

# ACHIEVING AND VERIFYING ULTRA-LOW PHOSPHORUS FOR WASTEWATER DISCHARGE OR REUSE

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## Abstract

According to the USEPA's Nutrient Pollution website, "nutrient pollution is one of America's most widespread, costly and challenging environmental problems, and is caused by excess nitrogen and phosphorus in the air and water" [USEPA (2013)]. Phosphorus (P) in the water increases algae growth, which can kill off the waterway's plant and animal life, produce harmful dioxins when disinfected for drinking water, and create a decline in the tourism, fishing, and real estate industries. To combat this problem, several areas in the U.S. now, or will soon, require low levels of phosphorus in the effluent of wastewater plants discharging to state waterways. One such example of this is the Cahaba River basin in Alabama; wastewater plants discharging more than 1 MGD (3,788 m<sup>3</sup>/day) into this river - or tributaries feeding it - will be required to meet an average monthly total phosphorus limit of 0.043 mg/l by 2022.

To determine how to consistently meet these low phosphorus limits, a pilot study was conducted in December of 2012 at the Buxahatchee Wastewater Treatment Plant (WWTP) in Calera, AL. The main plant processes are a sequencing batch reactor (SBR) secondary system and a cloth media filtration (CMF) tertiary system. To achieve the required ultra-low phosphorus level, a sidestream of the filter effluent was passed through an ultrafiltration (UF) pilot unit. This paper describes the system parameters required to obtain ultra-low effluent phosphorus levels. In addition, some of the challenges encountered in the study are discussed, along with how these challenges were overcome.

## Materials and Methods

### Experimental Facilities

The City of Calera, AL owns and operates the Buxahatchee WWTP, where domestic wastewater from the City is treated prior to disposal into nearby Buxahatchee Creek. The plant is permitted for an average daily flow of 1.5 MGD (5,682 m<sup>3</sup>/day) and a peak daily flow of 3 MGD (11,364 m<sup>3</sup>/day), and currently treats an average daily flow of approximately 0.6 MGD (2,273 m<sup>3</sup>/day). As shown in Figure 1, the treatment process consists of an influent screen and grit removal system, dual-basin SBR, post-equalization basin, 2-train CMF system, and chlorine contact basin. Waste solids are removed from the SBR basins, treated in an aerobic digester, and sent to a centrifuge for dewatering. Digester supernatant and centrifuge centrate are transferred back to the influent pump station. Aluminum sulfate (alum) is added to the SBR feed in

proportion to the influent flow. If required, alum can also be added to each SBR basin during its React phase, to the inlet to the post-equalization basin, to the digester supernatant, and to the centrate.

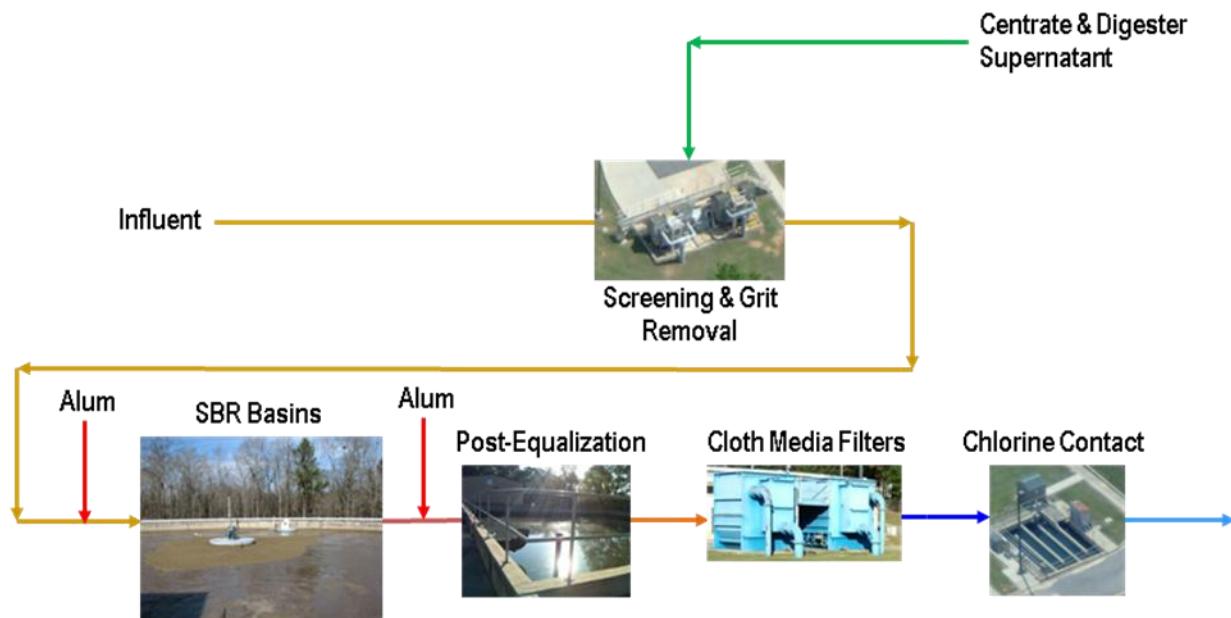
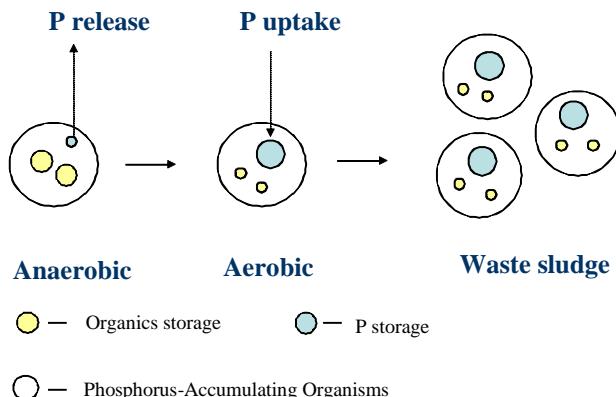


