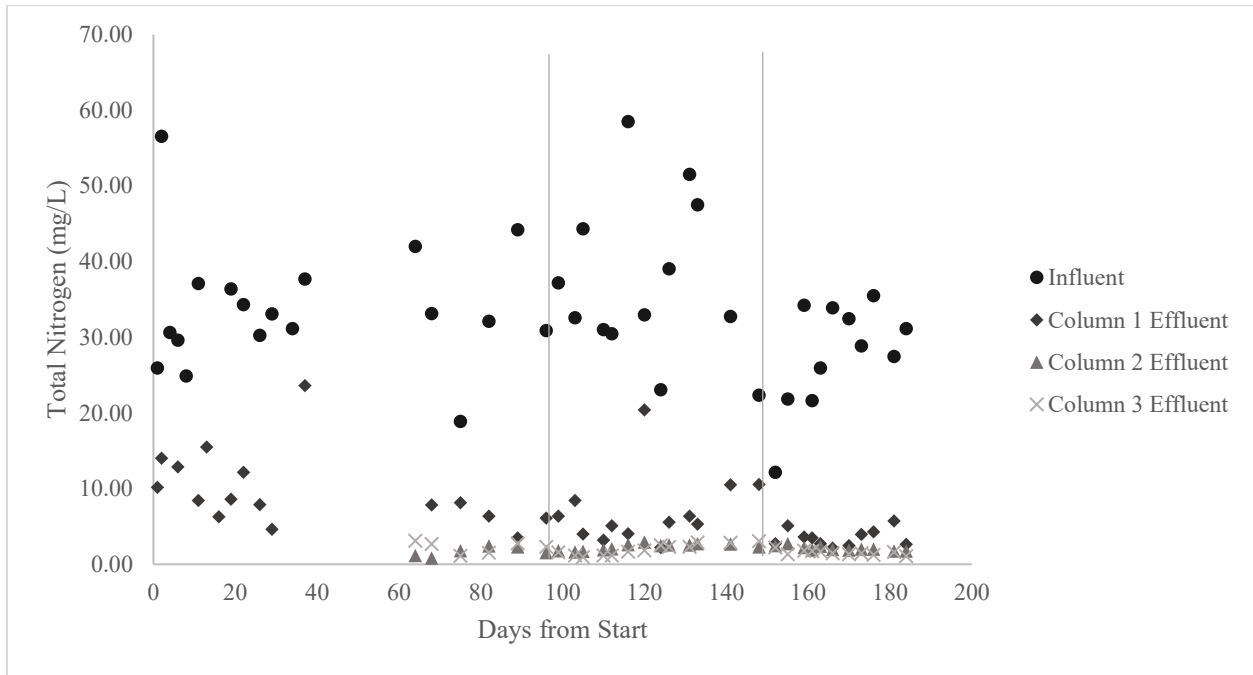


Figure 11. System 1, Total Nitrogen

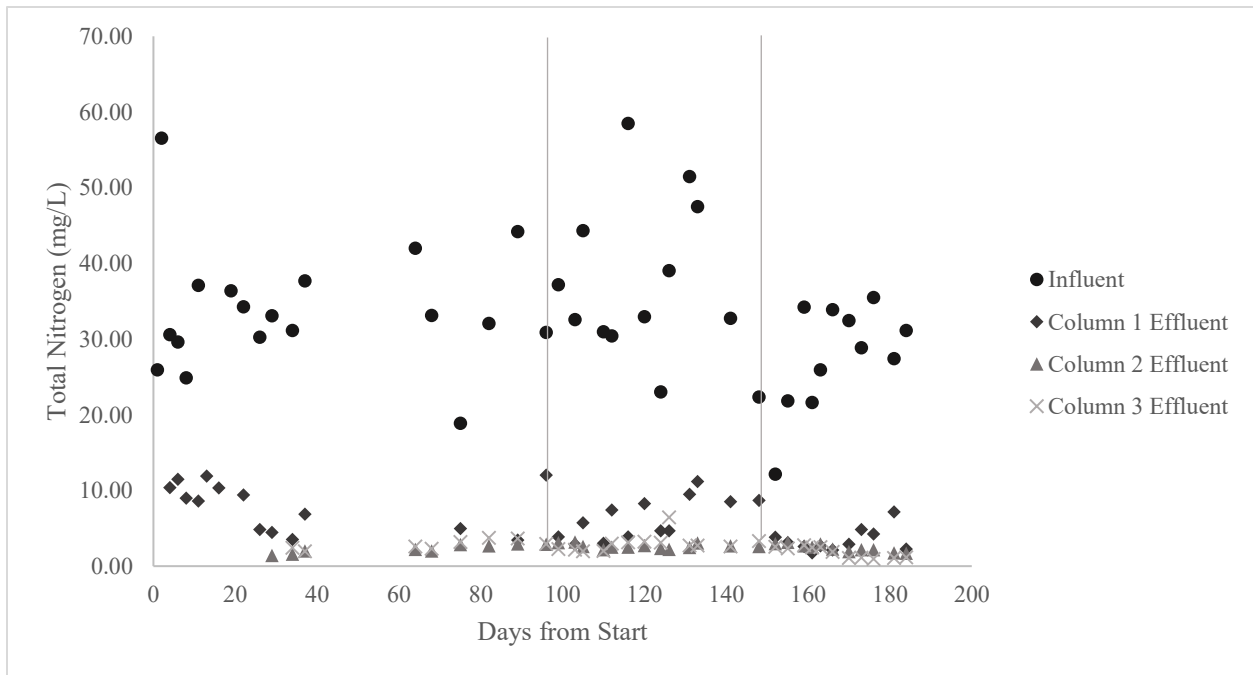


Figure 12. System 2, Total Nitrogen

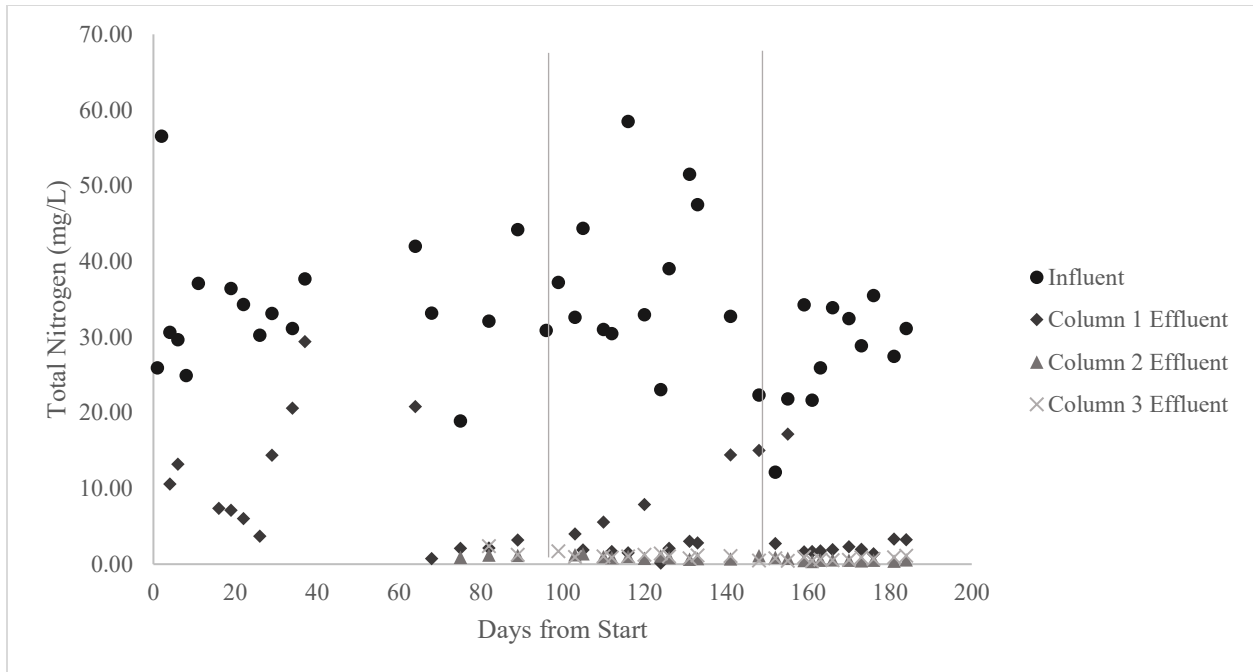


Figure 13. System 3, Total Nitrogen

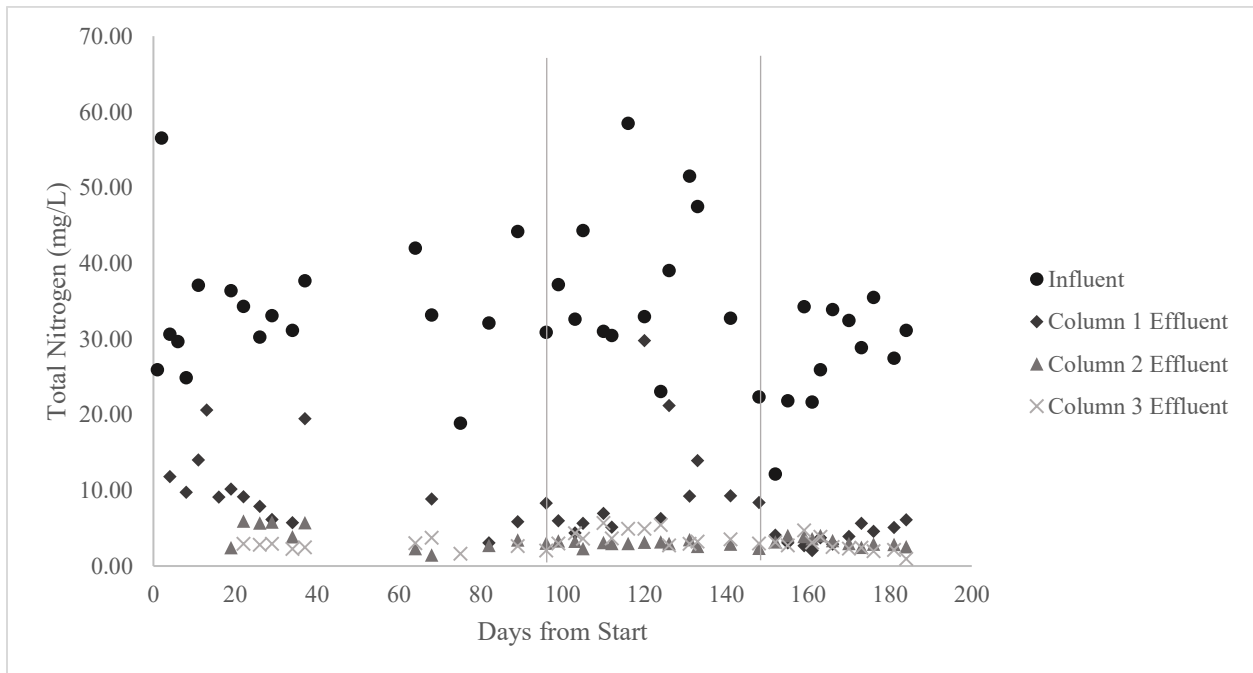


Figure 14. System 4, Total Nitrogen

Nitrogen, Nitrate

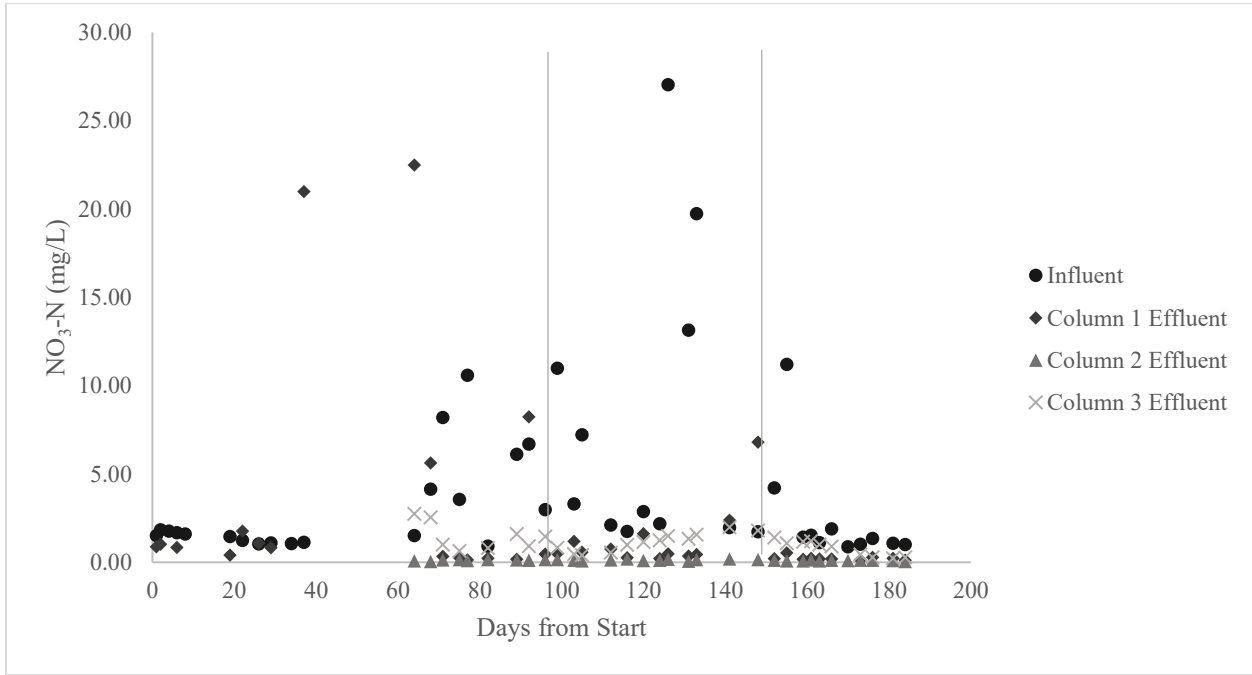


Figure 15. System 1, Nitrate as Nitrogen

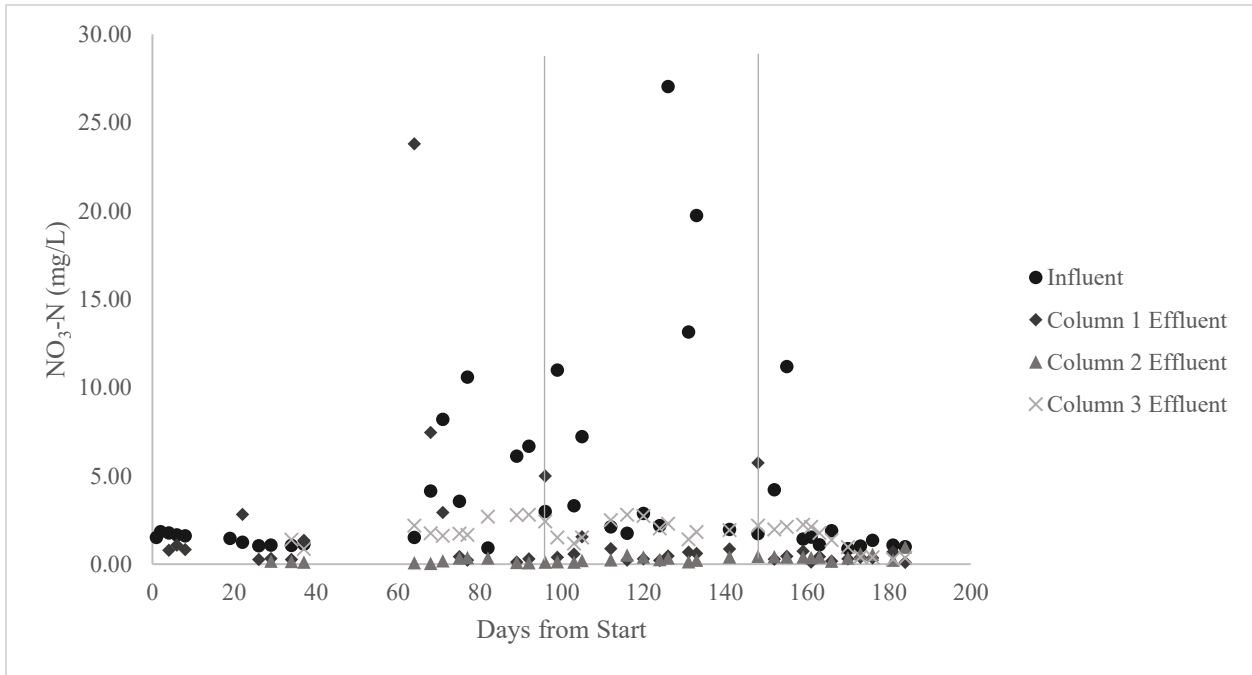


Figure 16. System 2, Nitrate as Nitrogen

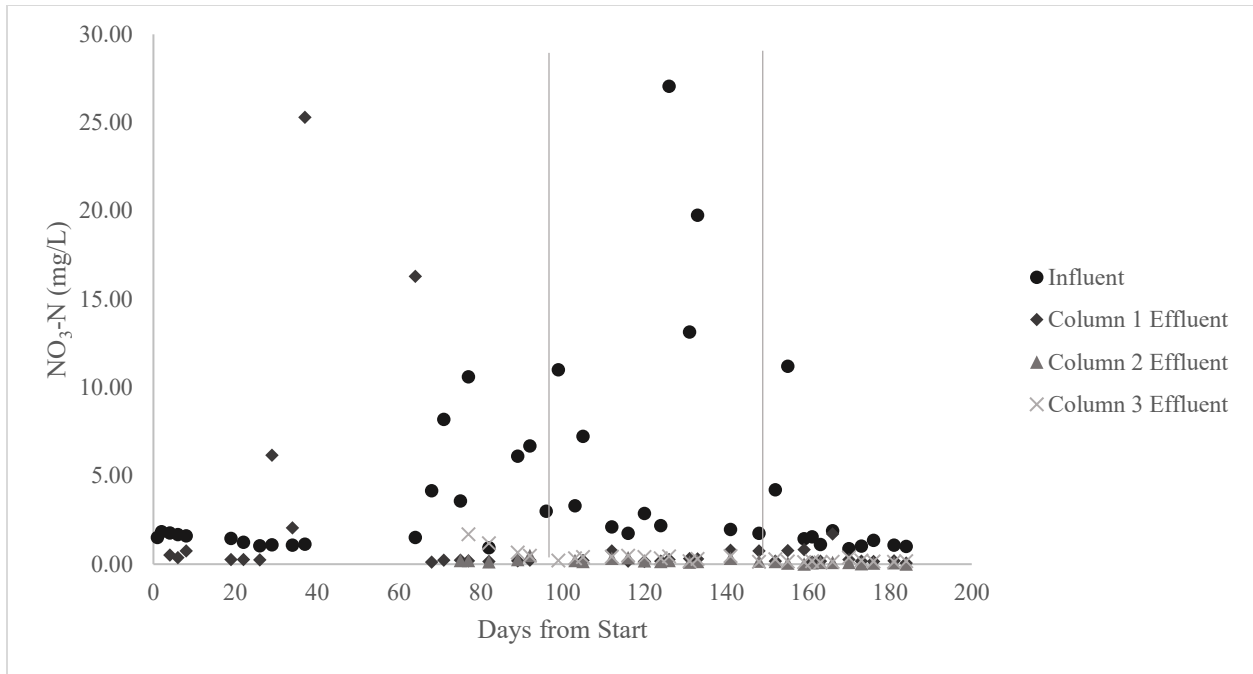


Figure 17. System 3, Nitrate as Nitrogen

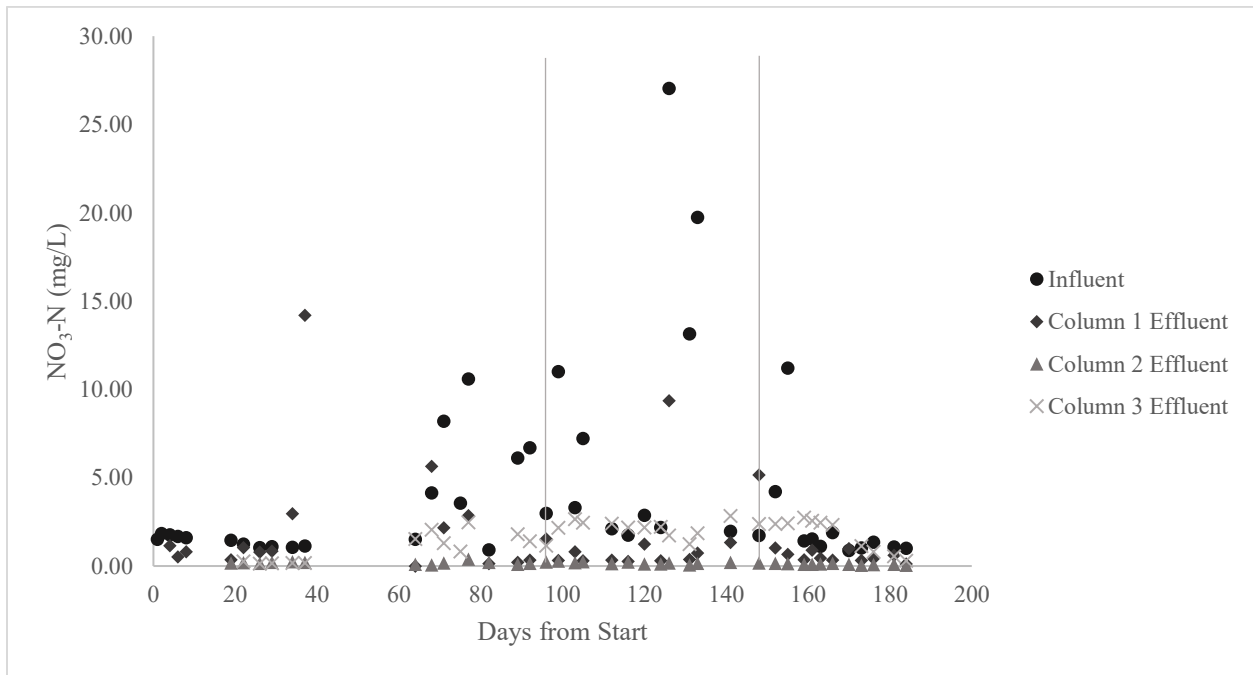


Figure 18. System 4, Nitrate as Nitrogen

Nitrogen, Ammonia

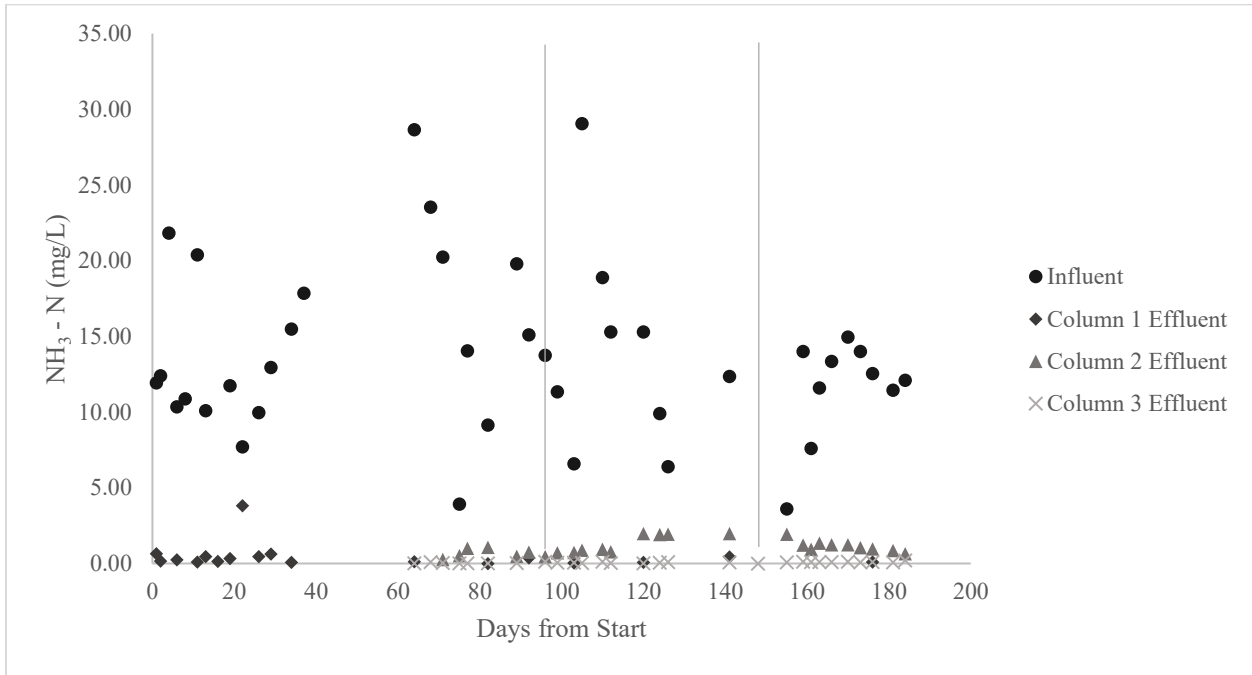


Figure 19. System 1, Ammonia as Nitrogen

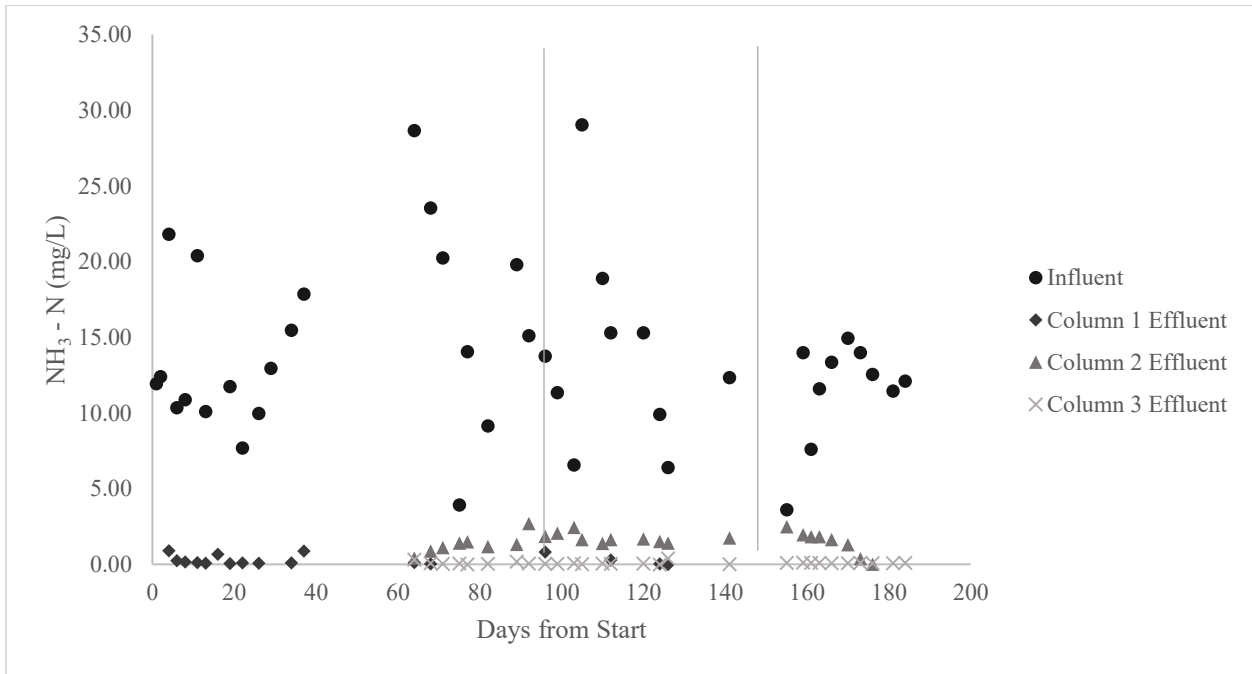


Figure 20. System 2, Ammonia as Nitrogen

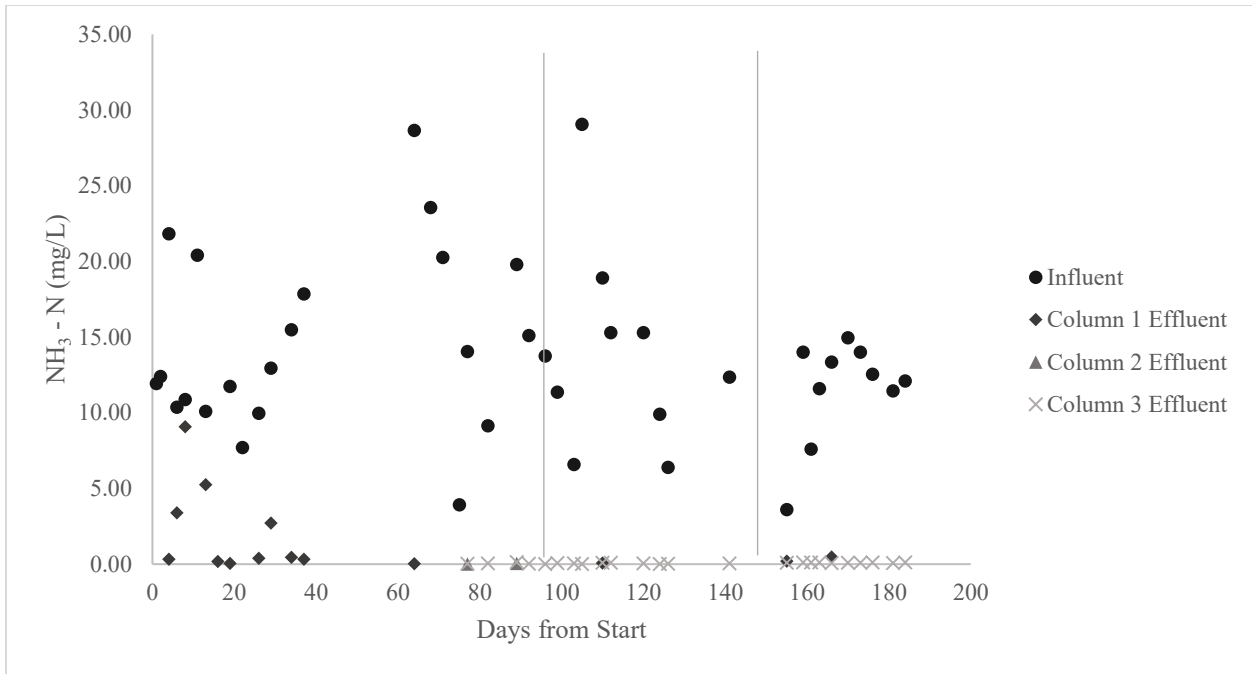


Figure 21. System 3, Ammonia as Nitrogen

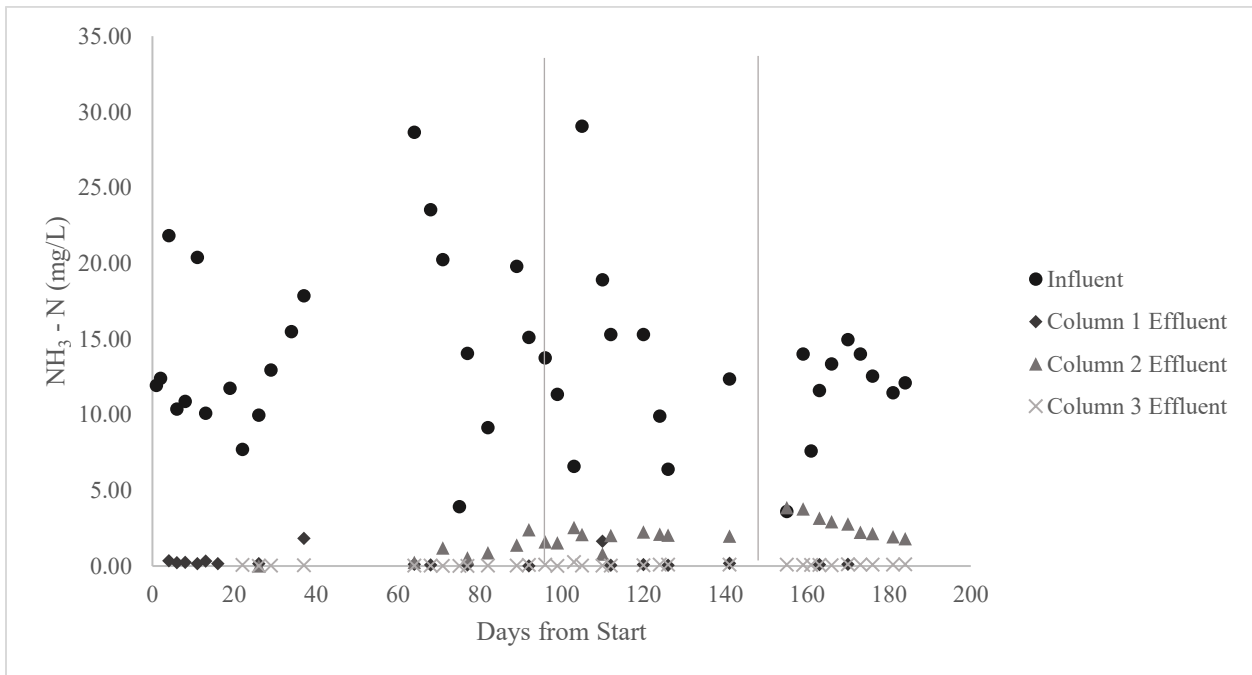


Figure 22. System 4, Ammonia as Nitrogen

pH

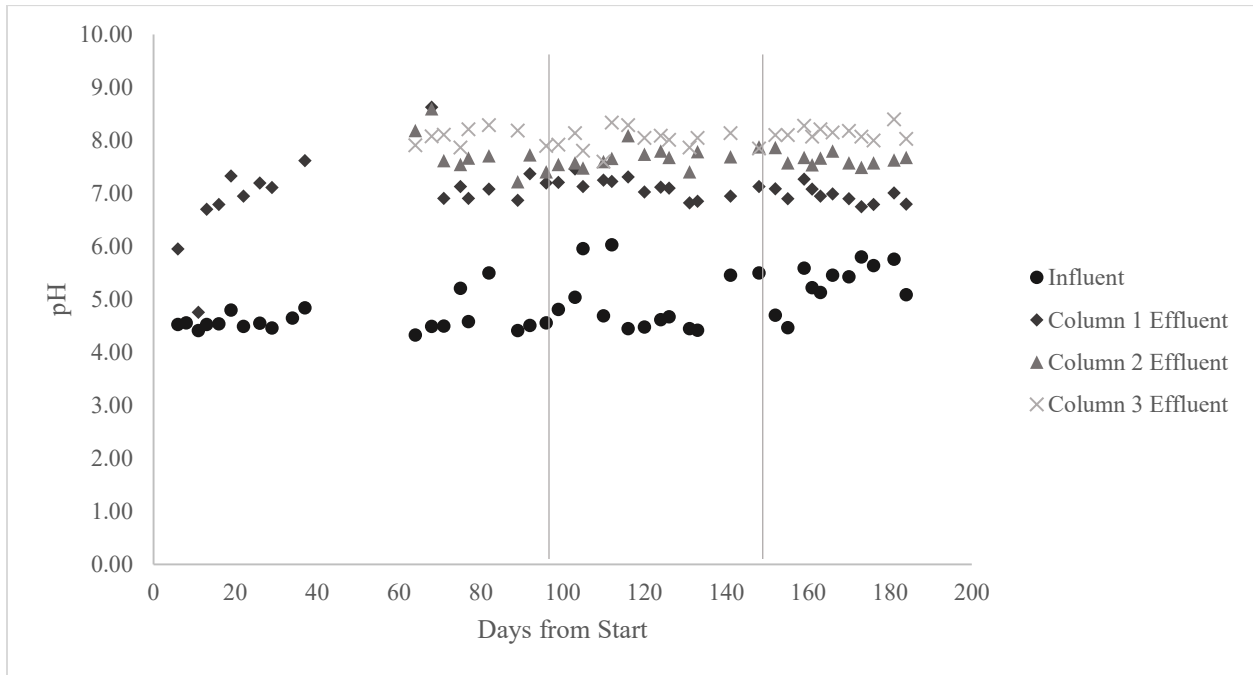


Figure 23. System 1, pH

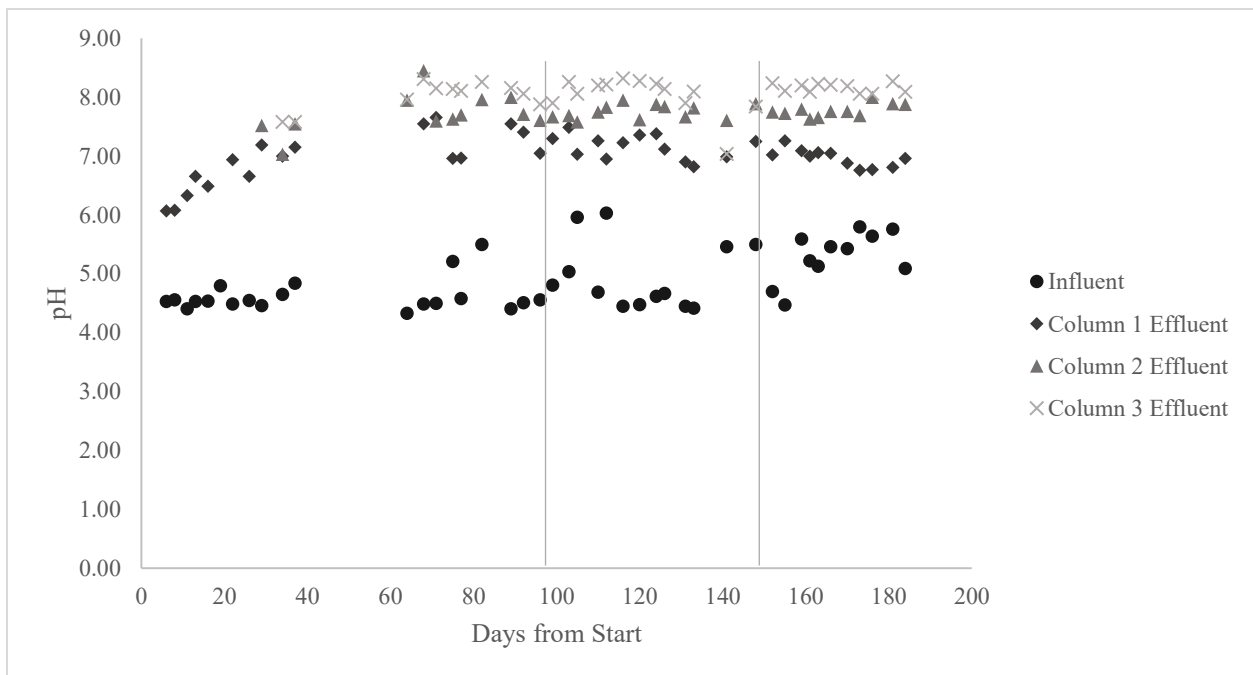


Figure 24. System 2, pH

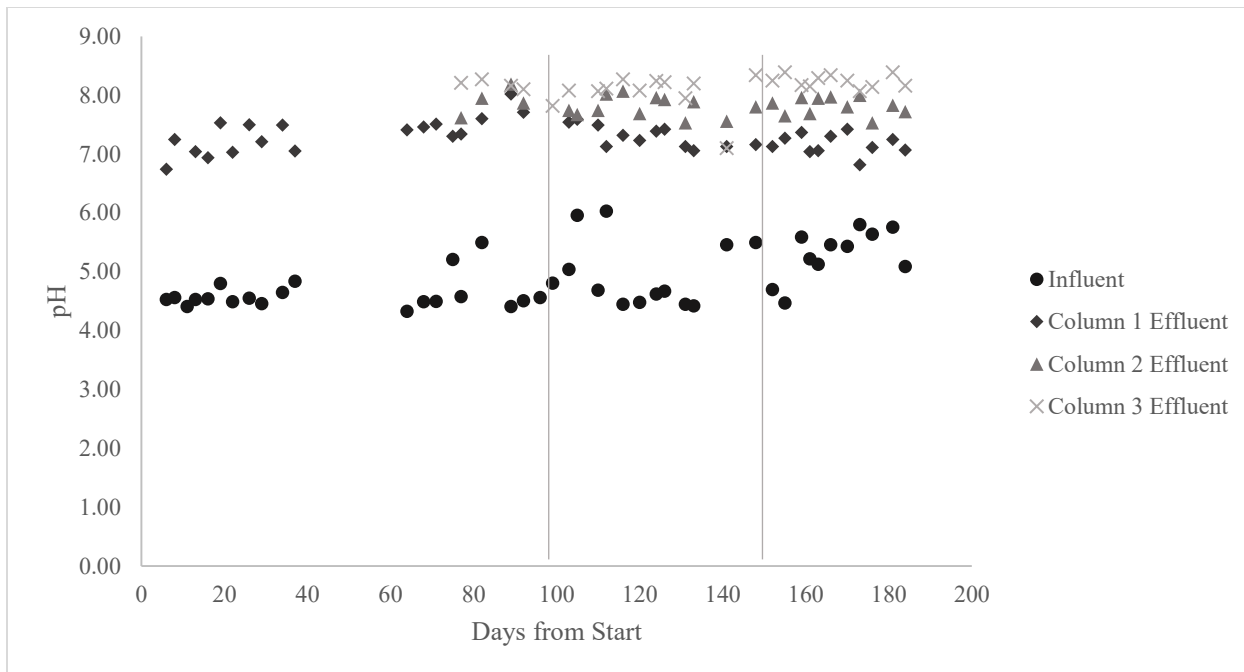


Figure 25. System 3, pH

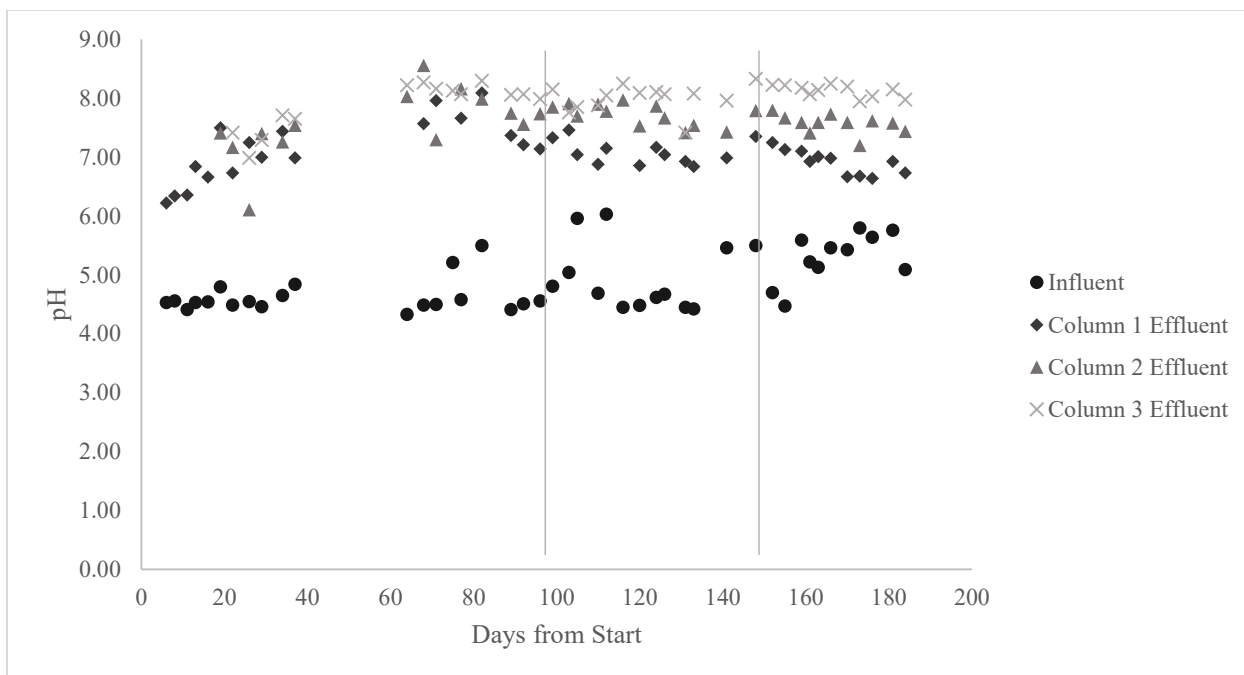


Figure 26. System 4, pH

Alkalinity

Total alkalinity was measured on four separate occasions during Phase 2. Results from System 1, the Control System, and System 4, the treatment system, are shown in Figure 27. The error bars represent standard deviation.

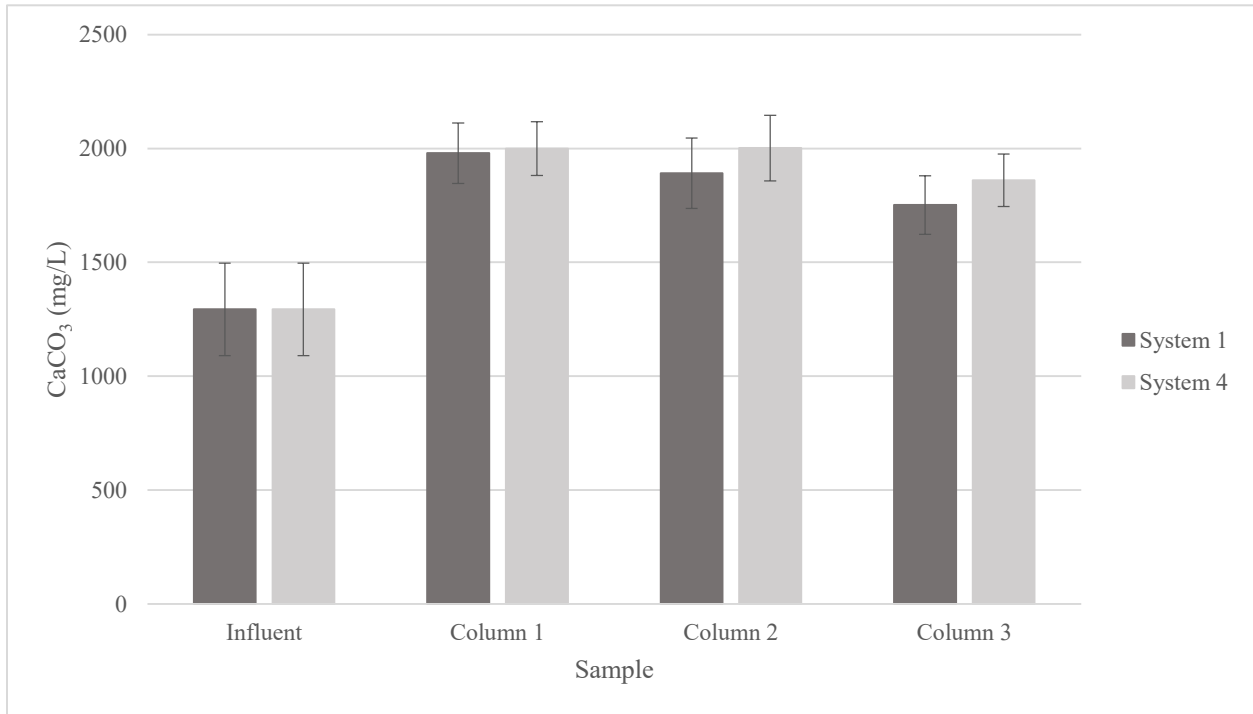


Figure 27. Average Total Alkalinity in Systems 1 and 4

Total Phosphorus

The total percent removal of total phosphorus from each system is shown in Table 7 and is separated by phase. The average influent concentrations for Phases 1, 2, and 3 were 18.4 mg/L P, 22.2 mg/L P, and 26.7 mg/L P, respectively. These concentrations were reduced to below the detection limit of 0.5 mg/L in 94% of all final effluent samples. Of the total removal, an average of 83%, 74%, and 68% removal occurred in the first column during Phases 1, 2, and 3, respectively.

Table 7. Total Percent Removal of Total Phosphorus

Phase	System 1	System 2	System 3	System 4
Phase 1	99.9%	99.0%	99.6%	98.9%
Phase 2	99.2%	99.3%	99.0%	97.7%
Phase 3	99.7%	99.7%	99.3%	99.1%

Across all of the systems, Phase 1 had the lowest concentrations in the effluent of the first column and Phase 3 had the highest. However, the influent concentration of wastewater also increased at approximately the same rate. Percent removal, as shown in Table 7, indicates that the phases did not have an influence on removal of total phosphorus.

In Phases 2 and 3, the systems with clinoptilolite, tire chips, and oyster shells (Systems 3 and 4) had slightly less removal than the systems with just gravel (System 1), and gravel and clinoptilolite (System 2). However, this was less than 1% difference and can be considered negligible at this high level of removal. Based on this, the adsorption media did not influence removal of phosphorus.

The main mechanism of removal of total phosphorus was adsorption to the gravel in the columns. Although microbial uptake removes some phosphorus, it is negligible in comparison to physical adsorption. This removal mechanism is unlikely to be influenced by varying the application times or reducing the temperature, as shown in Table 7. Although this study did not find the breakthrough point of phosphorus adsorption to the gravel, previous research on vertical flow constructed wetlands has shown that eventually the adsorption capacity of the gravel will be reached.²³ Due to the higher concentrations of total phosphorus found in winery wastewater, an alternative means of phosphorus removal, such as PO4Sponge, is critical.

