Field Validation of Enhanced Biological Phosphorus Removal (EBPR) in the AquaSBR System

Introduction

In response to growing concerns surrounding water pollution, many wastewater treatment facilities (WWTF) in the U.S. are receiving increasingly stringent discharge permits. As a point source, WWTFs are easier to regulate than non-point sources like agricultural or urban rainfall run-off. First enforced by the EPA under the Clean Water Act of 1972, these permits are now focusing to limit the amount of nutrients discharged to receiving waters and reduce resulting eutrophication outbreaks. This forces wastewater treatment plants (WWTP) to implement biological removal technologies and/or chemical addition when necessary.

Phosphorus is one of the most regulated nutrients for wastewater treatment plants. Reduction of phosphorus can be achieved biologically and by chemical precipitation. Enhanced biological phosphorus removal (EBPR) is a biological nutrient removal (BNR) pathway that is commonly used to meet these strict effluent regulations [11], given its many advantages over chemical precipitation.

Aqua-Aerobic Systems (AASI) has been designing SBR systems since 1984 with over 1,100 AquaSBR systems installed around the world. This study will review the operation of some of these systems and modifications to the operation in order to enhance the biological phosphorus removal capabilities.

Biological Phosphorus Removal in an SBR Process:

EBPR relies on phosphorus accumulating organisms (PAO) to assimilate volatile fatty acids (VFA) using energy derived from phosphate bond cleavage [2] and convert them into polyhydroxyalkanoates (PHA)[1] under anaerobic conditions, followed by the oxidation and metabolism of PHA under a cycling of aerobic/anoxic conditions [17]. The energy released from this metabolism is used to form polyphosphate bonds between the orthophosphates previously released in the anaerobic stage during VFA assimilation [14]. As this energy is considerably larger than the energy used to store the PHA, the uptake amount of phosphorus is expected to be larger than the amount released [4]. This is commonly known as "luxury uptake" of phosphorus. A simplified EBPR concept is shown in figure 1.

[1] VFAs transform into PHAs by using the ATP generated by the hydrolysis of polyphosphate *(Lanham et al., 2013; Xu et al., 2013)*, and the source of reducing equivalents is divided between glycolysis and the TCA cycle depending on sludge characteristics. Glycolysis is likely to be the major metabolic pathway *(Oehmen et al., 2007; Lanham et al., 2013).*

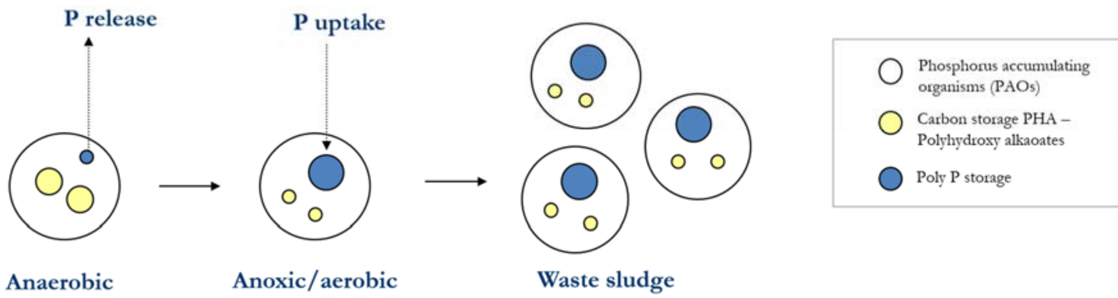

Figure 1. Biological Phosphorus Removal simplified concept

In an SBR system, anaerobic conditions can be found in the mix fill (MF) phase, followed by aerobic/anoxic conditions in the react fill (RF) phase required for luxury uptake of phosphorus. A lesser known fact of the biological phosphorus removal process is that denitrification can help enhance the performance of the system. Since anaerobic conditions are required for EBPR in the SBR system, by removing nitrates prior to the next phase, the system will reach anaerobic conditions sooner, providing more time at the beginning of the cycle for phosphorus release (figure 2). The ability of the SBR technology to create alternating anoxic and aerobic conditions found in the react fill and react phases, allows for conversion of organic nitrogen and ammonia nitrogen to nitrate/nitrite and finally to nitrogen gas.