Figure 1. Buxahatchee WWTP Layout

The SBR system consists of two (2) 900,000-gallon (3,400-m<sup>3</sup>) circular basins and is designed for both biological and chemical phosphorus removal. The aeration system operates completely independent of the basin mixing so that anaerobic, aerobic, and anoxic conditions are achieved in each SBR basin during the different operating phases. When the screened wastewater enters the basin during an anaerobic phase, the phosphorus-accumulating organisms (PAOs) in the basin release phosphorus in order to provide the energy needed to consume the wastewater organics and to create new cell mass (see Figure 2). Then, when oxygen is added to the basin during the aerobic phase, the PAOs consume as much phosphorus as they can – a process known as “luxury uptake” – including much of the phosphorus in the influent wastewater.

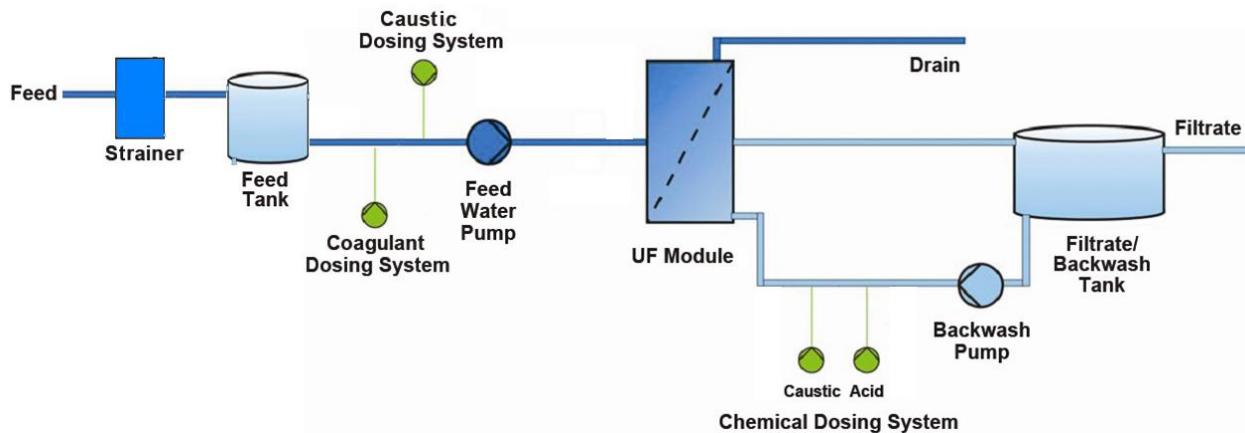


**Figure 2.** Biological Phosphorus Removal

Most of the remaining phosphorus in the basin reacts with the alum injected into the influent to form aluminum phosphate ( $\text{AlPO}_4$ ), which is not very soluble at fairly neutral pHs and settles with the biomass to the bottom of the basin during the Settle phase. The SBR's subsequent Decant phase prevents most of the phosphorus-laden biomass and  $\text{AlPO}_4$  from entering the SBR effluent, and they are eventually pumped from the basin to the digester. The control system allows adjustment of the SBR operating parameters and alum dosages to optimize both the biological and chemical phosphorus removal processes.

The CMF system consists of two 6-disk filters, each providing  $3,477 \text{ ft}^2$  ( $323 \text{ m}^2$ ) of effective filtration area and featuring nylon cloth media with a nominal particle removal rating of approximately 0.0004 inches ( $10 \mu\text{m}$ ). The filters use an outside-to-inside, vertically mounted configuration that allows heavier solids to settle to the bottom of the filter tanks, where they are periodically vacuumed to drain. As a filtration layer develops on the cloth, the tank level rises until a high setpoint is reached, which initiates a backwash step. The filters remove most of the phosphorus-rich biomass and  $\text{AlPO}_4$  precipitate that were not settled out in the SBR or post-equalization basins.