COD

The total percent of COD removed from each system and phase is shown in Table 8. The average influent concentration of COD varied throughout the study but overall stayed between 5,000 to 6,000 mg/L. Phase 1 had an average influent concentration of 6,189 mg/L, Phase 2 was 4,997 mg/L, and Phase 3 was 5,851 mg/L. Despite the varying influent concentrations, 90.4% of all effluent samples were below 50 mg/L and 33.7% were below the detection limit of 20 mg/L. Of the total removal, an average of 92%, 95%, and 95% removal occurred in the first column during Phases 1, 2, and 3, respectively.

²³ Campbell, E. L., Safferman, S. I. 2015. Design criteria for the treatment of milking facility wastewater in a cold weather vertical flow wetland. Transaction of the ASABE, 58(6)1509-1519.

Table 8. Total Percent Removal of COD

Phase	System 1	System 2	System 3	System 4
Phase 1	99.6%	99.5%	99.6%	97.4%
Phase 2	99.4%	99.5%	99.5%	98.6%
Phase 3	99.7%	99.7%	99.7%	99.6%

There is no clear influence of phase or adsorption media on the removal of COD as nearly all systems and phases show greater than 99% removal. The only exceptions to this are Phases 1 and 2 of System 4. Even so, these are still both over 97% total removal of COD.

The main mechanism of removal of COD is by microbial activity within the columns, which can occur in both aerobic and anoxic conditions. At the beginning of Phase 1, it can be observed in each system that Column 1 effluent concentrations begin high (approximately 1,500 to 2,000 mg/L) but seem to reach an equilibrium effluent concentration of approximately 240 mg/L within 11 days. Despite higher effluent concentrations from Column 1 in each system, there did not appear to be impact on the final effluent concentration from Column 3 of each system.

Nitrogen, Total

The percent of total nitrogen removed from each system and phase is shown in Table 9. The influent concentration varied substantially throughout the study. The average influent concentration of each phase was 33.8 mg/L N, 37.2 mg/L N and 27.7 mg/L N. This variation was likely a result of microbial degradation within the influent container and subsequent efforts were made to maintain the nitrogen levels by supplementing the wastewater with ammonium chloride. However, the varying influent concentrations did not have a large impact on performance of each system as the average effluent concentrations from all the systems were 2.4 mg/L in Phase 1, 2.5 mg/L in Phase 2, and 1.7 mg/L in Phase 3. An average of 72% of total removal occurred within the first column of each system during Phase 1, 78% during Phase 2, and 85% during Phase 3.

Table 9. Total Percent Removal of Total Nitrogen

Phase	System 1	System 2	System 3	System 4
Phase 1	93.4%	90.9%	94.9%	92.0%
Phase 2	94.0%	91.3%	96.9%	88.4%
Phase 3	93.6%	92.3%	97.2%	89.0%

In Systems 1, 2, and 3, Phase 1 had the poorest percent removal, however, in System 4, Phase 1 had the best percent removal. Overall, there was no clear trend of the influence of the phase on system performance. System 1 performed marginally better than Systems 2 and 4, but System 3 performed the best overall. However, it is unlikely that the high performance of System 3 can be attributed to the adsorption media but was rather just inevitable experimental noise because System 4, which also had adsorption media, performed the worst overall.