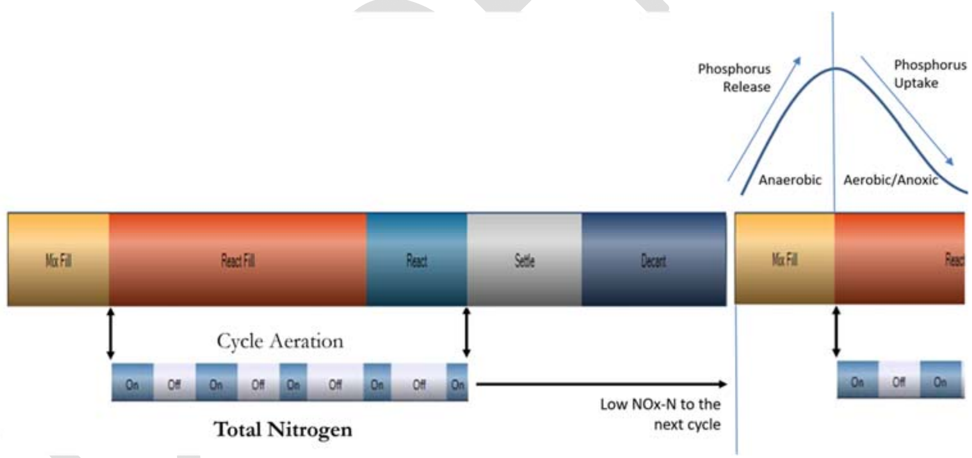

Figure 2. TN removal to improve phosphorus release

Study and Methods

Based on the more stringent requirements around the US, in recent years most of Aqua-Aerobic Systems' biological systems have been designed for BNR. A study of several AquaSBR installations was completed to validate biological phosphorus removal performance, and show how modifications to the cycle structure further enhance this removal with minimal or no additional cost to the facility. The WWTPs included in the study were selected based on current or future permit requirements, operator interest in BNR, geographic location, size, age, and current general operation. A total of sixteen (16) plants were contacted for the study. Ten (10) of the plants provided influent and effluent data to evaluate the performance, and six (6) plants actively participated by willing to modify the operation and perform additional tests (table 1).

Table 1. Active plants participation summary

	Adjustments	Chemical Addition	Nutrient Profile
Cambridge-Oakland WWTF Cambridge, WI	A	N	Y
Canton Borough WWTP Canton Borough, PA	A	N	Y
Clear Lake Sanitary District Clear Lake, IA	P	N	Y
Hutto South WWTP Hutto, TX	AP	N	N
Mt. Pleasant WWTP Mount Pleasant, IA	AP	N	Y
Peterborough WWTF Peterborough, NH	A	Y	Y
A = aeration timers; P = phase timers			

The basis of the study included a combination of lengthening the mix fill phase/anaerobic period at the beginning of the cycle, and lengthening or adding anoxic periods during react fill and react phases to enhance total nitrogen removal. In addition, if the plant was adding chemical to precipitate phosphorus, the addition was discontinued a few weeks before testing or any modification started.

Total phosphorus and orthophosphate were analyzed in the influent and effluent. In addition, most plants profiled the phosphorus concentration throughout a cycle before and after making the changes. This profile was created by sampling and analyzing the phosphorus concentration every 5 to 10 minutes during mix fill, react fill and react phases. These profiles helped validate if the modifications improved the phosphorus release in the anaerobic period, resulting in a larger amount of phosphorus stored in the cellular mass under the subsequent aerobic conditions.

Discussion and Results

Adjustments to AquaSBR time-based structures were implemented for varying durations of time. Periods of several days and in some cases a few weeks were allowed for the biomass at these facilities to acclimate to the changes. The effects of these changes were assessed mainly by repeating the phosphorus profile analyses. Below are the summaries of modifications and the findings for each plant.

Cambridge WWTP, WI

The Cambridge AquaSBR is a dual basin SBR System that was designed for phosphorus removal. The plant receives approximately 4 mg/l TP and averages 0.5 mg/l effluent TP with chemical addition. The current plant permit includes an effluent TP limit of 1 mg/L, but does not include a total nitrogen requirement. Therefore, the operators did not need to setup anoxic times for denitrification and the aeration was on at all times during the react phases, and controlled by a DO sensor.

Chemical addition was interrupted a few months prior to the start of the study and the system continued to safely meet all permit requirements. The average influent BOD:P ratio for this plant is 44:1 and at other times 60:1 due to increased BOD loading from a distillery. The higher BOD:P ratios benefit the BioP removal process.