During the study, a portion of the wastewater in each CMF effluent chamber was fed through hoses to the UF pilot plant (see Figure 3). A centrifugal pump in the pilot pumped the filtered effluent through a 0.012 inch ( $300 \mu\text{m}$ ) wire strainer, which was used to remove large particles that could damage the membrane fibers. Once through the strainer, the flow filled a 120-gallon (450-liter) feed tank.



**Figure 3.** Flow Diagram for the UF Pilot Plant

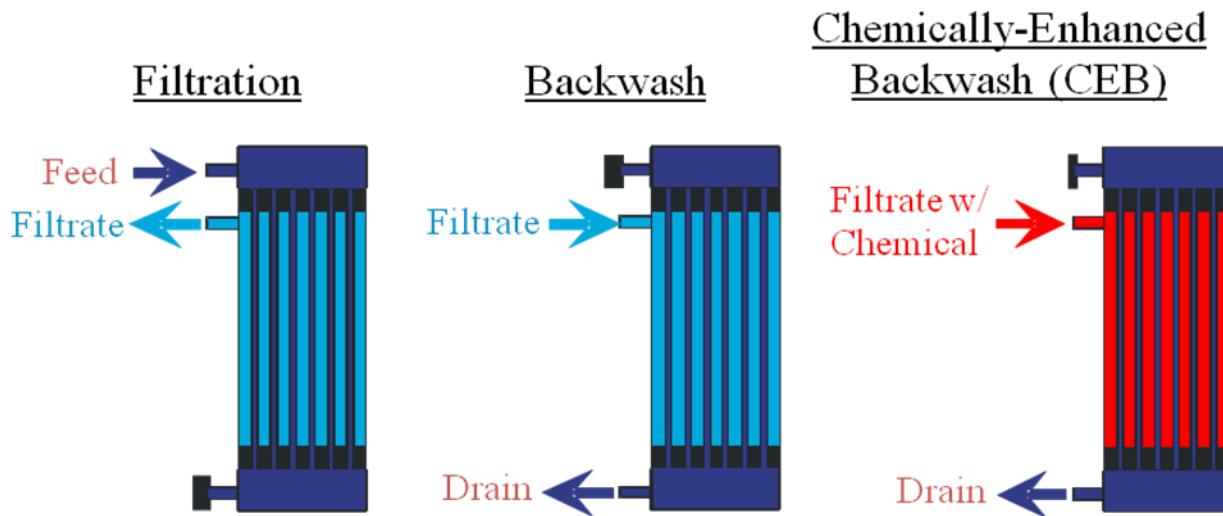
Alum was injected into the wastewater prior to entering the membrane module in order to react with any dissolved reactive phosphorus still present in the wastewater, forming an AlPO<sub>4</sub> precipitate that could be filtered out by the membrane. During each pilot run, this alum concentration was varied to determine its affect on the final effluent phosphorus levels.

The UF pilot plant included a piping loop between the alum injection point and the membrane module that was made up of five separate chambers designed to allow adjustment of the alum retention time. Previous testing revealed that these have little to no affect on membrane performance; however, all five chambers were used for the purpose of this study, resulting in a 200-second retention time at the lower flow and a 125-second retention time at the higher flow.

The reaction of the alum with the phosphate lowered the pH of the wastewater. If the pH dropped below 6.5, caustic (NaOH) was injected into the wastewater to raise the pH, preventing the AlPO<sub>4</sub> from re-dissolving.

During filtration modes, filtered wastewater was pumped from the feed tank through a single 645 ft<sup>2</sup> (60 m<sup>2</sup>) UF module using a 3 HP (2.2 kW) feed pump. The module used was inge's dizzier® XL and contained about 2,000 polyethersulfone (PES) Multibore® fibers, each with (7) 0.035 inch (0.9 mm) bores. The nominal size of the membrane pores on the inside of each bore was  $8 \times 10^{-7}$  inch (0.02 µm), resulting in a molecular weight cutoff of 150,000 Daltons.

During filtration, filtered wastewater was introduced to the inside of each fiber bore with filtrate (permeate) forced to the outside of the membrane (i.e. inside-out), as shown under the Filtration mode in Figure 4. The filtrate was transferred to the filtrate/backwash tank, where it flowed by gravity to a manhole and was pumped back to the influent pump station.