Total nitrogen decreased throughout each system as a result of microbial activity within the columns. In the aerobic conditions of Columns 1 and 3, total nitrogen decreased due to nitrification. Some denitrification also occurred in the first column as a result of pockets of anoxic environments within the aerobic columns. Total nitrogen decreased in the second column

of each system as a result of the anoxic conditions that were caused by the saturated cell. Residual total nitrogen in the final effluent of each system is expected to be nitrate and organic nitrogen.

Nitrogen, Nitrate

Influent concentrations varied widely throughout the study resulting in varying effluent concentrations. Average influent concentrations were 3.09 mg/L N in Phase 1, 7.84 mg/L N in Phase 2, and 2.43 mg/L N in Phase 3. Overall, the second column in each system behaved as expected as the concentrations of nitrate in the second column effluent of each system had been reduced by an average of 92%, 93%, and 87% in Phases 1, 2, and 3, respectively. However, nitrogen increased in the third column in Systems 1, 2, and 4, resulting in low total percent removals, shown in Table 10. System 4 particularly had minimal average removal in Phase 3 due to several instances where the final effluent concentration was greater than the influent concentration. However, these effluent concentrations did not exceed 2.75 mg/L N.

Table 10. Total Percent Removal of Nitrate

Phase	System 1	System 2	System 3	System 4
Phase 1	61.7%	20.6%	59.6%	76.7%
Phase 2	63.7%	34.3%	89.2%	28.6%
Phase 3	59.4%	24.0%	86.6%	7.1%

Final effluent concentrations were consistent for each system across the three phases. Increases in nitrate concentration in the final effluent were more influenced by higher influent concentrations than by phase. Although System 4 exhibited the best performance in Phase 1, it was the worst in Phases 2 and 3. However, System 3 performed the best in Phases 2 and 3, indicating that variation in system performance was not a result of adsorption media in the system.

Nitrate decreased as a result of denitrification, promoted by anoxic conditions. Reductions in nitrate from the first column of each system indicate that anoxic conditions were present. This is unexpected due to the downward direction of wastewater flow, which allows oxygen to be present within the column, but it is possible due to the heterogeneity of gravel and the growth of biofilm within the columns. The saturated environment in the second column allowed for nearly complete removal of nitrate by denitrification. Nitrate increased through the third column due to nitrification of any residual ammonia in the wastewater.

Nitrogen, Ammonia

Ammonia was removed completely and immediately by the first column of every system to a concentration below the detection limit of 1 mg/L N. This was true regardless of the influent concentration which averaged 14.6 mg/L N in Phase 1, 12.7 mg/L N in Phase 2, and 11.5 mg/L N in Phase 3, and spiked as high as 29 mg/L N. In Systems 1, 2, and 4, the effluent of Column 2 had detectable levels of ammonia in Phases 2 and 3, however, this was always completely removed in Column 3. All final effluent samples collected during the study were below the

detection limit. Consequently, this resulted in an average of 100% removal in each system and phase, as shown by Table 11.