With a plant that is already doing well on BioP removal due to the BOD:P ratio, we still wanted to see how much more the system could be improved. This plant was a perfect example to validate the impact of denitrification to help on phosphorus removal. Modifications of their cycle structure included adding approximately 40 minutes of anoxic time in order to achieve some denitrification.

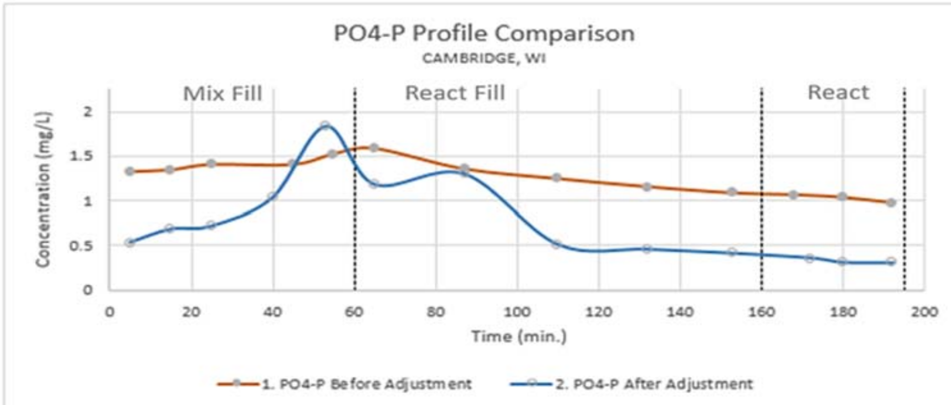

Figure 3. Phosphate profile in the AquaSBR at Cambridge, WI
Before and after cycle modifications

The average phosphorus removal during the first half of 2019 was 85%. After achieving denitrification at the plant, the phosphorus removal increased to above 90%. This is due to the better release of phosphorus with the mix fill phase going anaerobic sooner due to less nitrates in the effluent. Figure 3 shows one cycle with the improved phosphorus release and uptake.

Canton Borough, PA

This plant is a dual basin SBR system designed for nutrient removal. It was designed for an influent BOD of 300 mg/l and TP of 8 mg/l. However, the phosphorus in the influent averages 14.5 mg/l in the influent with an influent BOD5 of 121 mg/l. This results on a BOD:P ratio of 8.3, while BOD:P ratios of over 15 [1] and that COD:P ratios over 40 [14] are favorable for EBPR. This plant did have some removal of phosphorus, however, as expected due to the low carbon, poor release of phosphorus during the anaerobic time was experienced as seen in figure 4.

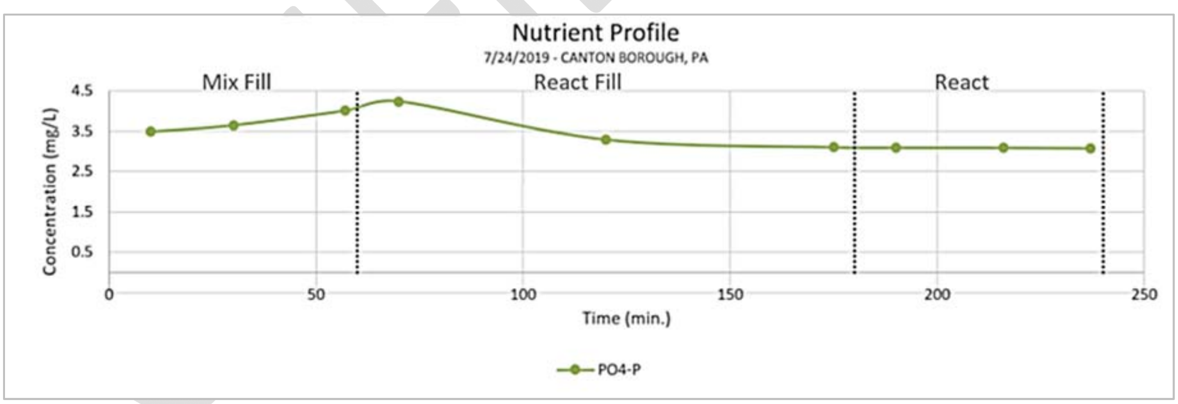

Figure 3. Phosphate profile in the AquaSBR at Canton Borough, PA

The system was already operating with an extended mix fill phase of 60 minutes. Modifications included adding anoxic periods during react fill and react to try to enhance nitrogen removal. However, due to the low influent carbon, there was no appreciable difference on the phosphorus release.