**Figure 4.** UF Operating Modes

A variable-frequency drive (VFD) on the membrane feed pump was used to maintain a constant flow through the membrane during each pilot run. The feed pressure to the membrane was monitored, and was found to increase throughout the filtration process as the biomass and chemical solids in the wastewater collected on the membrane surfaces. To remove these solids, a periodic backwash was performed in which filtrate was pumped in the reverse direction through the membrane (from outside the fibers to inside the fiber bores) using a 5 HP (3.7 kW) backwash pump, as shown under the Backwash mode in Figure 4.

Some solids on the membrane are not removed with the backwashes; therefore, the membrane was cleaned periodically with caustic and hydrochloric acid to dissolve any remaining organic and inorganic solids, respectively, as shown under the Chemically-Enhanced Backwash (CEB) mode in Figure 4. This was accomplished by dosing the chemical into the backwash water, soaking the membrane in the chemical, and then flushing it to drain with filtrate.

Filter effluent was alternated into the top and bottom of the fibers in order to achieve an even layer of solids on the membrane surface, which improves the effectiveness of the periodic backwash and CEB events. Likewise, backwash and CEB flows were alternated into the top and bottom of the fibers in order to clean the membrane surfaces more effectively.

Four sampling points were used during the pilot run to collect the wastewater samples:

- 24-hour composite samples from the chlorine contact basin (CMF effluent)
- Grab samples from the feed line downstream of the alum injection
- Grab samples from the filtrate line
- 24-hour composite samples from the filtrate/backwash tank (pilot effluent)

In addition, the pilot plant included the following instruments for monitoring parameters via the pilot's human-machine interface (HMI):

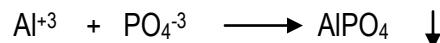
- top and bottom feed pressure transmitters,
- filtrate/backwash pressure transmitter,
- feed pH sensor with temperature measurement,
- feed and filtrate/backwash flow meters,
- feed and filtrate/backwash tank level sensors,
- filtrate/backwash pH meter with temperature measurement,
- feed turbidimeter, and
- filtrate/backwash turbidimeter (with sample pump and valves).

### **Key Parameters**

The key parameter used during the study was the total phosphorus (TP) concentration, particularly in the final effluent. The TP is made up of the following components, any of which can be in either the soluble (dissolved) or insoluble (particulate) form:

- Reactive Phosphorus (RP), also known as orthophosphate ( $\text{PO}_4^{3-}$ )
- Condensed Phosphates (CP) – polyphosphates (polymerized chains) or acid-hydrolyzable
- Organic Phosphates (OP), chemically-bound to organic molecules

During our study, most of the soluble forms of these TP components were first converted to an insoluble form via uptake into the biomass (biological removal) or reaction with alum (chemical removal) according to the following equation:



While the biomass can most easily consume RP, some CP and even a little OP are also taken in. The acid-hydrolyzable portion of the CP is often converted to RP by the biomass or through hydrolysis. Alum, however, only reacts with the RP form and will have no affect on the other two forms. Soluble CP or OP molecules larger than 150,000 Daltons were removed by the UF. The insoluble forms were then either settled in the SBR basins and pumped to the digester, or filtered out by the CMF or UF.

Because of this, the TP of the UF effluent was expected to consist mostly of smaller, soluble CP polyphosphate and OP molecules, but with some soluble RP that didn't react with the alum and a very small amount of insoluble particles smaller than the UF membrane nominal pore size (0.02  $\mu\text{m}$ ).

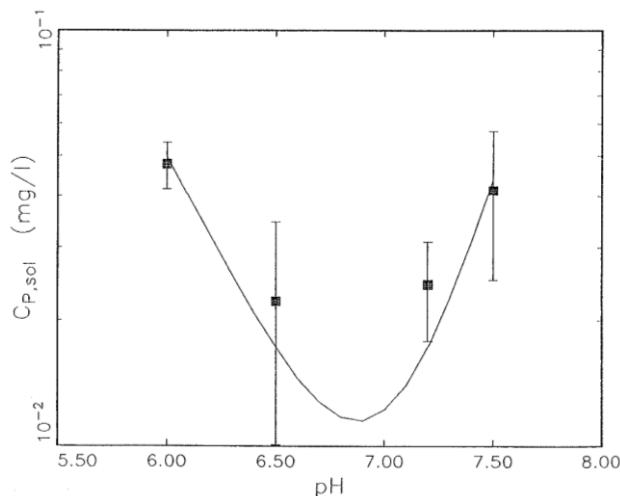
Therefore, the concentration of the soluble, non-reactive phosphorus (dissolved CP and OP) in the raw wastewater influent is a good indication of the minimum effluent phosphorus level that may be achievable.