Table 11. Total Percent Removal of Ammonia

Phase	System 1	System 2	System 3	System 4
Phase 1	100%	100%	100%	100%
Phase 2	100%	100%	100%	100%
Phase 3	100%	100%	100%	100%

There was no apparent impact of the phase on the final concentrations of ammonia in each system. Regardless of wastewater application frequency or temperature, the final effluent concentrations of ammonia were below 1 mg/L N. This did not appear to be impacted by the presence of adsorption media. Detectable levels of ammonia in the effluent of Column 2 were not a result of the adsorption media as System 1 (just gravel) exhibited these levels while System 3 (gravel, clinoptilolite, tire chips, and oyster shells) did not.

Ammonia was removed in the first and third column of each system by nitrification, which was a result of the aerobic conditions present in the columns. The increase in ammonia through the second column of Systems 1, 2, and 4 was hypothesized to be a result of moderate nitrogen fixation by free-living bacteria within the columns. However, it was unclear why System 3 did not also display this behavior. Regardless, this was not of concern as the final effluent concentrations from each system were consistently below detection limits.

pH

The total percent increase in pH from each system is shown in Table 12 and is separated by phase. The average influent pH for Phases 1, 2, and 3 was 4.62, 5.12, and 5.30, respectively. The pH of the wastewater increased throughout each system with the majority of the increase occurring in the first column (an average increase of 53%, 38%, and 32% during Phases 1, 2, and 3, respectively). Although this represents an overall decrease, there was an increase in the pH of the influent water. Together, these resulted in similar effluent values. The average effluent for each phase was 8.04, 8.09, and 8.17.

Table 12. Total Percent Increase in pH

Phase	System 1	System 2	System 3	System 4
Phase 1	75%	73%	77%	71%
Phase 2	58%	58%	59%	57%
Phase 3	54%	54%	55%	53%

Overall, System 3 had the highest percent increase in pH while System 4 had the lowest. Both systems contained gravel, clinoptilolite, tire chips, and oyster shells, so it is unlikely that variations in pH change were a result of the adsorption media or pH buffer.

Typically, nitrification results in a decrease in pH levels in wastewater. In this study, however, the pH levels increased with both nitrification and denitrification of the wastewater, which is hypothesized to have occurred because the gravel in the columns acts as a pH buffer, helping to stabilize the wastewater at a neutral pH. Although the exact composition of the gravel

in this study is unknown, limestone and other calcium carbonate rocks are commonly used as pH buffers and are often found in commercial gravel.

Alkalinity

The alkalinity concentrations significantly increased from an average influent of 1294 mg/L CaCO₃ to average effluents of 1979 mg/L CaCO₃ and 2000 mg/L CaCO₃ in the first columns of Systems 1 and 4, respectively. Alkalinity did not significantly change through the second column, with effluents averaging 1892 mg/L CaCO₃ for System 1 and 2002 mg/L CaCO₃ for System 4. Due to anoxic zones in the first columns of both systems, denitrification was occurring and leaving very little to transform in Column 2. Alkalinity decreased in Column 3 to 1752 mg/L CaCO₃ in System 1 and 1860 mg/L CaCO₃ in System 4, as a result of nitrification occurring in aerobic conditions. There was not a significant difference between the changes in alkalinity in the columns with and without media.

Alkalinity is an indicator of microbial activity and wastewater stability. Generally, alkalinity is destroyed during nitrification and recovered during denitrification.²⁴ However, in this study, alkalinity increased with the nitrification in the first column. Although the exact mechanism of this is unknown, Moreira, Boaventura, Brillas, and Vilar²⁵ found similar trends while treating winery wastewater. The increase in alkalinity through the wetlands demonstrates an increase in wastewater stability, which is important when considering on-site wastewater treatment.

Data on the Start Up study are presented in Figures 28 – 39.

²⁴ Michigan Department of Environmental Quality (MDEQ). Nitrification and Denitrification [PowerPoint slides]. Retrieved from https://www.michigan.gov/.../deq/wrd-ot-nitrification-denitrification_445274_7.ppt

²⁵ Moreira, F. C., Boaventura, R. A., Brillas, E., & Vilar, V. J. (2015). Remediation of a winery wastewater combining aerobic biological oxidation and electrochemical advanced oxidation processes. *Water Research*, 75, 95-108. doi:10.1016/j.watres.2015.02.029