	Influent				Effluent						
	Flow	BOD5	TSS	TP	CBOD	TSS	TKN	NH3-N	NOx-N	TN	TP
	MGD	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
AVG	0.26	121.28	160.00	14.50	3.79	5.38	1.22	0.35	1.45	2.67	5.02

Table 2. Canton Borough AquaSBR performance

The plant is meeting the permit on all parameters even at the lower BOD:P ratios. Based on literature review and experience on other SBR systems in this study, it can be concluded that biological phosphorus removal could be further improved with a higher influent BOD:P ratio.

Clear Lake, IA

Clear Lake Sanitary district has a four basin AquaSBR system. The system was operated on a 3-basin configuration which put the loading to the system at over 100% of design of the influent BOD and TKN. In comparison, phosphorus seemed to be as expected. Since the influent nitrogen concentration was higher than expected, it was not possible to modify the cycles to add anoxic time for denitrification enhancement, but the anaerobic phase at the beginning of the cycle was increased by 10 minutes, as shown on figure 4.

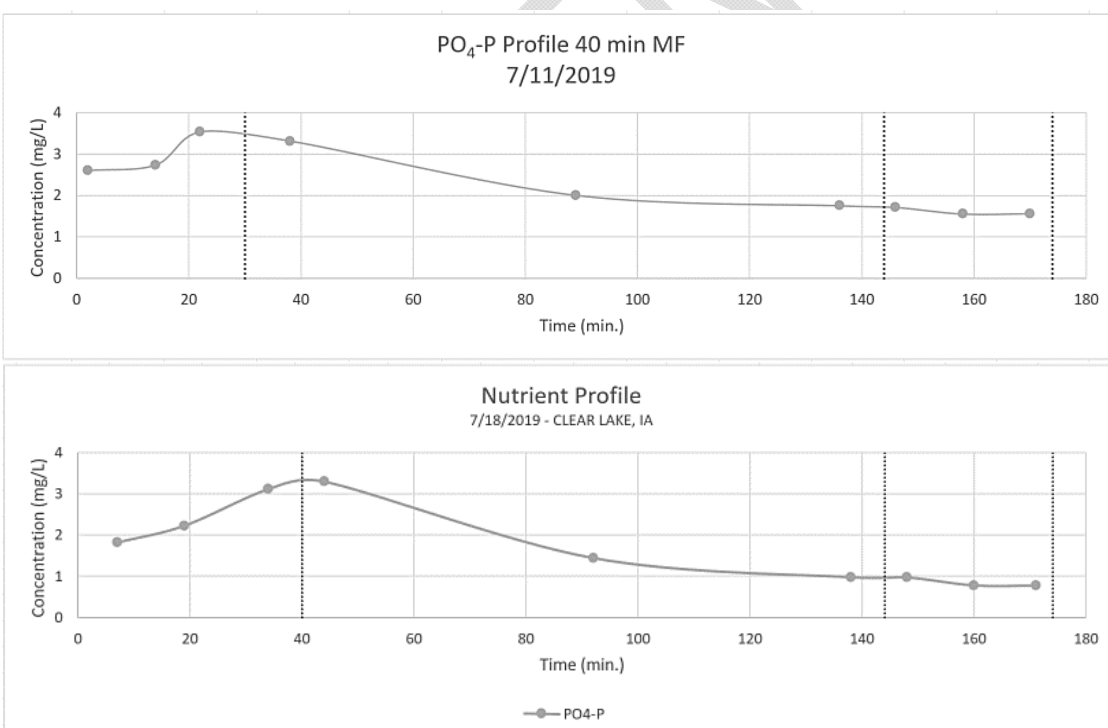

Figure 4. Phosphate profile in the AquaSBR at Clear Lake, IA
4(a) top: 30 min. MF phase and 4(b) bottom: 40 min MF phase

Simply by changing the mix fill phase, an immediate improvement on the phosphorus release can be seen, leading to a significantly higher phosphorus uptake. Release and uptake with 30 minutes mix fill phase reached 0.93 and 1.97 respectively, and with 40 min MF 1.48 and 2.53 respectively. The average effluent total phosphorus throughout the study was approximately 1 mg/l.