Another key parameter is the coagulant dosage, in this case the amount of alum used to react with the RP in the wastewater. This dosage is calculated as the ratio of aluminum to phosphorus on a mass basis, typically in mg Al<sup>+3</sup> per mg TP. During the study, the Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> (alum) concentration is set at different levels for each pilot run, and the Al<sup>+3</sup> (aluminum) concentration is calculated using the following equation:

$$\text{mg/l aluminum} = \text{mg/l alum} \times 31 \text{ g/mole Al}^{+3} / 350 \text{ g/mole Al}_2(\text{SO}_4)_3$$

At each set alum concentration, the alum dosage will vary proportional to changes in filtered water TP levels. Once the effluent TP was consistently below the desired level (0.043 mg/l) during the pilot study, the alum concentration was lowered incrementally to determine the minimum required alum dosage.

A third key parameter is the pH of the filtered water following alum addition. This is important because the solubility of the AlPO<sub>4</sub> is pH-dependent, as shown on the graph in Figure 5 [Argaman (1991)]. As you can see from the graph, AlPO<sub>4</sub> is most insoluble at a pH of approximately 6.9 and its solubility increases steadily at pHs below 6.5 and above 7.2.



**Figure 5.** Solubility of Aluminum Phosphate at Varying pHs

The final key parameter was membrane flux (MF). This is the rate at which flow (Q) passes through a given membrane area (A) and is calculated using the following equation:

$$MF = Q / A$$

The flux is defined in gallons per square foot of membrane per day (gfd) or liters per square meter of membrane per hour (l/mh). In all of the trial runs of the pilot systems, the feed flow was set to a specific value, and the speed of the membrane feed pump was automatically adjusted to maintain this value on the feed flow meter. Since the membrane area remained constant at 645 ft<sup>2</sup> (60 m<sup>2</sup>), the flux remained constant during each trial.

### **Experimental Design**

Prior to the study, operation of the existing system had been optimized for both biological and chemical phosphorus removal. In order to evaluate the TP removal capabilities of the UF pilot plant, the operating

parameters for the existing SBR and CMF systems remained the same for the duration of the study; these are shown in Table 1.

Description	Units	Value
SBR Cycles Per Day	No.	4
SBR Mix Fill Phase Time	Min.	50
SBR React Fill Phase Time	Min.	130
SBR React Phase Time	Min.	40
SBR Settle Phase Time	Min.	100
SBR Decant Phase Time	Min.	40
SBR Sludge Waste Time	Min.	16
Aeration Timer #1 TOTAL Time (all SBR blowers)	Min.	65
Aeration Timer #1 ON Time (all SBR blowers)	Min.	45
Aeration Timer #2 TOTAL Time (all SBR blowers)	Min.	65
Aeration Timer #2 ON Time (all SBR blowers)	Min.	45
Aeration Timer #3 TOTAL Time (all SBR blowers)	Min.	40
Aeration Timer #3 ON Time (all SBR blowers)	Min.	40
Aeration Timer #4 TOTAL Time (all SBR blowers)	Min.	0
Aeration Timer #4 ON Time (all SBR blowers)	Min.	0
Aeration Timer #5 TOTAL Time (all SBR blowers)	Min.	0
Aeration Timer #5 ON Time (all SBR blowers)	Min.	0
CMF Backwash Level Setpoint	Inches (mm)	12 (305)
CMF Backwash Timer	Hrs.	4

**Table 1.** SBR/CMF Parameters That Remained Constant During the Study

The pilot study was conducted from November 28, 2012 through December 19, 2012 and consisted of seven (7) separate test periods, each unique according to the aluminum concentration and influent flow/flux applied to the UF pilot (see Table 3).

During each test period, the filtration/backwash sequence consisted of four steps: filtration bottom, backwash bottom, filtration top, and backwash top. The CEB cleaning sequence consisted of seven steps for each of the two chemicals used: backwash top, backwash bottom, chemical introduction top, chemical introduction bottom, soak, rinse top, and rinse bottom. The backwash steps were identical to those used during the filtration sequence, as were the chemical introduction steps only the chemical is injected into the backwash flow. The rinse steps were done to flush the chemical out of the module before returning to the filtration/backwash sequence.

The primary cleaning sequence (CEB1) involved cleaning with caustic first, followed by cleaning with hydrochloric acid; a 5-minute filtration bottom step was placed between the two cleaning sequences to ensure that all of the caustic was flushed out of the module before the introduction of acid to avoid any

issues with isolated overheating. The secondary cleaning sequence (CEB2) involved cleaning with hydrochloric acid only.

Based on both previous pilot experience and inge's recommendations [Koti (2011)], several of the UF pilot parameters remained unchanged throughout the entire experiment (see Table 2).