Start Up Study

Total Phosphorus

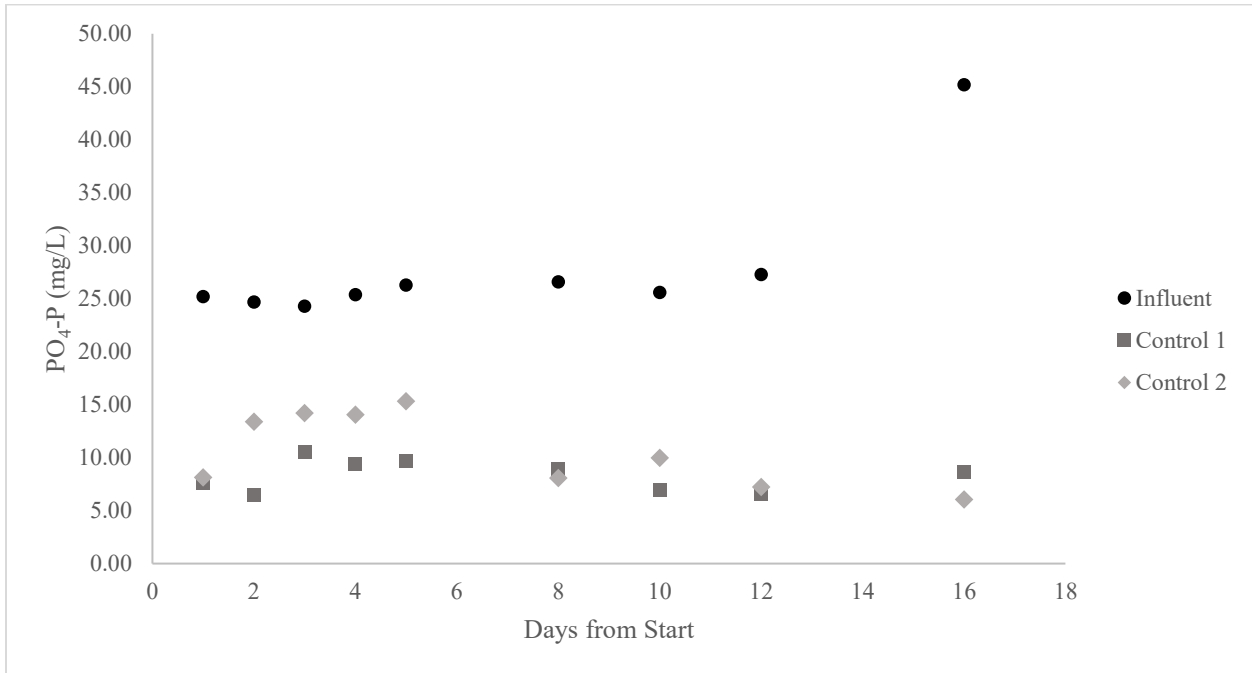


Figure 28. Control Columns, Total Phosphorus

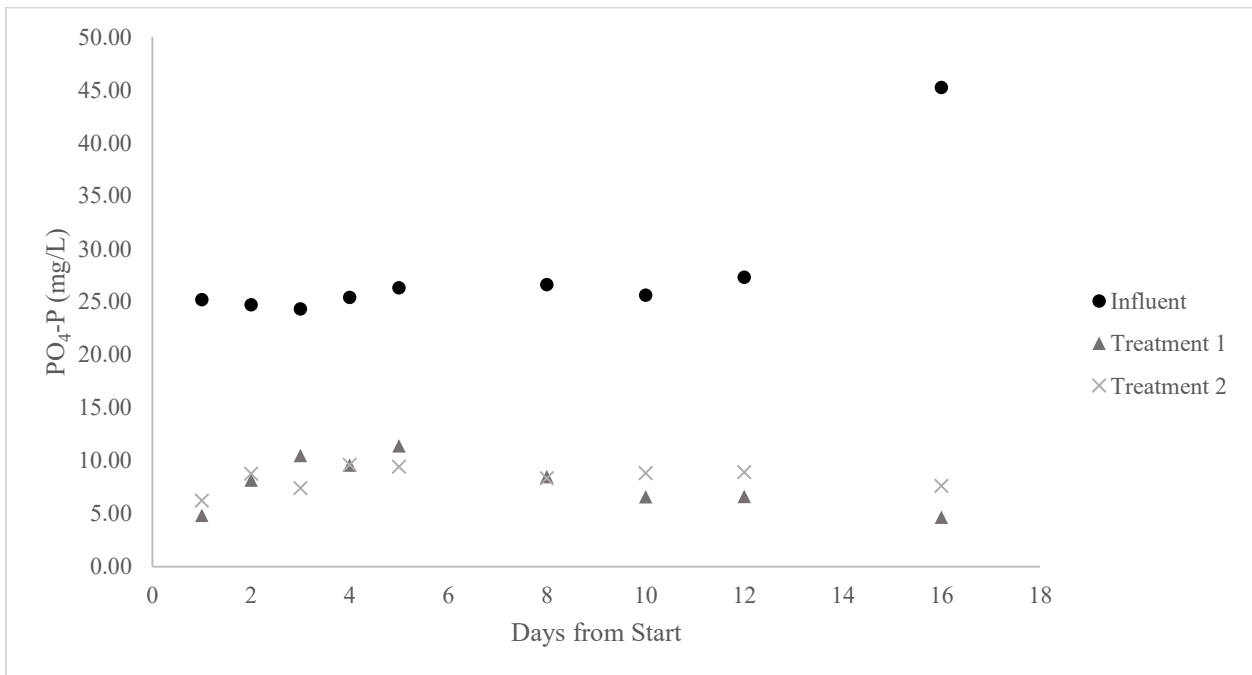


Figure 29. Treatment Columns, Total Phosphorus

Chemical Oxygen Demand

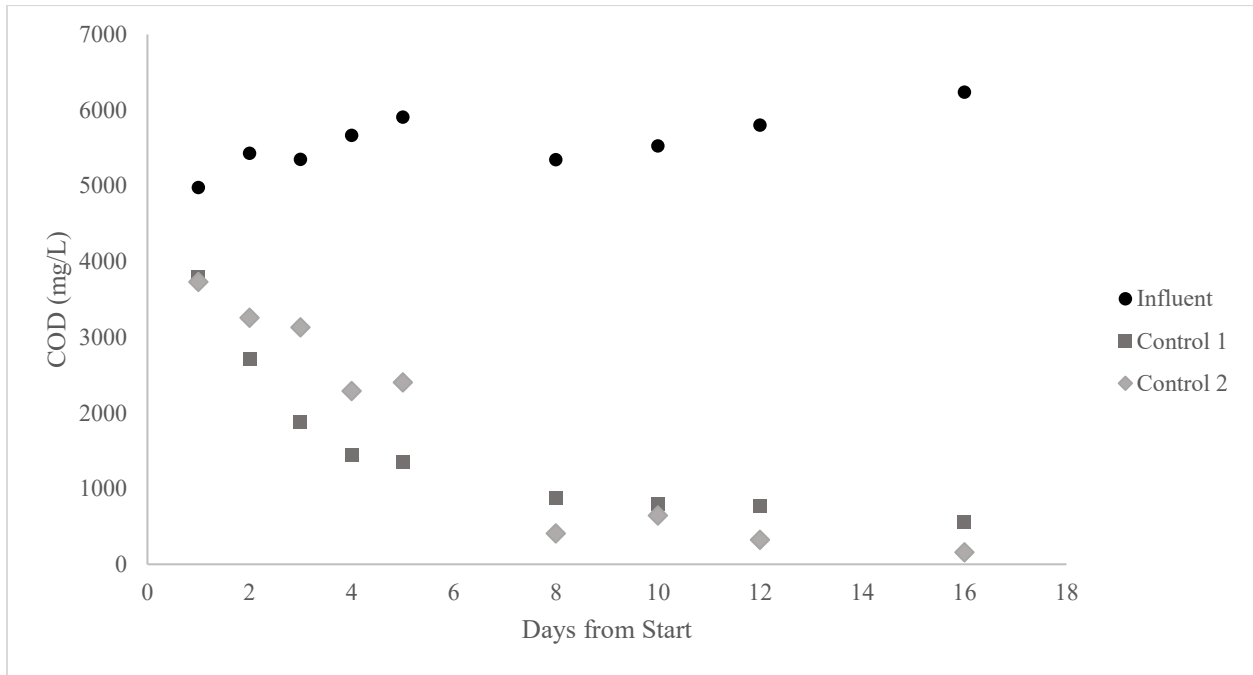


Figure 30. Control Columns, COD

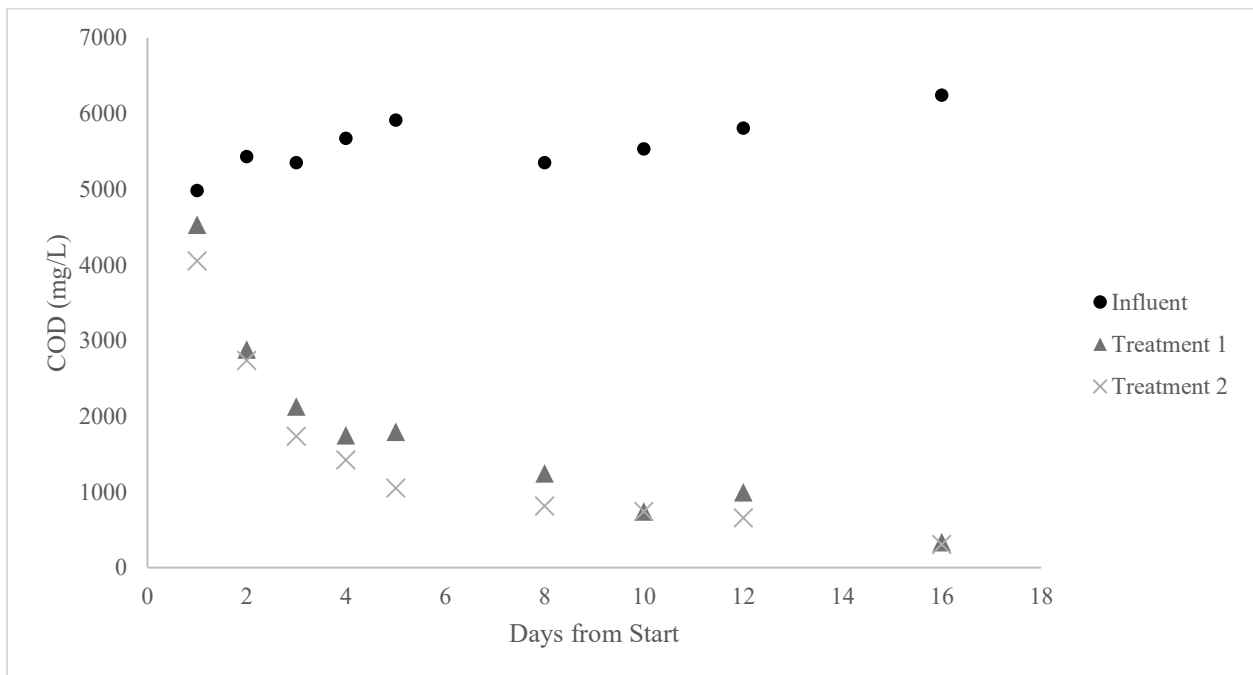


Figure 31. Treatment Columns, COD

Nitrogen, Total

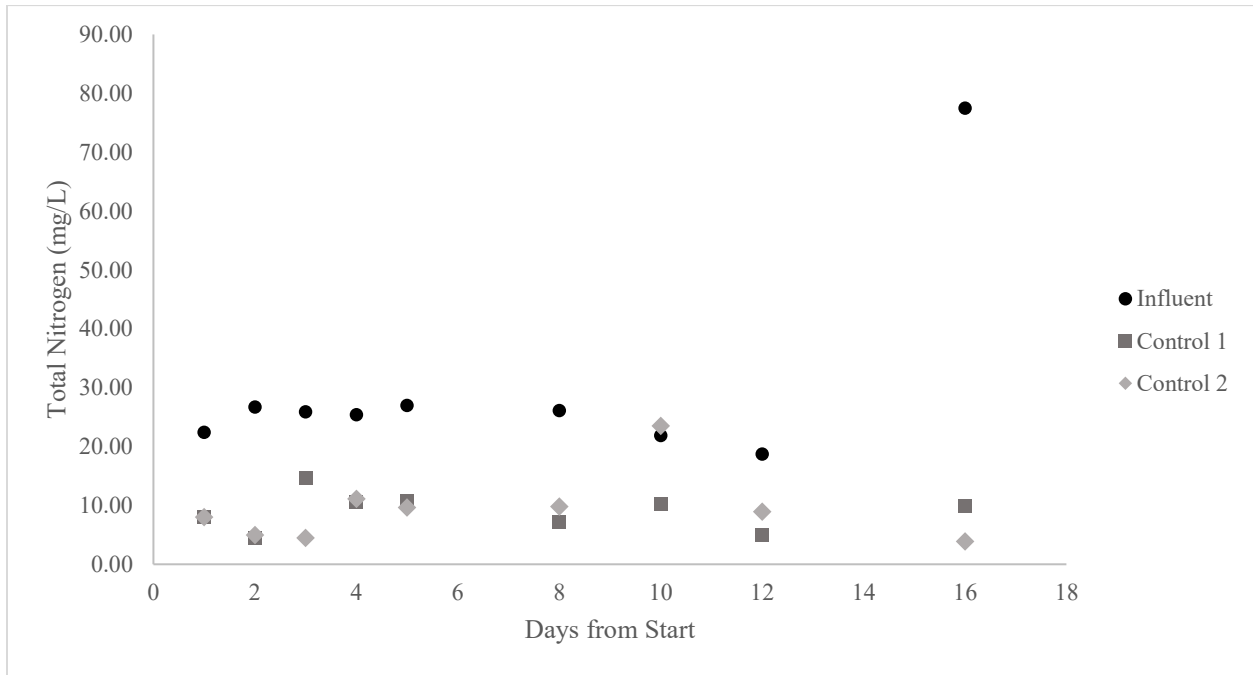


Figure 32. Control Columns, Total Nitrogen

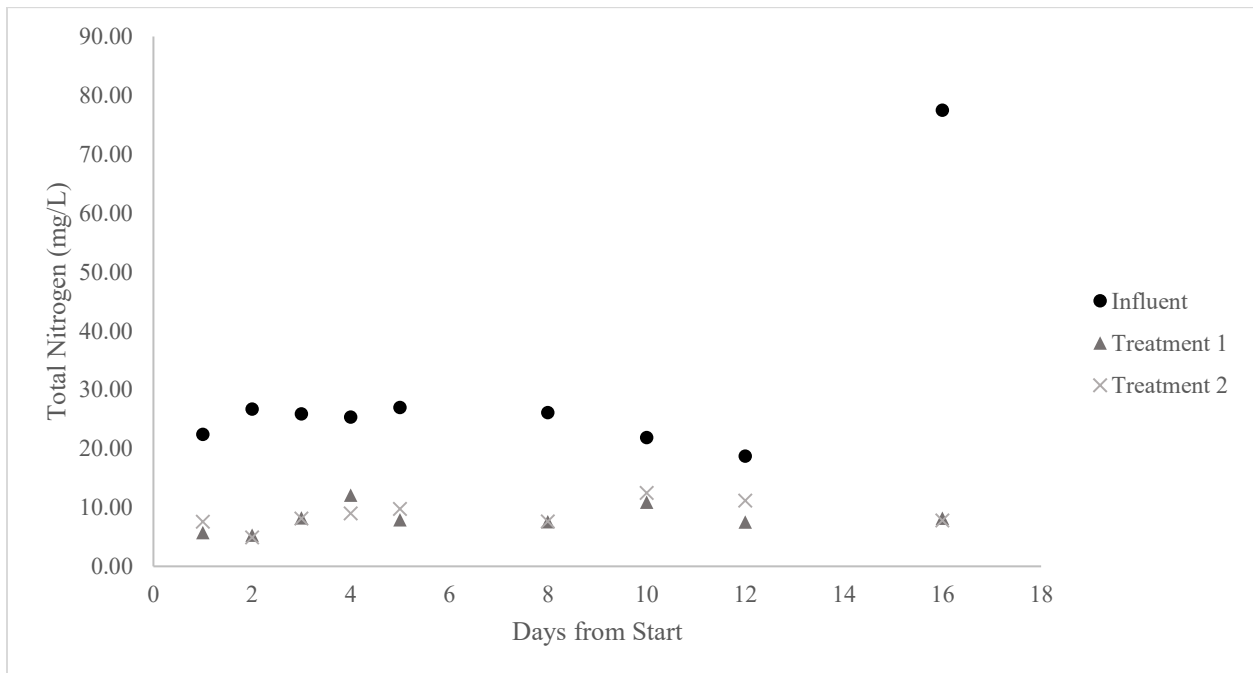


Figure 33. Treatment Columns, Total Nitrogen

Nitrogen, Nitrate

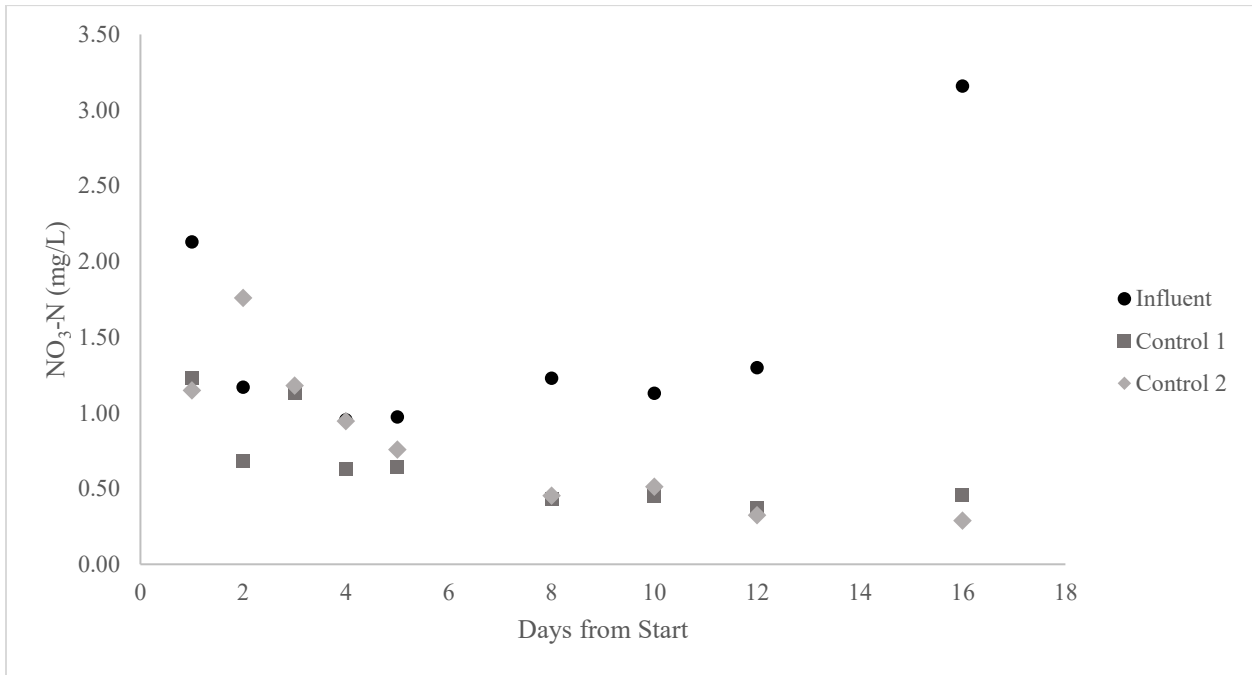


Figure 34. Control Columns, Nitrate as Nitrogen

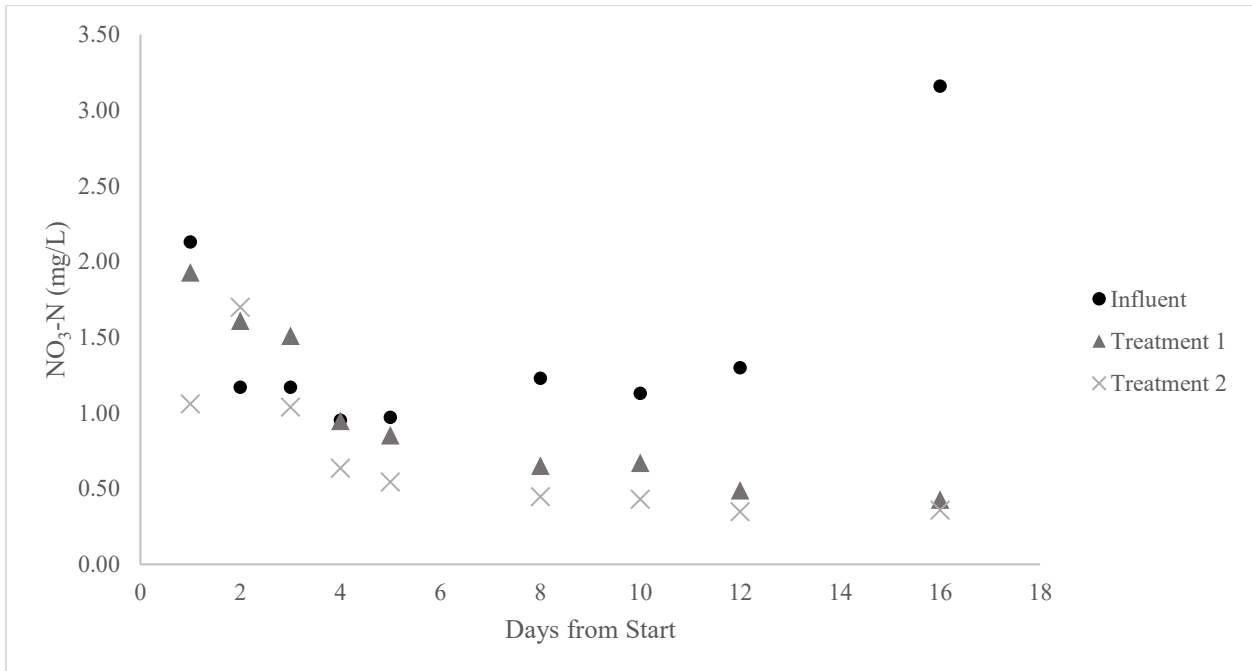


Figure 35. Treatment Columns, Nitrate as Nitrogen

Nitrogen, Ammonia

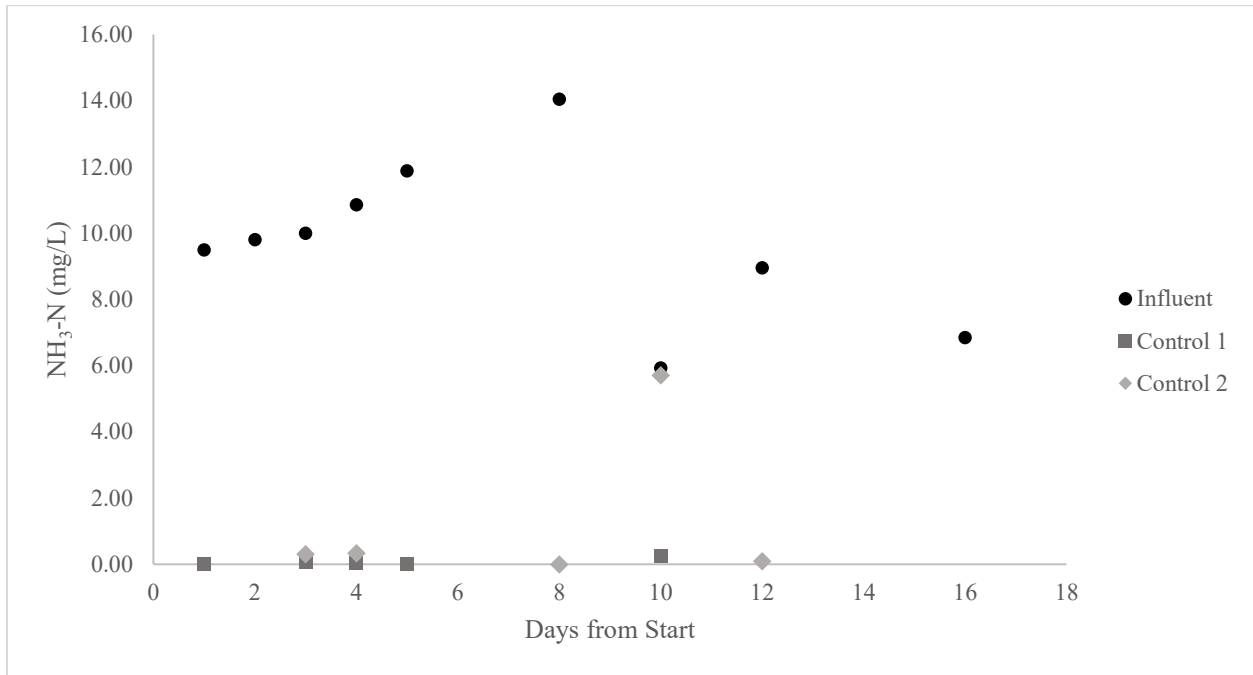


Figure 36. Control Columns, Ammonia as Nitrogen

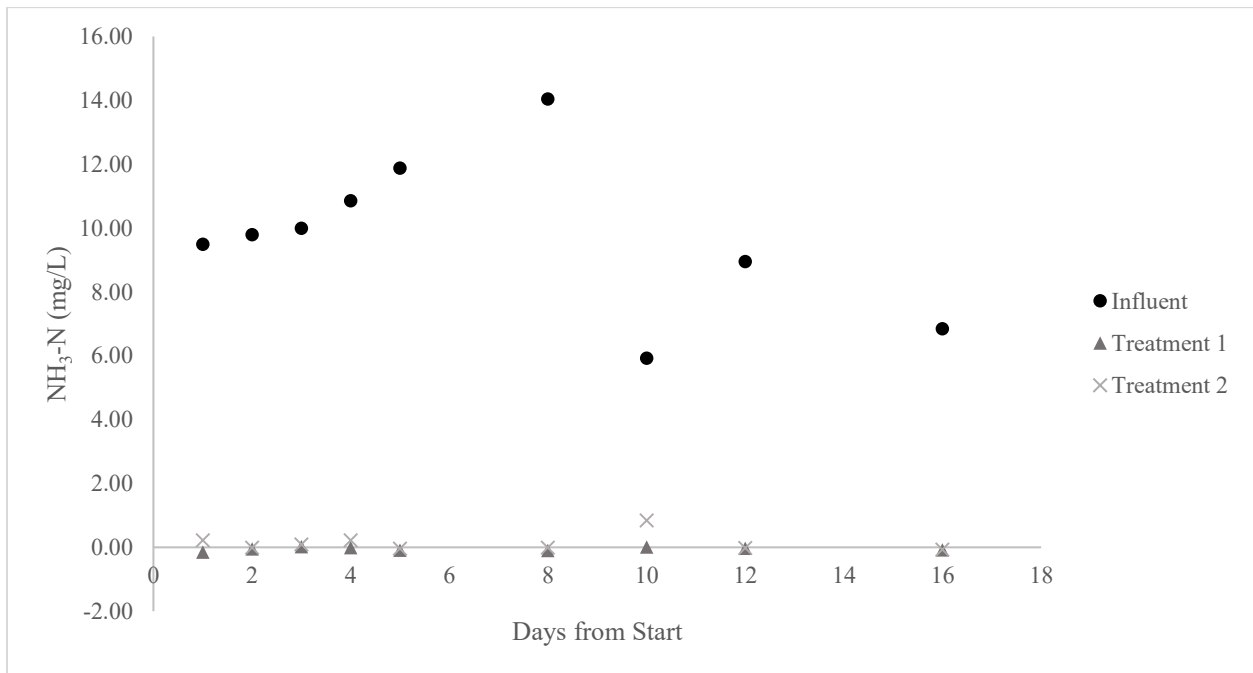


Figure 37. Treatment Columns, Ammonia as Nitrogen

pH

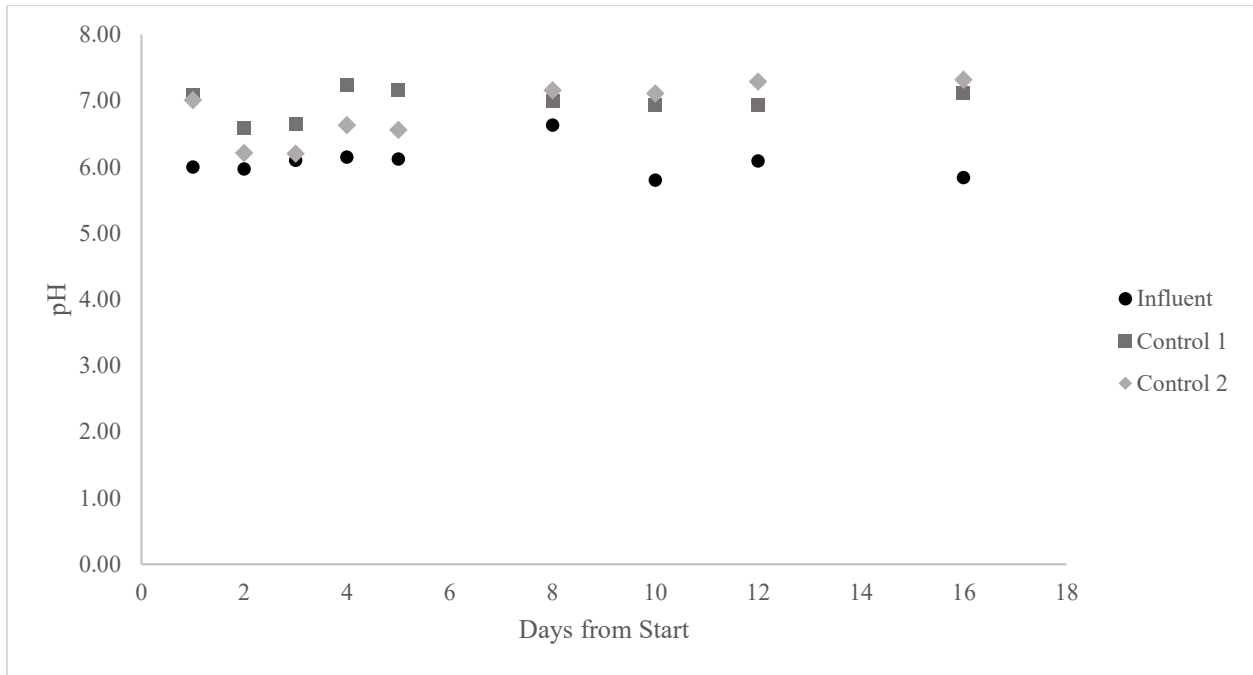


Figure 38. Control Columns, pH

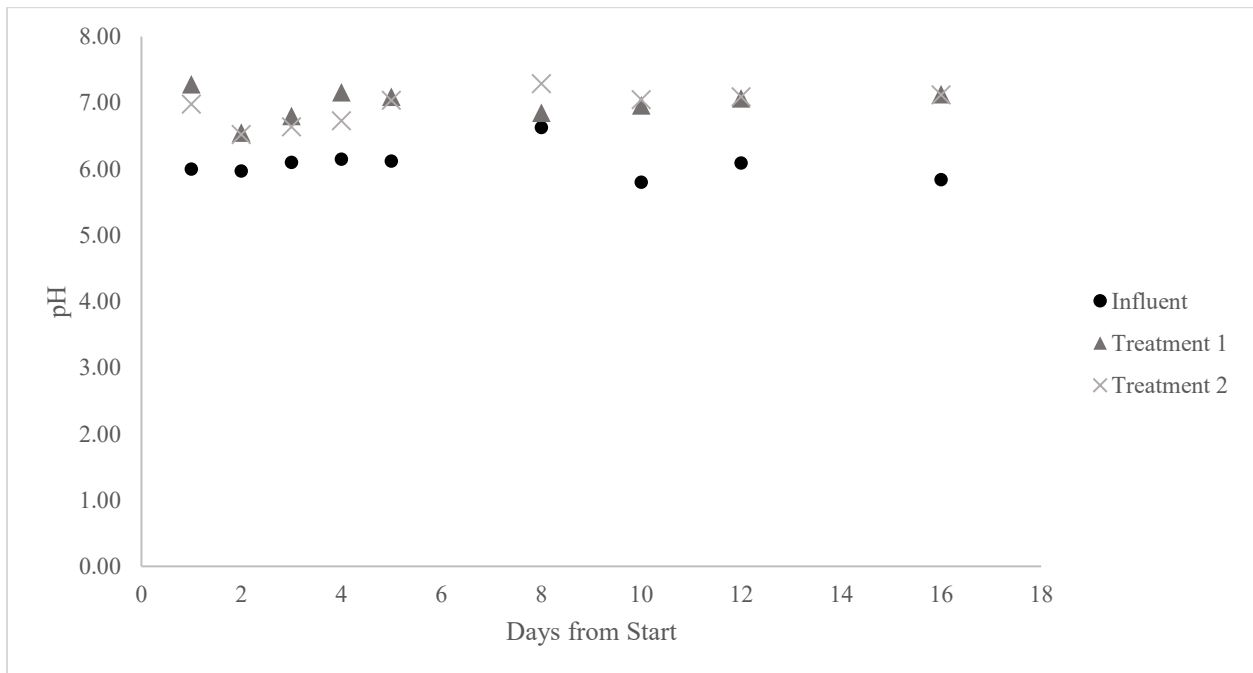


Figure 39. Treatment Columns, pH

Total Phosphorus

Both the control and treatment columns exhibited relatively constant effluent flows. The average effluent out of the control columns was 9.53 mg/L P and the average effluent from the treatment columns was 8.10 mg/L P. The average influent concentration of the wastewater was 27.8 mg/L P, which was most similar to Phase 3 of the Column Study, having an average influent concentration of 26.7 mg/L P. During Phase 3 of the Column Study, effluent concentrations from the first column of System 1 (equivalent to the control columns) and System 2 (equivalent to the treatment columns) had reached equilibrium. Effluent concentrations from System 1 and 2 averaged 8.05 mg/L P and 8.15 mg/L P, respectively. These values from the Column Study are comparable to the effluent values observed in the control and treatment columns in the Start Up Study. This immediate removal of phosphorus to equilibrium concentrations supports the concept that adsorption to gravel is the main mechanism of phosphorus removal in a VFCW.