Hutto, TX

The Hutto Waste Water Treatment Plant AquaSBR system includes three SBR tanks and at the time of the study it was operating two tanks. The average phosphorus in the influent is 8.6 mg/l with a maximum month of 10.8 mg/l. BOD entering the plant is between 200 and 240 mg/l. This results on a BOD:P ratio of approximately 23. The plant historically has been reducing phosphorus by approximately 30 - 50% in the few months prior to the study.

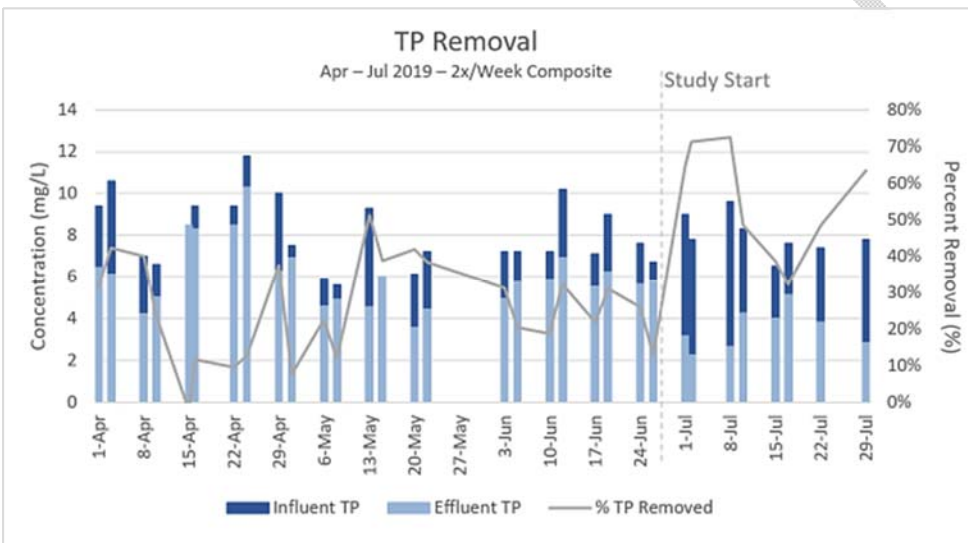

Figure 5. Influent vs. Effluent Phosphorus in the AquaSBR at Hutto, TX

Modifications to the cycle structure were made on June 27th. Anaerobic time was increased by lengthening the mix fill phase from 45 min to 60 minutes. Five minutes anoxic time per cycle was added during the react phases. The results were immediate and a sudden increase on phosphorus removal was noticed as seen on figure 5. The removal showed over 70% in two consecutive sample days, which are significantly higher levels of removal than the previous 5 months. The system responded positively to the changes, even with the low BOD:P ratio experienced. However, some variability on the performance could be seen during the study, which can be attributed to the fluctuation on BOD:P ratio.

Mount Pleasant, IA

This plant is a 4-basin AquaSBR system installed in the year 2000. The plant receives over 80% of the loading and on occasion even over 100% of the design flow and loading. The plant was originally designed for nitrification only and no phosphorus requirement, but the city was interested in testing the nutrient removal capabilities of the plant.