Description	Units	Value
Filtration Time (Top or Bottom)	Min.	30
Backwash Time (Top or Bottom)	Sec.	30
Fast Flush Time (Top or Bottom)	Sec.	30
CEB1 Frequency	Hrs.	12
CEB2 Frequency	Hrs.	96
Caustic Introduction Top	Sec.	90
Caustic Introduction Bottom	Sec.	45
Acid Introduction Top	Sec.	60
Acid Introduction Bottom	Sec.	20
CEB Soak Time	Min.	15
CEB Rinse (Top or Bottom)	Sec.	40
Filtration Bottom Short Time (between caustic and acid)	Min.	5
Bulk Alum Concentration	%	48.5
Bulk NaOH Concentration	%	20
Bulk HCl Concentration	%	32
Caustic Introduction pH	pH	12.2
Acid Introduction pH	pH	2

**Table 2.** UF Pilot Parameters That Remained Constant During the Study

Table 3 gives the UF influent flow and aluminum concentration during each of the seven test periods. During the study, the aluminum concentration in the UF influent was changed periodically in response to the measured UF effluent TP levels. For instance, the effluent TP remained above the desired level during the first two test periods; therefore, the aluminum concentration was gradually increased until the effluent TP dropped during test period 3. During test period 4, the UF influent flow was increased to see if the effluent TP would stay below the required value; once verified, the aluminum concentration was then reduced gradually to determine the minimum dosage needed to meet the effluent TP requirement at this elevated flow rate (test periods 5 – 7).

Test Period	Al <sup>+3</sup> Concentration in UF Influent, mg/l	Influent Flow to UF, gpm (m <sup>3</sup> /hr)	Membrane Flux, gfd (l/mh)
1	2	13.2 (3.0)	29.5 (50)
2	4	13.2 (3.0)	29.5 (50)
3	8	13.2 (3.0)	29.5 (50)
4	8	21.1 (4.8)	47.2 (80)
5	4	21.1 (4.8)	47.2 (80)
6	2	21.1 (4.8)	47.2 (80)
7	1	21.1 (4.8)	47.2 (80)

**Table 3.** Pilot Test Periods

The UF pilot was operated at each test period for multiple days, and the system pressures, pHs, temperatures, flows, levels, and turbidities were automatically measured and recorded on both the HMI and the unit's personal computer (PC). The following tasks were performed daily:

- Samples were taken at each of the four sampling locations and analyzed.
- Chemical container levels were measured and topped off as needed.
- The influent strainer element was removed and cleaned.

#### ***Analytical Protocol***

Prior to the study, a CMF effluent sample was analyzed for soluble, non-reactive phosphorus (dissolved CP and OP) to determine the minimum effluent total phosphorus achievable.

Each of the four daily samples was analyzed for reactive and total phosphorus by the Aqua-Aerobic Systems, Inc. (AASI) technician at the pilot lab. To make sure the phosphorus values were correct, several of these samples were also analyzed by the City's sister facility, the Camp Branch, AL Wastewater Treatment Plant. Both labs used a Hach DR 2500 spectrophotometer and 45600 COD reactor and performed the analyses in accordance with US EPA Method 365.1 or 365.2, as prescribed by the 22<sup>nd</sup> edition of *Standard Methods for the Examination of Water & Wastewater*.

Total phosphorus analyses were also made on several pilot effluent samples by two independent labs: Lab Resource Systems (LRS) and Guardian Systems, Inc. Both of these laboratories are certified by AL and use an approved spectrophotometer and COD reactor in accordance with US EPA Method 365.1 or 365.2, as prescribed by the 22nd edition of *Standard Methods for the Examination of Water & Wastewater*.

## Results and Discussion

### UF Influent Phosphorus

The CMF effluent sample that was analyzed for soluble, non-reactive (condensed and organic) phosphorus was found to have less than the detectable level (0.02 mg/l) of this form of phosphorus. This indicates that it's theoretically possible to treat the CMF effluent down to non-detectable levels provided nearly all of the reactive phosphorus is converted to its insoluble form and the UF removes all of the remaining insoluble phosphorus.

Table 4 lists the total phosphorus values of the filtered feed to the UF pilot during the study. As you can see, the influent TP varied from 0.0424 to 0.699 mg/l and averaged 0.163 mg/l over the course of the study. The spike in influent TP was due to the installation of a new surface aerator in the post-equalization basin. Upon start-up, the aerator effectively mixed the settled solids, which were subsequently fed to the CMF system.

Sample Date	Sample Type	TP - AASI Analysis	TP - Plant Analysis
11/28/2012	grab	0.170	--
11/29/2012	composite	0.200	--
12/2/2012	composite	--	0.699
12/4/2012	composite	0.116	--
12/6/2012	composite	0.103	--
12/9/2012	composite	0.061	--
12/11/2012	composite	0.111	--
12/13/2012	composite	0.091	--
12/16/2012	grab	0.042	--
12/16/2012	composite	0.137	--
12/18/2012	grab	0.059	--

**Table 4.** Total Phosphorus of the UF Influent, in mg/l

### UF Effluent Phosphorus

Table 5 lists the total phosphorus values of the UF effluent during the study. The effluent TP varied from less than 0.020 (non-detectable) to 0.075 mg/l and averaged 0.023 mg/l over the course of the study.