COD

In both the control and treatment columns there was a consistent increase in percent removal over time. By the tenth day of operation, all of the columns had reached greater than 85% removal. Although effluent concentrations continued to decrease through the sixteenth day of operation, it was at a diminishing rate of reduction. These results align with those in the Column Study where the first column of each system reached equilibrium by the tenth day of operation. This indicates that inoculating the columns with secondary effluent wastewater did not impact the removal of COD in the first two weeks of operation.

Nitrogen, Total

Effluent total nitrogen concentrations from the control columns fluctuated over the course of the Start Up Study. However, it was within a range of 10 ± 5 mg/L N and averaged 9.2 mg/L N. The treatment columns did not have as much fluctuation in effluent concentrations but there was still some variation. The average effluent of the treatment columns was 8.5 mg/L N.

These results were consistent with effluent concentrations of System 1 and 2 in the Column Study, which had average effluent concentrations of 9.8 mg/L N and 8.9 mg/L N, respectively. Influent concentrations were also similar with the Column Study averaging 33.8 mg/L N and the Start Up Study averaging 30.2 mg/L N in the influent. These results show that inoculating the columns prior to operation did not have a strong impact on total nitrogen removal but that columns with clinoptilolite removed marginally more total nitrogen within the first two weeks of operation.

Nitrogen, Nitrate

Both the control and treatment columns showed immediate removal of nitrate with removal increasing as time went on. Although the increase in removal was slight, it supports the hypothesis that the growth of biofilm within the columns creates pockets of anoxic environments. The immediate removal of nitrogen, observed in both the Column Study and the

Start Up Study, supports the hypothesis that anoxic zones are present in the columns as a result of the heterogeneity of the gravel.

Nitrogen, Ammonia

In all of the columns, ammonia was immediately and completely removed to concentrations below the detection limit of 1 mg/L N. The cause of the outlier in Control 2 on Day 10 is not clear, however, it is not an operational concern as any residual ammonia is completely removed by the polishing column, as shown by the Column Study. The immediate and complete removal in both the control and treatment columns shows that inoculating the columns prior to operation is not necessary for removal of ammonia.

pH

An immediate increase in pH was observed in all of the columns. The increase in pH was consistent over time. There did not appear to be an impact of clinoptilolite on pH change as the average pH of the control columns was 6.90 and that the treatment column was 6.96. This supports the hypothesis that the gravel is responsible for acting as a pH buffer and adjusting the wastewater pH to neutral.

PO4Sponge Study

Data for the PO4Sponge study is presented in Figures 40 and 41.

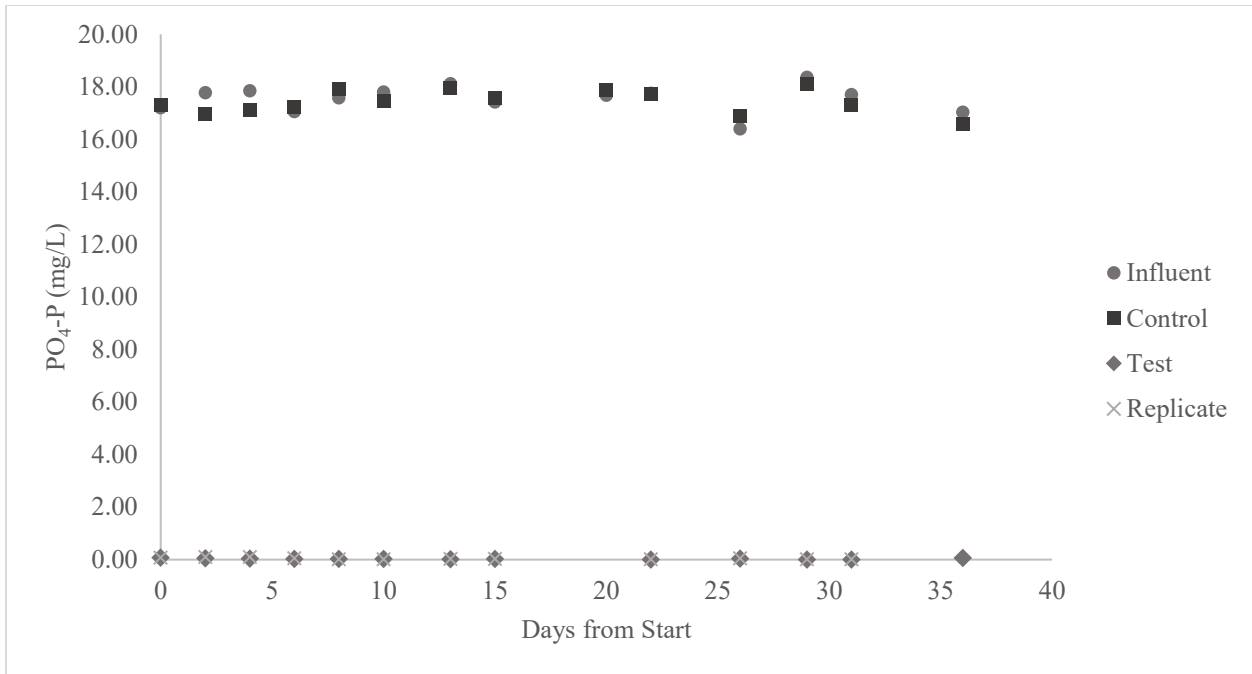


Figure 40. Influent and Effluent Concentrations from PO4Sponge Study

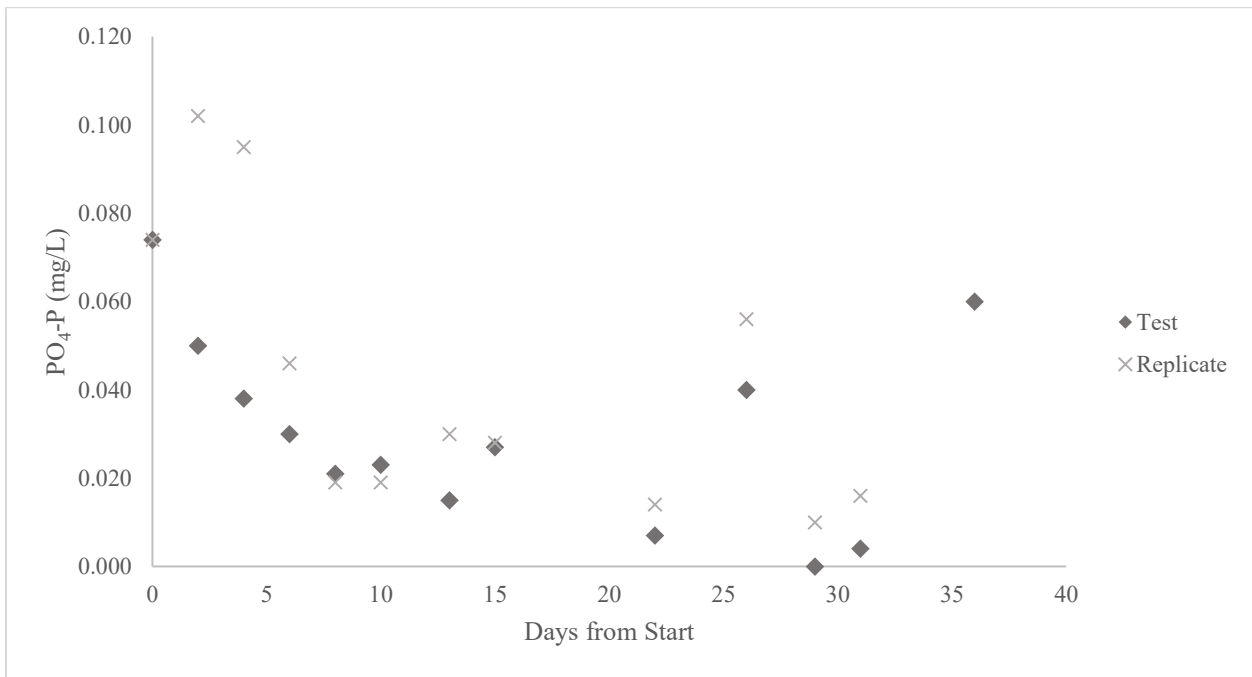


Figure 41. Effluent Concentrations from PO4Sponge Columns

Results of the PO4Sponge were consistent with previous studies in removing total phosphorus concentrations down to low levels. As was expected, the control column, which only had a 1-inch layer of gravel, removed only negligible amounts of phosphorus. The Test and Replicate columns of PO4Sponge performed better than expected and removed high levels of total phosphorus to less than 0.12 mg/L P total phosphorus. This is significantly lower than the expected value of 0.3 mg/L P. In 84% of the Test and Replicate samples, the effluent concentrations were less than or equal to 0.06 mg/L P. These results show that components in winery wastewater do not impact the performance of PO4Sponge and that loading the wastewater from the top does not reduce performance of the adsorption media. Consistent performance, regardless of the direction of wastewater flow, allows for flexibility in the full-scale design and implementation of a VFCW.

Wetland Modeling

A calibrated and validated model can help in the development of design criteria and operational strategies to maximize the treatment. This can save consider resources, when compared to experimentally testing all options. Modeling the VFCW was attempted using HYDRUS CW2D. HYDRUS CW2D is a finite element model for simulating two-dimensional water and solutes movement in soil. The HYDRUS CW2D model numerically solves the Richards' equation for water flow in unsaturated, partially saturated, and fully saturated soil. HYDRUS CW2D entails both aerobic and anoxic transformation and degradation processes for organic matter, nitrogen, and phosphorus. The following assumptions are made in HYDRUS CW2D.

- Organic matter is present only in the aqueous phase and all reactions occur only in the aqueous phase.
- Adsorption is assumed to be a kinetic process and considered for ammonium, nitrogen, and inorganic phosphorus.
- All microorganisms are assumed to be immobile.
- Lysis in HYDRUS CW2D represent all decay and loss processes of all microorganism involved and the rate of lysis does not represent the impact of environmental conditions.
- Heterotrophic bacteria of HYDRUS CW2D include all bacteria responsible for hydrolysis, mineralization of organic matter (aerobic growth), and denitrification (anoxic growth).

The limitation of HYDRUS CW2D include the following;

- Clogging can occur from particulate matters in the influent wastewater settling and excessive growth of bacteria (biofilm). The resulting pore size reduction is not considered in the model.
- Impact of environmental condition on pH are not considered in the model.
- Limited to a temperature range between 10 and 25 °C.

In order to use HYDRUS CW2D model, the model must be calibrated and validated using experimental data. Model calibration for water flow was conducted by inverse modeling using cumulative effluent volume. Inverse modeling in HYDRUS uses the initial estimate of the parameters to perform the simulation and compares the simulation results to the observed experimental data. The model is then re-run with modified set of parameter. The process is repeated until the modeled data closely match the observed experimental data.

Figure 42 shows the comparison of observed and fitted HYDRUS CW2D values for water flow. The performance of the calibrated and validated HYDRUS CW2D model were evaluated by efficiency (E), index of agreement (IA), and root mean squared error (RMSE). Values for calibration included a E of 0.67, IA of 0.93, and a RMSE of 22. For validation the E was 0.98, IA was 0.92, and RMSE was 25.

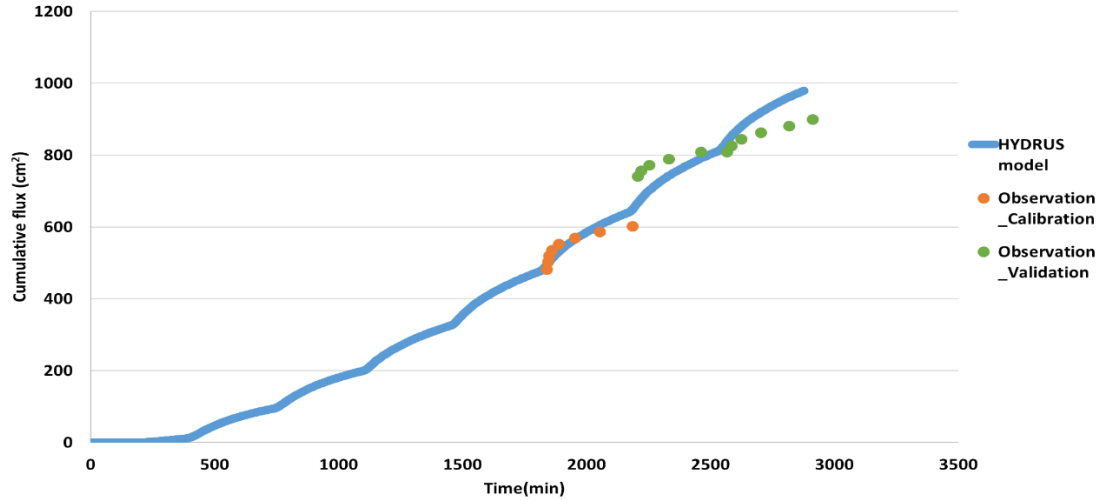


Figure 42. Model Calibration and Validation for Water Flow

Figure 43 shows the comparison of observed and fitted HYDRUS values for COD effluent concentrations. The model evaluation values for calibration included a E of 0.38, IA of 0.80, and a RMSE of 36. For validation the E was -0.01, IA was 0.68, and RMSE was 52.

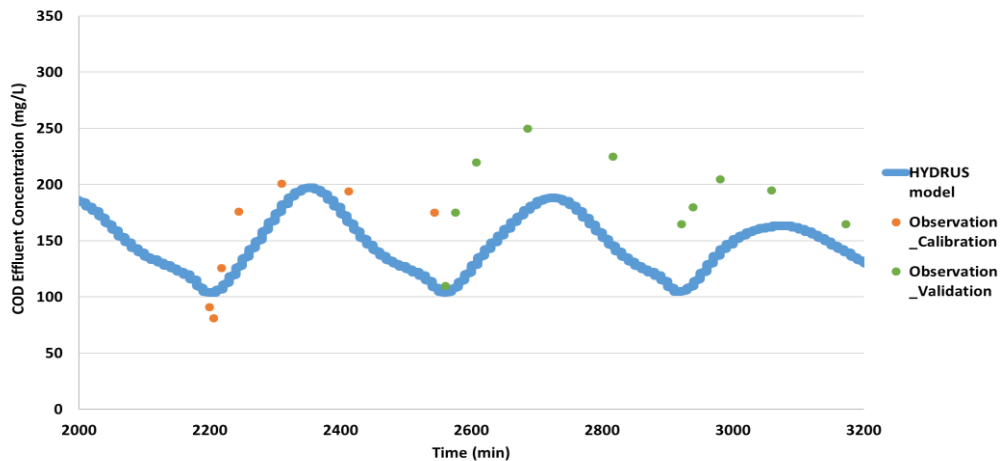


Figure 43. Model Calibration and Validation for Solute Flow

Overall, the HYDRUS CW2D modeling result showed similar trends to the experimental data, however, the performance of model calibration and validation could be improved with more frequent sampling. Also, nitrogen and phosphorus modeling should be attempted, which will entail substantially more data collection to calibrate and validate.

Conclusions

Overall performance of the VFCWs was satisfactory. Systems without nitrogen adsorption media performed as well as systems with the media. The VFCWs continued to treat the wastewater to low effluent concentrations even when subjected to varying loading concentrations and frequencies, and at reduced temperatures. Throughout the study, all final effluent concentrations were sufficiently below EGLE groundwater discharge limits. Effluent concentrations were considerably better than the quality of septic effluent, allowing for versatility in the final discharge of the treated wastewater.

Additionally, it was found that VFCWs began to remove nitrogen immediately upon operation, even without first being inoculated or including adsorption media. Over 85% of COD was removed in the first column within 10 days of beginning wastewater flow through a VFCW that had not previously been operated or inoculated. Further, the inclusion of the phosphorus adsorption media, PO4Sponge, was found to be an effective means of removing total phosphorus from winery wastewater to low effluent concentrations, regardless of the direction of wastewater flow.

These findings indicate that a VFCW is a robust onsite wastewater treatment system that can treat high strength wastewater down to groundwater discharge limits using a small surface area. This treatment system continues to perform satisfactorily under varying conditions and does not require enhancements with nitrogen adsorption media for high performance. The same NRCS standard used for milking facility wastewater can be used for winery wastewater so long as the wetland is sized with the organic loading rate of $1.06E-2$ lb COD/ft²/day. Assuming a conservative COD concentration of 6,000 mg/L, 7 gallons of wastewater produced per 1 gallon of wine, and 750 mL of wine in a bottle, this results in a VFCW with a surface area requirement of 6.5 ft² per bottle of wine produced per day.

Modeling using HYDRUS showed potential and justifies more development. This will require specialized reactor operation and additional analytical measurements.

Not all factors can be accounted for in a laboratory study and a smaller surface area may be feasible. A field demonstration at a Michigan winery is needed prior to wide-scale adoption of this technology.