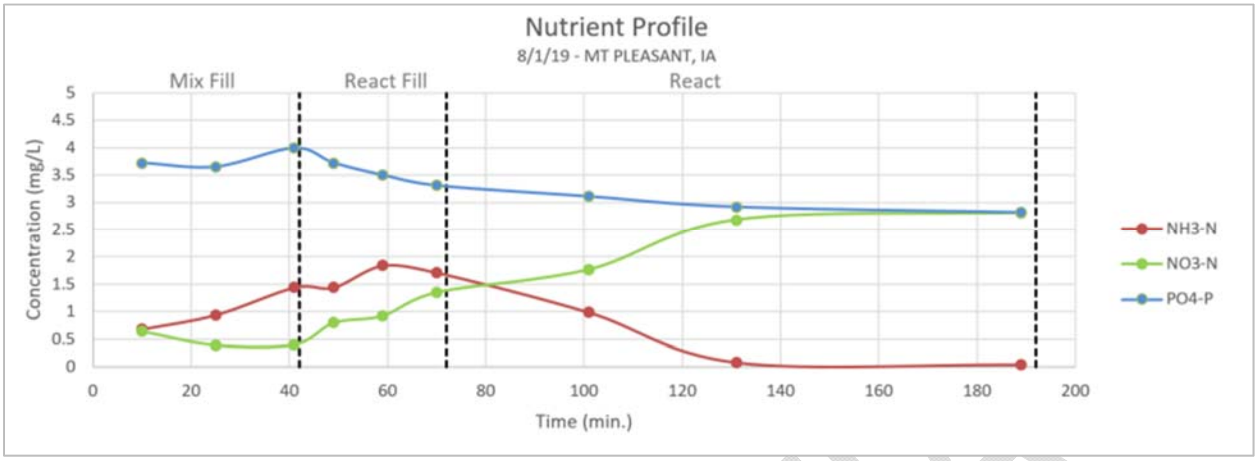

Figure 6. Mount Pleasant AquaSBR Operation 42 min MF and 107 min aeration

Changes were made to increase the anaerobic/mix fill time by 20 minutes, and increase the anoxic time for denitrification during the react phases. As shown in figure 7, this resulted in a better release and uptake of phosphorus. In addition the figure shows the profile of nitrogen with a decrease of the nitrates throughout the cycle compared to the previous operational structure.

Figure 7. Mount Pleasant AquaSBR Operation 62 min MF and 85 min aeration

The modifications of both anaerobic and anoxic time in the SBR at Mount Pleasant resulted in improved effluent phosphorus and nitrogen in the system. Phosphorus removal in 2019 prior to the study ranged from 35 – 55%, and during the study the removal increased to 42 – 62%.

Peterborough, NH

This plant already had an extended anaerobic period with the mix fill phase at 60 minutes and it was achieving great phosphorus removal, but the operator wanted to see how much more the system could be optimized. The only modifications were to the aeration timers during the react phases. Times were modified to add more anoxic time in two separate occasions.

Coagulant was being added prior to the study to precipitate phosphorus. Operators stopped adding chemical 10 days prior to the first phosphorus profile, shown in green on figure 8. At the end of the cycle the PO4-P was approximately 0.45 mg/l. After the aeration time changes, another phosphorus profile was performed, a week later. The effluent shows slight improvement on the PO_4-P, shown in red on figure 8, but the general trend is similar on both scenarios. It was determined that the plant was well optimized for biological phosphorus removal.

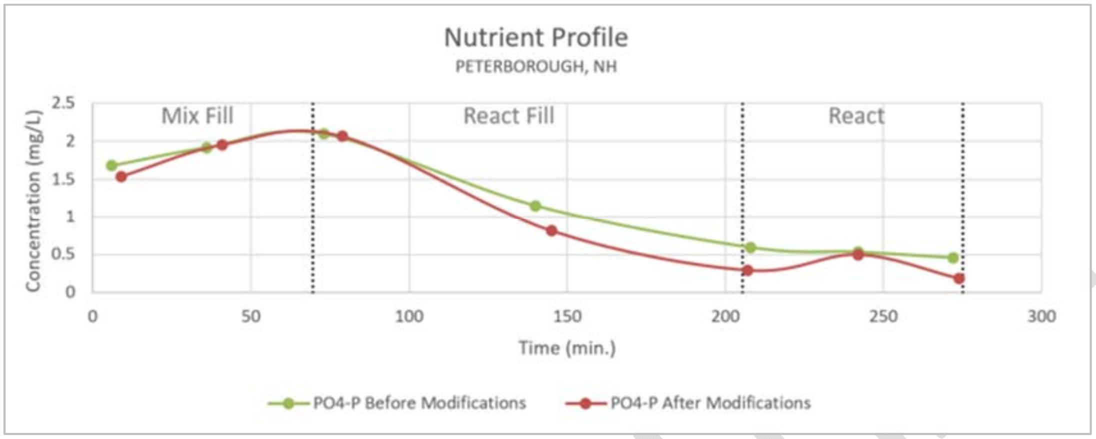

Figure 8. Peterborough AquaSBR operation before and after modifications

<u>AquaSBR Pilot Unit</u>

As part of Aqua-Aerobic Systems' Research and Development and internship programs, a 300 gallon AquaSBR pilot unit was setup at the Rock River Water Reclamation District (RRWRD) in Rockford, IL. The plant was setup for 5 cycles per day and was operated on different testing conditions. Daily composite samples were taken in the influent and effluent for two months of operation.