Another observation was the discrepancy in the results from different labs for the same samples. Upon investigation, the cause of the variance appeared to be the inconsistency with which the samples were handled during both the sampling and the testing procedure. Although the handling methods were appropriate for conventional effluent limits, the extremely low total phosphorus (0.043 mg/l) necessitated extraordinary precautions. Therefore, the EPA guidelines were followed more carefully (i.e., sample bottles were acid-washed, exposure to air was limited,

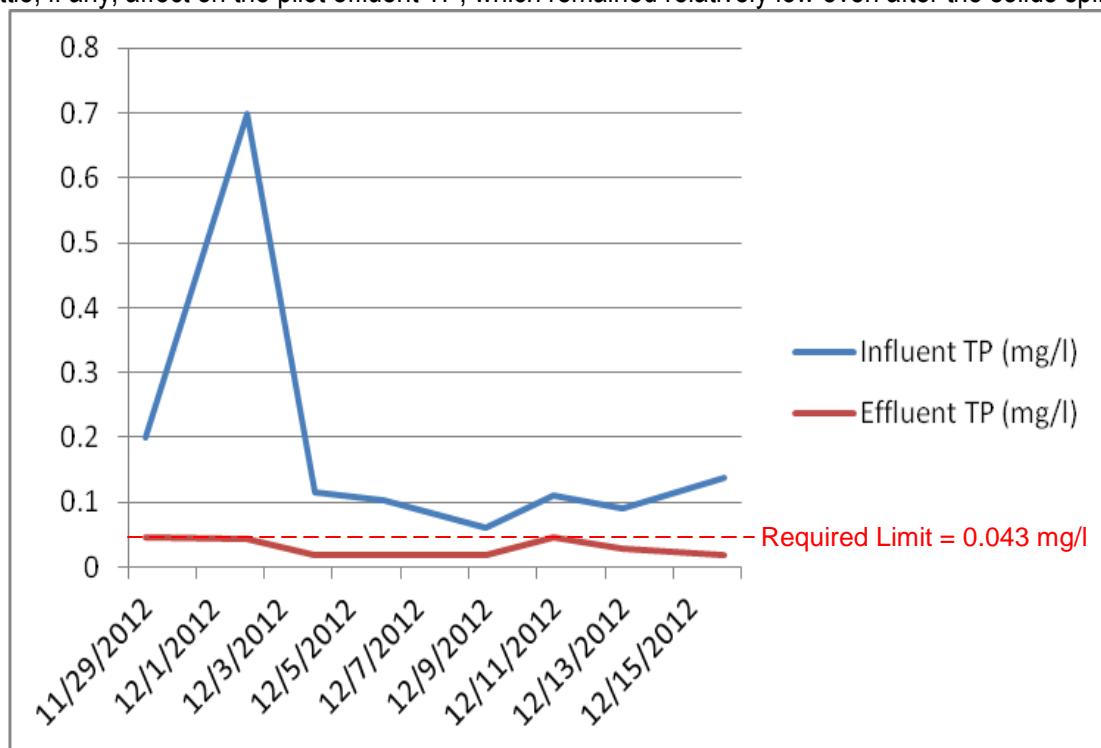
Sample Date	Sample Type	TP - Aqua Analysis	TP - Plant Analysis	TP - LRS Analysis	TP - Guardian Lab
11/29/2012	grab	< 0.020	--	--	--
11/29/2012	composite	0.045	--	--	--
11/30/2012	composite	< 0.020	--	--	--
12/1/2012	composite	< 0.020	--	--	--
12/2/2012	composite	0.043	0.061	--	--
12/3/2012	composite	0.034	--	--	--
12/4/2012	composite	< 0.020	--	0.075	--
12/5/2012	composite	0.038	--	0.050	--
12/6/2012	composite	< 0.020	--	--	--
12/7/2012	composite	< 0.020	< 0.020	--	--
12/8/2012	composite	< 0.020	< 0.020	--	--
12/9/2012	grab	< 0.020	--	< 0.020	--
12/9/2012	composite	< 0.020	--	< 0.020	0.050
12/10/2012	grab	--	--	--	0.050
12/10/2012	composite	< 0.020	--	--	--
12/11/2012	grab	< 0.020	--	--	--
12/11/2012	composite	0.046	--	--	--
12/12/2012	composite	0.026	--	--	< 0.020
12/13/2012	grab	0.059	--	--	< 0.020
12/13/2012	composite	0.029	--	--	--
12/14/2012	grab	0.026	--	--	--
12/14/2012	composite	< 0.020	--	--	--
12/15/2012	grab	0.055	--	--	--
12/15/2012	composite	0.038	--	--	--
12/16/2012	grab	0.029	--	--	--
12/16/2012	composite	< 0.020	--	--	--
12/17/2012	grab	< 0.020	--	--	--
12/17/2012	composite	< 0.020	--	--	--
12/18/2012	grab	< 0.020	--	--	--

**Table 5.** Total Phosphorus of the UF Effluent, in mg/l

samples were preserved properly, etc.); this greater attention to detail resulted in much more consistency among the testing facilities.