Appendix A: Column Study Data

Total Phosphorus

Table A1. Systems 1 and 2, Total Phosphorus

Days from start	Influent	System 1			System 2		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	14.8	1.79					
2	16.0	6.48					
4	33.9				3.02		
6	15.4	2.23			2.82		
8	18.4				2.30		
11	14.0	1.60			2.42		
13	14.3	2.20			3.14		
16		3.25			4.49		
19	15.2	2.26					
22	15.1	1.13			1.43		
26	15.3	1.64			0.88		
29	16.5	1.21			1.39	0.212	
34	20.6				2.19	0.216	0.034
37	17.4	0.974			1.98	0.237	0.025
64	20.6		0.110	0.010		0.150	0.606
68	19.4	4.95	0.094	-0.009		0.149	0.181
77	17.9	6.72	0.056	-0.008	3.45	0.121	0.288
82	16.5	3.90	0.040	0.032		0.010	0.234
89	23.4	2.60	0.103	0.045	2.80	0.159	0.082
92	22.0	4.29	0.149		4.59	0.131	0.108
96	22.1	4.05	0.158	0.106	7.14	0.186	0.159
97	Beginning of Phase 2						
99	21.4	5.88	0.162	0.068	5.28	0.159	0.132
103	19.3	5.04	0.194	0.094	4.68	0.111	0.159
105	21.1	5.19	0.075	0.023	4.56	0.001	0.026
110	22.6	5.58	0.183	0.058	4.56	0.135	0.092
112	20.0	5.25	0.258	0.028	8.13	0.116	0.080
116	26.9	5.34	0.236	0.077	6.08	0.017	0.026
120	24.0	6.57	0.816	1.32	6.75	0.215	0.106
124	19.8	3.81	0.092	0.136	5.07	0.165	0.270
131	23.0	5.25	0.063	0.055	6.30	0.248	0.390
133	22.2	5.22	0.102	0.199	7.41	0.187	0.196
141	24.2	5.16	0.095	0.075	7.88	0.138	0.075
148	21.4	6.00	0.115	0.123	5.73	0.117	0.341
152	Beginning of Phase 3						
152	44.0	6.78	0.110	0.067	7.11	0.140	0.091
155	20.8	8.04	0.110	0.075	6.06	0.070	0.060
159	27.0	5.79	0.269	0.025	6.33	0.214	0.069
161	24.1	8.82	0.265	0.127	8.28	0.385	0.096
166	24.5	6.36	0.258	0.006	6.78	0.731	0.109
170	26.7	7.05	0.379	0.098	9.87	0.161	0.033
173	26.5	9.99	0.502	0.120	9.51	0.300	0.166
176	28.8	10.3	0.375	0.143	10.4	0.403	0.065
181	27.0	7.89	0.670	0.075	8.61	0.482	0.049
184	17.4	9.42	0.636	0.092	8.52	0.241	0.032

Table A2. Systems 3 and 4, Total Phosphorus

Days from start	Influent	System 3			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	14.8						
2	16.0						
4	33.9	1.78			5.80		
6	15.4	1.80			1.92		
8	18.4	2.20			2.23		
11	14.0				2.09		
13	14.3	3.02			2.46		
16		3.12			2.92		
19	15.2	6.48			5.67	0.175	
22	15.1	1.87			3.06	0.495	0.245
26	15.3	1.48			3.38	0.541	0.144
29	16.5	2.19			3.53	0.567	0.193
34	20.6	1.67			2.91	0.457	0.206
37	17.4	2.94			4.68	0.585	0.222
64	20.6	2.55				0.323	0.183
68	19.4	2.22			3.63	0.187	0.328
77	17.9	2.96	0.111	0.090	3.39	0.204	0.092
82	16.5	3.54	0.173	0.049	3.36	0.164	0.102
89	23.4	3.18	0.181	0.067	5.67	0.197	0.087
92	22.0	5.52	0.173	0.076	8.1	0.286	0.112
96	22.1				6.09	0.261	0.504
97	Beginning of Phase 2						
99	21.4			0.472	6.12	0.230	0.168
103	19.3	2.49	0.111	0.055	5.04	0.150	0.222
105	21.1	3.99	0.086		6.03	0.136	0.006
110	22.6	5.28	0.115	0.071	8.40	0.148	0.858
112	20.0	3.51	0.052	0.074	6.21	0.044	0.230
116	26.9	6.18	0.046	0.026		0.223	0.350
120	24.0	5.73	4.45	0.849	8.40	0.260	2.79
124	19.8	4.08	0.174	0.230	4.62	0.277	0.950
131	23.0	6.93	0.531	0.306	5.64	0.265	0.175
133	22.2	5.64	0.223	0.163	7.86	0.210	0.288
141	24.2	6.96	0.146	0.114	5.19	0.146	0.134
148	21.4	6.93	0.205	0.074	4.83	0.113	0.061
152	Beginning of Phase 3						
152	44.0	6.06	0.280	0.086	5.13	0.284	0.090
155	20.8	9.90	0.294	0.046	6.06	0.338	0.135
159	27.0	5.85	0.373	0.235	7.20	0.591	0.266
161	24.1	6.99	0.367	0.126	8.07	0.658	0.335
166	24.5	10.6	0.807	0.109	6.30	0.631	0.022
170	26.7	7.17	0.830	0.086	10.4	0.899	0.23
173	26.5	7.71	0.713	0.163	10.4	0.919	0.406
176	28.8	7.71	1.21	0.236	11.2	1.01	0.224
181	27.0	8.98	0.937	0.234	9.75	1.36	0.076
184	17.4	8.98	1.49	0.436	7.26	1.28	0.369

Chemical Oxygen Demand

Table A3. Systems 1 and 2, COD

Days from start	Influent	System 1			System 2		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	5954	2208					
2	6724	3964					
4	6402				1582		
6	7780	2028			2012		
8	7140				1788		
11	6240	101			506		
13	7930	446			768		
16		279			1085		
22	6190	122			230		
26	6010	144			294		
29	7060	66			228	329	
37	5030	60			80	353	58
64	6650		36	18		39	21
68	5420	57	33	19		31	27
71	4900	476	51	12	96	32	12
77	4350	196	24	4	434	29	16
89	7980	144	83	39	150	179	36
92	3790	94	52		124	180	17
96	5850	134	86	40	850	270	26
97	Beginning of Phase 2						
103	2780	61	144	37	35	61	29
110	4340	179	96	22	71	36	26
116	3570	102	69	24	171	19	16
120	4120	258	56	25	113	25	30
124	6890	59	51	23	197	25	18
131	6120	419	35	26	538	29	19
133	5650	285	30	33	640	153	19
141	6280	136	38	20	246	23	15
148	5220	170	31	22	116	21	21
152	Beginning of Phase 3						
152	8110	138	52	18	134	28	14
159	6030	196	54	22	135	22	15
161	5560	210	38	16	92	22	13
163	4190	222	51	22	143	34	21
166	5400	99	56	17	150	40	17
170	5990	266	37	22	432	18	16
173	5630	504	34	15	383	25	37
176	5980	455	37	22	505	33	15
181	5930	345	75	21	351	26	16
184	5690	346	87	22	214	20	14

Table A4. Systems 3 and 4, COD

Days from start	Influent	System 3			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0		Beginning of Phase 1					
1	5954						
2	6724						
4	6402	260			2144		
6	7780	233			1250		
8	7140	197			1339		
11	6240				198		
13	7930	140			373		
16		521			495		
22	6190	109			147	814	390
26	6010	76			358	960	428
29	7060	123			220	963	454
37	5030	35			50	717	235
64	6650	61				51	32
68	5420	10			28	42	50
71	4900	282			94	76	18
77	4350	41	15	28	88	46	28
89	7980	160	49	46	232	98	60
92	3790	148	25	14	420	66	18
96	5850				405	70	40
97		Beginning of Phase 2					
103	2780		33	31	94	61	122
110	4340	287	23	27	963	38	60
116	3570	48	28	18		57	76
120	4120	78	17	29	544	51	93
124	6890	35	24	19	127	57	47
131	6120	147	15	16	315	70	45
133	5650	110	23	20	655	40	23
141	6280	322	17	22	130	30	19
148	5220	406	32	20	52	30	16
152		Beginning of Phase 3					
152	8110	125	124	20	85	38	22
159	6030	214	24	24	230	34	25
161	5560	39	16	16	371	31	22
163	4190	271	22	19	357	37	41
166	5400	276	19	13	260	42	20
170	5990	199	19	20	755	42	22
173	5630	494	14	22	440	66	22
176	5980	71	18	18	643	88	22
181	5930	375	15	12	526	110	11
184	5690	179	19	22	131	121	9

Nitrogen, Total

Table A5. Systems 1 and 2, Total Nitrogen

Days from start	Influent	System 1			System 2		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	25.93	10.16					
2	56.544	14.04					
4	30.62				10.40		
6	29.64	12.90			11.50		
8	24.9				8.99		
11	37.11	8.44			8.62		
13		15.50			11.90		
16		6.30			10.36		
19	36.4	8.62					
22	34.3	12.14			9.44		
26	30.25	7.90			4.86		
29	33.1	4.62			4.46	1.41	
34	31.15				3.54	1.61	2.46
37	37.7	23.60			6.88	2.01	1.96
64	42		1.18	3.12		2.22	2.61
68	33.15	7.84	0.83	2.67		2.04	2.31
75	18.9	8.16	1.80	1.11	4.96	2.87	3.19
82	32.1	6.38	2.42	1.53		2.70	3.75
89	44.2	3.48	2.29	2.76	3.46	2.94	3.67
96	30.9	6.12	1.54	2.31	12.06	2.93	2.97
97	Beginning of Phase 2						
99	37.2	6.38	1.79	1.61	3.88	3.10	2.26
103	32.6	8.42	1.64	1.17	2.86	3.19	2.19
105	44.35	4.00	1.73	0.964	5.76	2.60	1.97
110	31	3.18	1.94	1.16	3.02	2.21	2.03
112	30.45	5.08	2.06	1.15	7.44	2.54	3.01
116	58.5	4.03	2.60	1.69	3.87	2.54	3.15
120	32.95	20.40	2.93	1.83	8.26	2.73	3.23
124	23.05	2.24	2.48	2.51	4.70	2.38	3.13
126	39.05	5.56	2.56	2.31	4.70	2.22	6.45
131	51.5	6.38	2.57	2.30	9.52	2.47	2.76
133	47.5	5.32	2.73	2.89	11.2	3.07	2.74
141	32.75	10.52	2.67	2.88	8.52	2.69	2.61
148	22.35	10.56	2.29	3.09	8.70	2.60	3.34
152	Beginning of Phase 3						
152	12.15	2.74	2.46	2.21	3.82	3.01	2.59
155	21.85	5.12	2.73	1.34	3.12	3.15	2.34
159	34.25	3.62	2.23	1.79	2.62	2.70	2.77
161	21.65	3.50	1.88	1.76	1.77	2.52	2.50
163	25.95	2.74	2.41	1.69	2.68	2.97	2.53
166	33.9	2.14	1.96	1.48	2.14	2.28	1.91
170	32.45	2.48	1.89	1.35	2.90	1.94	1.11
173	28.85	3.94	2.00	1.48	4.84	2.18	1.14
176	35.5	4.28	2.02	1.24	4.28	2.20	0.959
181	27.45	5.74	1.75	1.64	7.18	1.78	1.09
184	31.15	2.66	1.74	1.07	2.26	1.71	1.19

Table A6. Systems 3 and 4, Total Nitrogen

Days from start	Influent	System 3			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0		Beginning of Phase 1					
1	25.93						
2	56.544						
4	30.62	10.58			11.82		
6	29.64	13.20					
8	24.9				9.74		
11	37.11				14.00		
13					20.60		
16		7.37			9.11		
19	36.4	7.12			10.16	2.43	
22	34.3	6.02			9.14	5.96	2.95
26	30.25	3.68			7.88	5.68	2.80
29	33.1	14.40			6.16	5.81	2.93
34	31.15	20.60			5.72	3.88	2.28
37	37.7	29.40			19.48	5.73	2.49
64	42	20.80				2.31	3.04
68	33.15	0.732			8.88	1.47	3.74
75	18.9	2.08	0.908				1.65
82	32.1	2.12	1.19	2.37	3.06	2.74	
89	44.2	3.18	1.14	1.25	5.88	3.43	2.65
96	30.9				8.32	3.01	2.04
97		Beginning of Phase 2					
99	37.2			1.71	5.98	3.31	2.99
103	32.6	4.00	1.25	0.929	4.38	3.26	4.33
105	44.35	1.86	1.38		5.64	2.32	3.60
110	31	5.54	0.986	1.02	6.96	3.13	5.68
112	30.45	1.668	0.874	0.861	5.16	2.99	3.66
116	58.5	1.49	1.02	1.03		2.99	4.92
120	32.95	7.90	0.795	1.26	29.8	3.16	4.92
124	23.05	0.13	1.06	1.43	6.28	3.19	5.44
126	39.05	2.10	0.868	1.05	21.2	2.98	2.74
131	51.5	3.02	0.65	0.786	9.22	3.51	2.95
133	47.5	2.82	0.745	1.16	13.92	2.61	3.23
141	32.75	14.42	0.712	1.09	9.30	2.89	3.54
148	22.35	15.02	1.12	0.498	8.40	2.33	2.97
152		Beginning of Phase 3					
152	12.15	2.72	0.895	0.760	4.08	3.19	3.17
155	21.85	17.18	0.759	0.442	3.06	4.03	2.74
159	34.25	1.62	0.47	0.941	2.70	3.93	4.70
161	21.65	1.67	0.348	0.441	2.04	3.61	3.13
163	25.95	1.74	0.531	0.600	3.74	4.03	3.87
166	33.9	1.92	0.547	0.532	2.92	3.36	2.50
170	32.45	2.32	0.532	0.546	3.92	2.99	2.30
173	28.85	1.97	0.438	0.924	5.66	2.49	2.45
176	35.5	1.36	0.528	0.679	4.60	2.92	1.99
181	27.45	3.33	0.388	0.914	5.08	2.85	2.15
184	31.15	3.24	0.548	1.12	6.12	2.56	0.947

Nitrogen, Nitrate

Table A7. Systems 1 and 2, Nitrate as Nitrogen

Days from start	Influent	System 1			System 2		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	1.51	0.89					
2	1.84	1.04					
4	1.77				0.799		
6	1.67	0.846			1.08		
8	1.61				0.829		
19	1.46	0.404					
22	1.24	1.77			2.82		
26	1.04	1.08			0.267		
29	1.09	0.829			0.316	0.173	
34	1.07				0.260	0.152	1.40
37	1.13	21			1.35	0.116	0.860
64	1.51	22.5	0.08	2.74	23.8	0.095	2.19
68	4.15	5.63	0.039	2.54	7.46	0.058	1.75
71	8.20	0.343	0.145	1.01	2.93	0.204	1.61
75	3.57	0.257	0.163	0.645	0.425	0.358	1.73
77	10.6	0.13	0.093		0.230	0.377	1.66
82	0.924	0.222	0.156	0.813		0.368	2.70
89	6.12	0.175	0.143	1.61	0.126	0.107	2.79
92	6.69	8.24	0.118	0.916	0.308	0.084	2.81
96	2.99	0.465	0.152	1.46	5.00	0.118	2.42
97	Beginning of Phase 2						
99	11.0	0.495	0.151	0.829	0.396	0.134	1.52
103	3.31	1.19	0.127	0.457	0.583	0.123	1.18
105	7.23	0.566	0.092	0.407	1.56	0.213	1.51
112	2.11	0.763	0.131	0.557	0.889	0.245	2.49
116	1.75	0.269	0.193	0.986	0.238	0.514	2.81
120	2.87	1.63	0.095	1.16	0.303	0.413	2.73
124	2.18	0.205	0.113	1.24	0.210	0.271	2.02
126	27.1	0.487	0.171	1.50	0.473	0.351	2.30
131	13.2	0.361	0.074	1.34	0.683	0.138	1.41
133	19.8	0.440	0.150	1.57	0.607	0.228	1.82
141	1.97	2.38	0.188	1.99	0.862	0.410	1.94
148	1.74	6.81	0.162	1.81	5.74	0.457	2.18
152	Beginning of Phase 3						
152	4.21	0.202	0.115	1.40	0.288	0.423	1.97
155	11.2	0.535	0.076	1.08	0.458	0.410	2.12
159	1.43	0.168	0.078	1.18	0.735	0.420	2.24
161	1.54	0.226	0.140	1.20	0.132	0.378	2.12
163	1.11	0.189	0.091	1.01	0.432	0.415	1.78
166	1.89	0.188	0.122	0.895	0.169	0.180	1.37
170	0.882	-0.1	0.100	-0.085	0.309	0.365	0.982
173	1.03	0.143	0.122	0.446	0.395	0.594	0.421
176	1.35	0.286	0.113	0.288	0.362	0.564	0.394
181	1.08	0.228	0.095	0.224	0.704	0.227	0.283
184	1.00	0.122	0.045	0.292	0.105	0.983	0.355

Table A8. Systems 3 and 4, Nitrate as Nitrogen

Days from start	Influent	System 3			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0		Beginning of Phase 1					
1	1.51						
2	1.84						
4	1.77	0.512			1.16		
6	1.67	0.369			0.516		
8	1.61	0.757			0.803		
19	1.46	0.267			0.349	0.181	
22	1.24	0.264			1.04	0.190	0.270
26	1.04	0.248			0.781	0.161	0.130
29	1.09	6.16			0.848	0.204	0.147
34	1.07	2.06			2.97	0.242	0.173
37	1.13	25.3			14.2	0.213	0.169
64	1.51	16.3			ab > 3.5	0.107	1.53
68	4.15	0.112			5.65	0.060	2.06
71	8.20	0.227			2.17	0.180	1.30
75	3.57	0.227	0.209				0.832
77	10.6	0.185	0.215	1.69	2.85	0.390	2.48
82	0.924	0.153	0.131	1.18	0.136	0.202	
89	6.12	0.181	0.257	0.657	0.211	0.100	1.80
92	6.69	0.233	0.490	0.478	0.341	0.154	1.40
96	2.99				1.54	0.235	1.15
97		Beginning of Phase 2					
99	11.0			0.205	0.313	0.289	2.17
103	3.31		0.214	0.337	0.799	0.190	2.65
105	7.23	0.203	0.155	0.401	0.309	0.250	2.46
112	2.11	0.742	0.333	0.423	0.329	0.130	2.40
116	1.75	0.179	0.364	0.482	0.262	0.223	2.18
120	2.87	0.148	0.180	0.409	1.24	0.119	2.19
124	2.18	0.163	0.145	0.331	0.303	0.128	2.23
126	27.1	0.255	0.204	0.440	9.36	0.178	1.74
131	13.2	0.317	0.113	0.175	0.366	0.072	1.25
133	19.8	0.294	0.154	0.295	0.734	0.159	1.85
141	1.97	0.780	0.33	0.456	1.34	0.202	2.84
148	1.74	0.752	0.178	0.127	5.15	0.169	2.38
152		Beginning of Phase 3					
152	4.21	0.178	0.148	0.282	1.02	0.161	2.39
155	11.2	0.770	0.062	0.160	0.665	0.132	2.42
159	1.43	0.815	0.010	0.119	0.352	0.106	2.75
161	1.54	0.122	0.071	0.175	0.891	0.109	2.57
163	1.11	0.164	0.090	0.097	0.439	0.115	2.45
166	1.89	1.71	0.101	0.138	0.331	0.160	2.33
170	0.882	0.268	0.106	0.375	0.991	0.096	-0.100
173	1.03	0.166	0.034	0.210	0.315	0.039	1.13
176	1.35	0.145	0.059	0.149	0.427	0.083	0.806
181	1.08	0.192	0.086	0.127	0.610	0.100	0.562
184	1.00	0.067	0.012	0.179	0.114	0.043	0.302