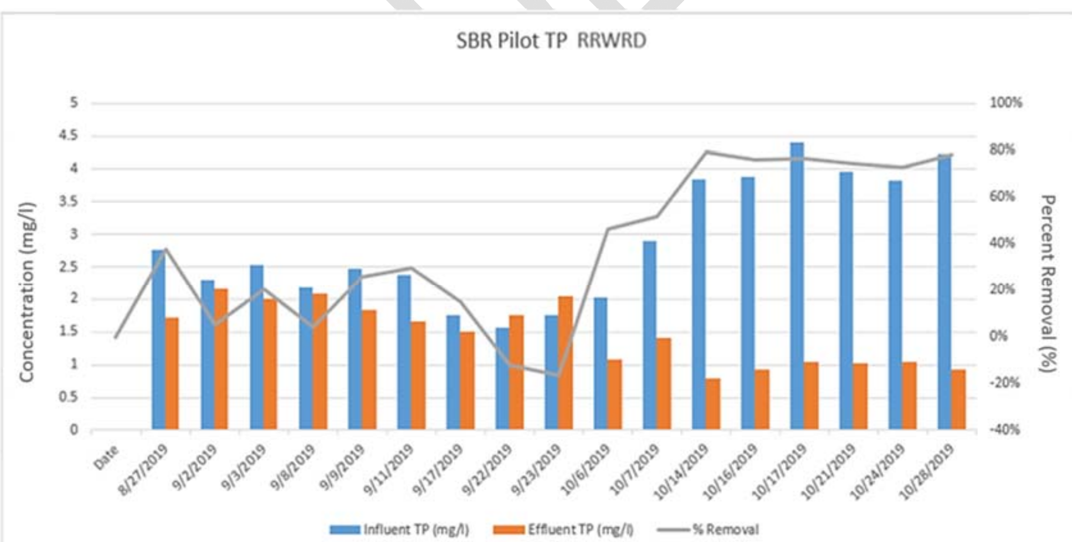

Figure 9. Phosphorus Removal Performance on AquaSBR Pilot Unit at RRWRD

In the first month shown in figure 9, low performance can be seen on phosphorus removal with an average of 20% removal. This was due to not wasting sludge in an attempt to build up the mixed liquor in the system which was part of this particular study. Biological phosphorus removal incorporates phosphorus into the bacteria, in addition solids contain particulate organic phosphorus. When solids wasting was started on the second month, as shown in figure 9, phosphorus removal increased significantly, with a consistent removal of approximately 80%, even though the influent TP increased during this time.

Conclusions

These case studies demonstrate various methods that can be used within the AquaSBR process to maximize nutrient removal. In most cases, these improvements were made simply by modifying phase times. This flexibility is one of the major advantages of the time-based approach used in the AquaSBR process. While there are variables that are outside of the operator's control in a full-scale plant, such as influent composition and proportion, temperature, regional weather, etc., the AquaSBR provides the flexibility of modifying the cycle times, which gives the operator a way to control the in-basin environment as required for treatment.

This study aimed to validate the phosphorus removal performance for several AquaSBR systems, by modifying the anaerobic and anoxic times in the system to validate the positive impact on biological phosphorus removal.

This study demonstrated that:

- Extending the anaerobic period during the mix fill phase yields better biological phosphorus release and subsequent luxury uptake.
- Adding or extending anoxic times to achieve denitrification will result in lower nitrate content in the bulk liquid, promoting anaerobic conditions sooner in the next cycle, therefore earlier phosphorus release.
- Carbon to phosphorus (C:N) ratios affect the performance of biological phosphorus removal. At low ratios (<25:1) biological phosphorus removal is possible but may not be consistent.
- Proper sludge wasting is important to achieve lower effluent phosphorus.

Future Work (What's Next)

Based on this work and the findings, AASI is currently working on studying advanced biological phosphorus removal technologies to meet even lower effluent phosphorus biologically, as well as meeting consistent effluent TP on weak wastewater with low C:N ratios. This work includes how MLSS fermentation/side-stream EBPR (S2EBPR) may further enhance biological phosphorus removal. Additionally, the study will incorporate monitoring and control of the system based on instrumentation, such as oxidation-reduction potential (ORP) to determine how to optimize the phosphorus removal performance.

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