## UF Pilot Performance

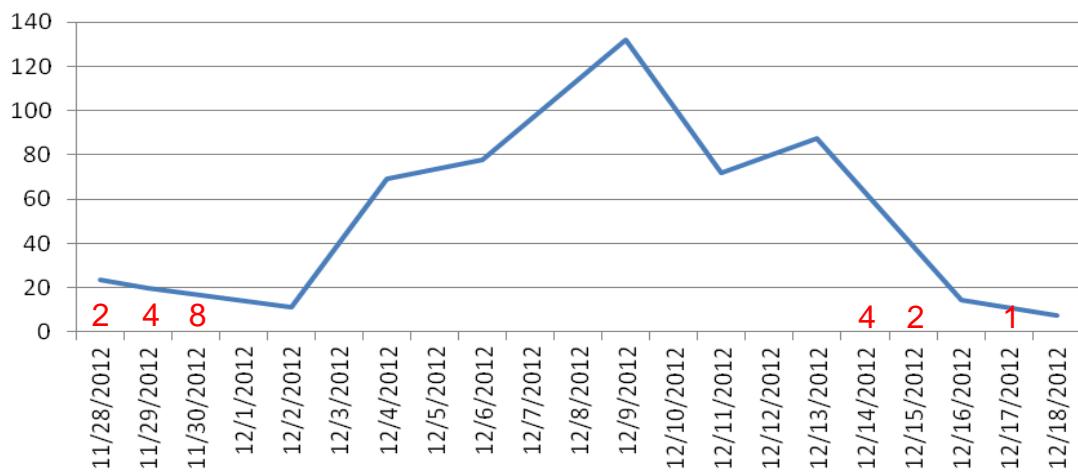
Figure 6 gives a graphical representation of UF performance, showing both influent and effluent total phosphorus values for each day of the study. As you can see, the influent TP excursion on December 2 had little, if any, affect on the pilot effluent TP, which remained relatively low even after the solids spike.



**Figure 6.** Total Phosphorus (TP) Concentrations in UF Influent and Effluent

## Alum Dosage

The alum dosage used during the pilot is shown as a blue line in Figure 7, measured as mg of Al+3 per mg influent TP. The red numbers refer to the Al concentration in mg/l and are placed on the date this concentration was set. The alum concentration was increased early in the pilot study because the effluent TP level was initially higher than the desired 0.043 mg/l. Once the



### **Figure 7. Alum Dosage and Aluminum Concentrations**

effluent TP was consistently below this level, the alum concentration was lowered to make sure the effluent TP didn't go back up. The final concentration (1 mg/l as Al), which equates to an alum dosage of 7.3 mg Al+3 per mg of influent TP, still resulted in an effluent TP below the level detectable with the Hach spectrophotometer (0.02 mg/l). Because of this, it's likely that the alum dosage can be lowered even more without exceeding the 0.043 mg/l limit.

### **Conclusions**

The study showed that the combination of SBR, CMF, and UF was able to consistently lower the total phosphorus (TP) in a domestic wastewater to below the detectable level defined in the standard EPA procedure for TP analysis (0.02 mg/l), even at an elevated flux of 47.2 gfd (80 lmh). The average effluent TP level was determined to be 0.023 mg/l over the course of the study, which included several samples thought to be higher in TP than they actually were due to the accidental introduction of phosphorus into the samples. These ultra-low effluent TP values were achievable in part due to the effectiveness of the existing SBR and CMF systems to remove phosphorus both biologically and chemically down to an average of 0.16 mg/l TP. Yet even at a CMF effluent of 0.7 mg/l, the UF was able to reduce the TP to below the required level of 0.043 mg/l.

The alum dosage needed to achieve a non-detectable TP level in the effluent was found to be as low as 7.3 mg Al+3 per mg of influent TP, even at the higher flux (47.2 gfd, or 80 lmh). Achieving the desired effluent TP level (0.043 mg/l) will require even less alum. For the alum to be this effective, it's critical that the pH of the treated UF influent be kept above 6.5; this makes sure the resultant aluminum phosphate remains as insoluble as possible so it can be removed by the membrane.

Lastly, the importance of using proper and repeatable sampling and testing procedures cannot be overemphasized. At the ultra-low TP concentrations required, even minuscule levels of phosphorus can contaminate a sample and render it out-of-compliance. Verifying that very low levels of TP were indeed being achieved required careful handling of each sample, including acid-rinsing of the sample bottles and avoidance of sample contact with anything that might have even a trace of phosphorus in it.

## References

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