Nitrogen, Ammonia

Table A9. Systems 1 and 2, Ammonia as Nitrogen

Days from start	Influent	System 1			System 2		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	11.94	0.646					
2	12.40	0.158					
4	21.82				0.904		
6	10.36	0.239			0.243		
8	10.88				0.174		
11	20.40	0.091			0.122		
13	10.10	0.448			0.090		
16		0.140			0.672		
19	11.75	0.338			0.056		
22	7.70	3.81			0.093		
26	9.97	0.453			0.080		
29	12.95	0.625			-0.004	-0.294	
34	15.48	0.078			0.093		
37	17.85				0.878	-0.074	-1.080
64	28.65	0.112	-0.047	0.009	0.115	0.412	0.320
68	23.55	-0.020	-0.098	-0.090	0.031	0.875	-0.080
71	20.25	-0.032	0.270	-0.031	-0.062	1.12	-0.028
75	3.93	-0.002	0.519	0.004	-0.019	1.42	0.057
77	14.05	-0.144	1.01	-0.024	-0.011	1.50	-0.002
82	9.15	0.000	1.08	-0.021		1.17	-0.034
89	19.80	-0.177	0.483	-0.026	-0.285	1.32	-0.191
92	15.10	0.363	0.763		-0.011	2.70	0.054
96	13.75	-0.058	0.461	-0.120	0.815	1.85	-0.043
97	Beginning of Phase 2						
99	11.35	-0.034	0.702	-0.053	-0.069	2.06	-0.036
103	6.58	0.036	0.726	-0.055	-0.041	2.44	-0.081
105	29.05	-0.172	0.874	-0.043	-0.323	1.64	-0.016
110	18.90	-0.041	0.946	-0.115	-0.173	1.39	-0.065
112	15.30	-0.005	0.780	-0.028	0.297	1.65	-0.040
120	15.30	0.079	1.97	-0.019	-0.042	1.69	-0.056
124	9.90	-0.061	1.91	-0.051	0.031	1.51	0.002
126	6.40	-0.024	1.93	0.107	0.001	1.41	0.393
141	12.35	0.438	1.97	-0.076	-0.020	1.76	-0.017
152	Beginning of Phase 3						
155	3.61	-0.029	1.94	-0.077	-0.117	2.50	-0.110
159	14.00	-0.001	1.22	-0.119	-0.086	1.96	-0.115
161	7.60	-0.031	0.947	-0.091	-0.098	1.83	-0.112
163	11.60	-0.072	1.34	-0.096	-0.100	1.83	-0.099
166	13.35	-0.059	1.24	-0.101	-0.085	1.64	-0.084
170	14.95	-0.072	1.24	-0.112	-0.086	1.30	-0.090
173	14.00	-0.082	1.05	-0.077	-0.079	0.378	-0.109
176	12.55	0.092	0.965	-0.096	-0.098	0.022	-0.091
181	11.45	-0.187	0.856	-0.072	-0.096	-0.077	-0.072
184	12.10	-0.203	0.642	-0.207	-0.089	-0.252	-0.104

Table A10. Systems 3 and 4, Ammonia as Nitrogen

Days from start	Influent	System 3			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
1	11.94						
2	12.40						
4	21.82	0.327			0.353		
6	10.36	3.39			0.217		
8	10.88	9.08			0.246		
11	20.40				0.164		
13	10.10	5.25			0.336		
16		0.186			0.151		
19	11.75	0.053			-0.017	-0.036	
22	7.70	-0.016			-0.027	-0.047	-0.079
26	9.97	0.396			0.168	0.009	-0.018
29	12.95	2.72			-0.015	-0.110	-0.038
34	15.48	0.454					
37	17.85	0.316			1.83	-0.031	-0.059
64	28.65	0.040			0.113	0.241	-0.032
68	23.55	-0.056			0.067	-0.007	-0.043
71	20.25	-0.250			-0.053	1.20	-0.013
75	3.93	-0.005	-0.009				-0.014
77	14.05	-0.010	0.005	-0.031	0.080	0.547	-0.006
82	9.15	-0.168	-0.041	-0.055	-0.057	0.870	-0.043
89	19.80	-0.045	0.046	-0.130	-0.051	1.38	-0.040
92	15.10	-0.218	-0.016	-0.020	0.007	2.41	-0.076
96	13.75				-0.120	1.59	-0.095
97	Beginning of Phase 2						
99	11.35			0.070	-0.001	1.53	-0.011
103	6.58		-0.037	-0.046	-0.161	2.55	-0.258
105	29.05	-0.269	-0.034		-0.279	2.09	-0.026
110	18.90	0.067	-0.018	-0.099	1.65	0.788	-0.044
112	15.30	-0.028	-0.029	-0.086	0.049	2.02	0.032
120	15.30	-0.045	-0.056	-0.051	0.092	2.25	0.045
124	9.90	-0.062	-0.239	0.011	-0.001	2.10	0.098
126	6.40	-0.023	-0.022	-0.038	0.049	2.05	-0.099
141	12.35	-0.027	-0.027	-0.041	0.188	1.98	-0.092
152	Beginning of Phase 3						
155	3.61	0.189	-0.094	-0.098	-0.039	3.87	-0.087
159	14.00	-0.098	-0.094	-0.108	-0.08	3.77	-0.078
161	7.60	-0.049	-0.386	-0.121	-0.108	-0.07	-0.074
163	11.60	-0.116	-0.085	-0.113	0.092	3.17	-0.075
166	13.35	0.465	-0.055	-0.076	-0.049	2.93	-0.059
170	14.95	-0.009	-0.105	-0.090	0.112	2.78	-0.112
173	14.00	-0.059	-0.105	-0.087	-0.063	2.24	-0.097
176	12.55	-0.097	-0.108	-0.105	-0.083	2.15	-0.09
181	11.45	-0.092	-0.072	-0.076	-0.067	1.94	-0.09
184	12.10	-0.073	-0.142	-0.118	-0.072	1.80	-0.11

pH

Table A11. Systems 1 and 2, pH

Days from start	Influent	System 1			System 2		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
6	4.53	5.95			6.07		
8	4.56				6.08		
11	4.41	4.76			6.33		
13	4.53	6.70			6.66		
16	4.54	6.79			6.49		
19	4.80	7.33					
22	4.49	6.95			6.94		
26	4.55	7.20			6.66		
29	4.46	7.11			7.19	7.52	
34	4.65				7.00	7.03	7.58
37	4.84	7.62			7.15	7.55	7.58
64	4.33		8.19	7.91		7.95	7.96
68	4.49	8.63	8.60	8.08	7.55	8.45	8.31
71	4.50	6.91	7.62	8.11	7.66	7.60	8.15
75	5.21	7.13	7.55	7.87	6.96	7.63	8.14
77	4.58	6.91	7.67	8.21	6.97	7.70	8.11
82	5.50	7.08	7.71	8.29		7.96	8.26
89	4.41	6.87	7.22	8.19	7.55	8.00	8.16
92	4.51	7.37	7.73		7.41	7.71	8.06
96	4.56	7.20	7.41	7.90	7.05	7.61	7.88
97	Beginning of Phase 2						
99	4.81	7.21	7.55	7.92	7.30	7.67	7.90
103	5.04	7.46	7.58	8.14	7.49	7.69	8.26
105	5.96	7.13	7.48	7.81	7.03	7.58	8.06
110	4.69	7.25	7.60	7.60	7.26	7.75	8.20
112	6.03	7.23	7.66	8.34	6.95	7.83	8.22
116	4.45	7.31	8.09	8.29	7.23	7.95	8.32
120	4.48	7.03	7.74	8.05	7.36	7.62	8.28
124	4.62	7.12	7.80	8.09	7.38	7.88	8.23
126	4.67	7.10	7.68	8.01	7.12	7.84	8.14
131	4.45	6.82	7.41	7.87	6.90	7.67	7.90
133	4.42	6.85	7.79	8.05	6.82	7.82	8.10
141	5.46	6.95	7.69	8.14	6.99	7.61	7.04
148	5.50	7.13	7.88	7.85	7.25	7.89	7.84
152	Beginning of Phase 3						
152	4.70	7.09	7.87	8.10	7.02	7.75	8.24
155	4.47	6.90	7.58	8.10	7.26	7.73	8.11
159	5.59	7.27	7.68	8.28	7.09	7.80	8.20
161	5.22	7.08	7.54	8.07	7.00	7.63	8.09
163	5.13	6.95	7.67	8.21	7.06	7.66	8.23
166	5.46	6.99	7.80	8.15	7.05	7.76	8.21
170	5.43	6.90	7.58	8.18	6.88	7.76	8.19
173	5.80	6.75	7.49	8.07	6.76	7.69	8.06
176	5.64	6.79	7.58	8.00	6.77	8.00	8.06
181	5.76	7.01	7.63	8.40	6.81	7.89	8.27
184	5.09	6.80	7.68	8.03	6.96	7.88	8.09

Table A12. Systems 3 and 4, pH

Days from start	Influent	System 3			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
0	Beginning of Phase 1						
6	4.53	6.74			6.22		
8	4.56	7.25			6.34		
11	4.41				6.36		
13	4.53	7.04			6.84		
16	4.54	6.94			6.66		
19	4.80	7.53			7.50	7.41	
22	4.49	7.03			6.73	7.17	7.42
26	4.55	7.50			7.25	6.11	6.99
29	4.46	7.21			7.00	7.40	7.29
34	4.65	7.49			7.44	7.26	7.71
37	4.84	7.05			6.99	7.54	7.65
64	4.33	7.41				8.03	8.22
68	4.49	7.46			7.57	8.56	8.27
71	4.50	7.51			7.96	7.30	8.16
75	5.21	7.30					8.13
77	4.58	7.34	7.62	8.21	7.66	8.16	8.07
82	5.50	7.60	7.95	8.27	8.09	7.99	8.30
89	4.41	8.02	8.19	8.16	7.37	7.75	8.06
92	4.51	7.71	7.87	8.10	7.21	7.56	8.07
96	4.56				7.14	7.74	7.99
97	Beginning of Phase 2						
99	4.81			7.82	7.33	7.85	8.15
103	5.04	7.54	7.74	8.08	7.46	7.91	7.76
105	5.96	7.59	7.67		7.04	7.70	7.85
110	4.69	7.49	7.74	8.07	6.88	7.90	7.88
112	6.03	7.13	8.02	8.11	7.15	7.78	8.05
116	4.45	7.32	8.07	8.27		7.97	8.25
120	4.48	7.23	7.69	8.08	6.86	7.53	8.09
124	4.62	7.39	7.96	8.24	7.17	7.87	8.11
126	4.67	7.42	7.93	8.22	7.04	7.67	8.07
131	4.45	7.13	7.53	7.95	6.93	7.42	7.42
133	4.42	7.06	7.89	8.20	6.84	7.54	8.08
141	5.46	7.13	7.56	7.10	6.99	7.43	7.96
148	5.50	7.16	7.80	8.34	7.35	7.79	8.33
152	Beginning of Phase 3						
152	4.70	7.13	7.87	8.25	7.25	7.80	8.23
155	4.47	7.27	7.65	8.39	7.13	7.67	8.22
159	5.59	7.37	7.96	8.17	7.10	7.59	8.18
161	5.22	7.04	7.69	8.15	6.93	7.41	8.07
163	5.13	7.06	7.95	8.29	7.01	7.59	8.14
166	5.46	7.30	7.97	8.34	6.98	7.73	8.25
170	5.43	7.42	7.80	8.25	6.67	7.59	8.20
173	5.80	6.82	8.00	8.07	6.68	7.20	7.95
176	5.64	7.11	7.53	8.14	6.64	7.62	8.03
181	5.76	7.25	7.83	8.39	6.93	7.58	8.15
184	5.09	7.07	7.72	8.16	6.73	7.44	7.98

Alkalinity

Table A13. System 1 and 4, Total Alkalinity

Days from start	Influent	System 1			System 4		
		Column 1 Effluent	Column 2 Effluent	Column 3 Effluent	Column 1 Effluent	Column 2 Effluent	Column 3 Effluent
128	1305	1837.5	1805	1690	-	-	-
129	1070	2000	1800	1665	1865	1845	1730
135	1240	-	-	-	2085	2030	1950
142	1560	2100	2070	1900	2050	2130	1900

Appendix B: Start Up Study Data

Total Phosphorus

Table B1. Influent and Effluent Total Phosphorus Concentrations

Days from Start	Influent (mg/L PO ³⁻ ₄ -P)	Control 1 (mg/L PO ³⁻ ₄ -P)	Control 2 (mg/L PO ³⁻ ₄ -P)	Treatment 1 (mg/L PO ³⁻ ₄ -P)	Treatment 2 (mg/L PO ³⁻ ₄ -P)
1	25.2	7.63	8.15	4.83	6.23
2	24.7	6.48	13.4	8.16	8.76
3	24.3	10.6	14.2	10.5	7.41
4	25.4	9.39	14.1	9.57	9.60
5	26.3	9.72	15.3	11.4	9.42
8	26.6	8.94	8.10	8.49	8.34
10	25.6	6.96	10.0	6.57	8.82
12	27.3	6.57	7.23	6.63	8.91
16	45.2	8.67	6.06	4.65	7.62

Chemical Oxygen Demand

Table B2. Influent and Effluent COD Concentrations

Days from Start	Influent (mg/L)	Control 1 (mg/L)	Control 2 (mg/L)	Treatment 1 (mg/L)	Treatment 2 (mg/L)
1	4980	3790	3730	4530	4050
2	5430	2715	3260	2880	2735
3	5350	1875	3130	2125	1735
4	5668	1448	2289	1747	1419
5	5910	1352	2402	1793	1047
8	5347	877	407	1242	811
10	5530	795	645	740	740
12	5805	775	322	992	657
16	6240	555	160	335	305

Nitrogen, Total

Table B3. Influent and Effluent Total Nitrogen Concentrations

Days from Start	Influent (mg/L)	Control 1 (mg/L)	Control 2 (mg/L)	Treatment 1 (mg/L)	Treatment 2 (mg/L)
1	22.5	8.10	8.04	5.76	7.62
2	26.8	4.42	4.99	5.31	4.96
3	25.9	14.6	4.51	8.26	8.14
4	25.4	10.6	11.1	12.1	9.00
5	27.0	10.7	9.63	7.92	9.75
8	26.2	7.19	9.8	7.58	7.66
10	21.9	10.3	23.5	10.9	12.5
12	18.8	4.96	8.97	7.54	11.2
16	77.5	10.0	3.87	8.20	7.80

Nitrogen, Nitrate

Table B4. Influent and Effluent Nitrate as Nitrogen Concentrations

Days from Start	Influent (mg/L NO ₃ -N)	Control 1 (mg/L NO ₃ -N)	Control 2 (mg/L NO ₃ -N)	Treatment 1 (mg/L NO ₃ -N)	Treatment 2 (mg/L NO ₃ -N)
1	2.13	1.23	1.15	1.93	1.06
2	1.17	0.685	1.76	1.61	1.70
3	1.17	1.13	1.18	1.51	1.04
4	0.954	0.629	0.947	0.949	0.636
5	0.973	0.647	0.758	0.853	0.544
8	1.23	0.435	0.454	0.652	0.447
10	1.13	0.450	0.513	0.672	0.430
12	1.30	0.369	0.325	0.490	0.349
16	3.16	0.459	0.288	0.429	0.358

Nitrogen, Ammonia

Table B5. Influent and Effluent Ammonia as Nitrogen Concentrations

Days from Start	Influent (mg/L NH ₃ -N)	Control 1 (mg/L NH ₃ -N)	Control 2 (mg/L NH ₃ -N)	Treatment 1 (mg/L NH ₃ -N)	Treatment 2 (mg/L NH ₃ -N)
1	9.50	0.008	-0.086	-0.145	0.220
2	9.80	-0.017	-0.011	-0.047	-0.011
3	10.0	0.088	0.303	0.027	0.094
4	10.9	0.031	0.339	-0.004	0.224
5	11.9	0.013	-0.078	-0.082	-0.033
8	14.1	-0.046	0.001	-0.098	-0.008
10	5.93	0.261	5.71	0.017	0.844
12	8.95	-0.036	0.096	-0.024	-0.018
16	6.85	-0.022	-0.095	-0.078	-0.062

pH

Table B6. Influent and Effluent pH Levels

Days from Start	Influent	Control 1	Control 2	Treatment 1	Treatment 2
1	6.00	7.09	7.01	7.28	6.98
2	5.97	6.59	6.21	6.55	6.52
3	6.10	6.64	6.2	6.8	6.64
4	6.15	7.24	6.63	7.16	6.73
5	6.12	7.17	6.56	7.09	7.04
8	6.63	6.99	7.16	6.85	7.29
10	5.80	6.94	7.11	6.96	7.05
12	6.09	6.94	7.29	7.07	7.09
16	5.84	7.11	7.32	7.13	7.12

Appendix C: PO4Sponge Study Data

Table C1. Influent and Effluent Total Phosphorus Concentrations

Days from Start	Influent (mg/L PO³⁻₄-P)	Control (mg/L PO³⁻₄-P)	Treatment 1 (mg/L PO³⁻₄-P)	Treatment 2 (mg/L PO³⁻₄-P)
0	17.20	17.30	0.074	0.074
2	17.78	16.98	0.050	0.102
4	17.85	17.12	0.038	0.095
6	17.06	17.24	0.030	0.046
8	17.58	17.92	0.021	0.019
10	17.80	17.48	0.023	0.019
13	18.12	17.96	0.015	0.030
15	17.42	17.58	0.027	0.028
20	17.68	17.88	-	-
22	17.76	17.72	0.007	0.014
26	16.40	16.90	0.040	0.056
29	18.36	18.12	0.000	0.010
31	17.70	17.30	0.004	0.016
36	17.04	16.58	0.060	-