OBTAINING VERY LOW NUTRIENT LEVELS USING A BATCH MBR WITH MINIMAL CHEMICAL ADDITION

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Abstract

As a result of the Chesapeake Bay Watershed Initiative (CBWI) of 2010, many of the wastewater treatment plants discharging to affected waterways have been required to meet progressively lower effluent nitrogen and phosphorus levels. In addition, many of these same plants have experienced growth in the communities they serve and need increased hydraulic and organic capacity as well. This combination is best satisfied with a membrane bioreactor (MBR) system, which produces excellent effluent quality and higher capacity with minimal changes to the existing infrastructure. A special type of MBR system – one that operates in a batch mode – has been used to achieve very low effluent nutrient levels with less carbon and coagulant addition than standard MBRs.

One example of this is the expansion of the wastewater treatment plant in Shepherdstown, WV. After 32 years as a conventional extended aeration plant with no effluent nutrient requirements, this facility was handed its first set of nitrogen and phosphorus discharge limits – 3 mg/l total nitrogen and 0.3 mg/l total phosphorus - in order to comply with the CBWI. In addition, growth in the surrounding community demanded the plant increase its capacity from a peak flow of 0.8 MGD to 2.2 MGD. To meet the lower nutrient limits, nearly triple the flow through the existing tanks, and minimize the increase in operating costs, the Town chose to go with a batch MBR process. The system was designed and constructed, and placed on-line in the Spring of 2012.

Since being placed in service, the system has consistently achieved less than 3 mg/l TN and has obtained effluent TP values as low as 0.055 mg/l, both with much less chemical than that used in flow-through MBR systems. This paper evaluates the plant data gathered over the last two years and details several reasons why the plant is performing so well with so little chemical addition.

Project Background

Existing Facilities

The Town of Shepherdstown is on the very eastern-most tip of West Virginia, as shown below in Figure 1. The town presently has about 1,200 permanent residents and about 4,400 students – 4,200 are undergraduates and another 200 are seeking post-graduate degrees. The Town owns and operates the wastewater treatment plant, where wastewater from the township – mostly domestic - is treated prior to disposal into the adjacent Potomac River. The plant was brought on-line in 1978, when it was permitted for an average daily flow (ADF) of 0.4 MGD (1,515 m3/day) and a maximum daily flow (MDF) of 0.8 MGD (3,030 m3/day). Just prior to the expansion, the plant was treating summer flows of approximately 0.3 MGD (1,140 m3/day) ADF and 0.43 MGD (1,630 m3/day) MDF, and school-year flows of about 0.375 MGD (1,420 m3/day) ADF and 0.69 MGD (2,615 m3/day) MDF.

Figure 1. Location of Shepherdstown WWTP

As shown in Figure 2, the treatment process consisted of a main pump station, coarse screen, (2) aeration basins, (2) clarifiers, chlorine contact tank, and a cascade aeration outfall structure. Waste solids were pumped from the clarifiers, treated in an aerobic digester, and sent to drying beds for dewatering. Digester supernatant was transferred back to the headworks. Sodium bisulfite was added to the outfall to remove any free chlorine prior to discharge in the river.

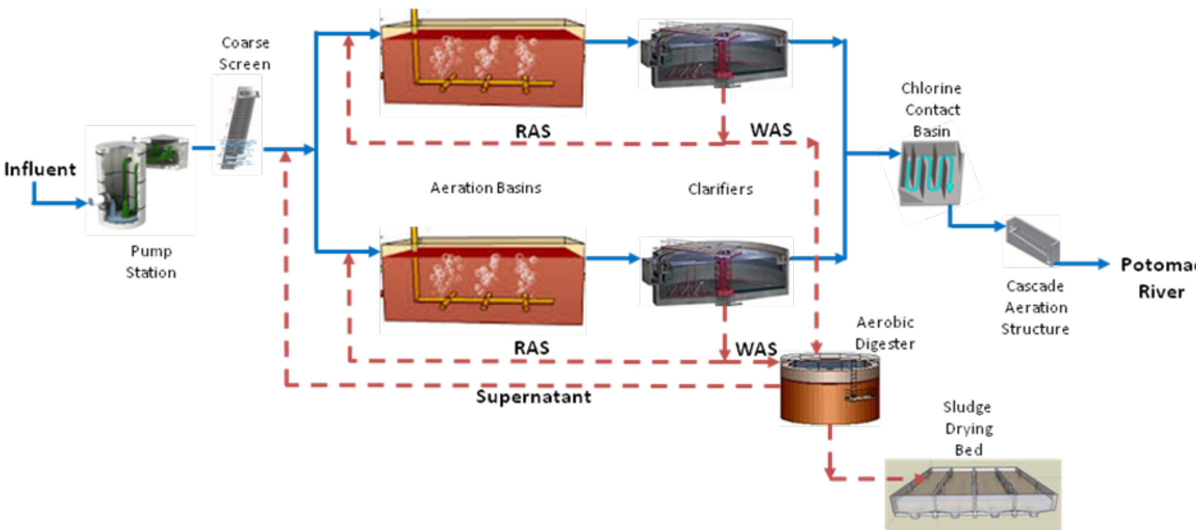

Figure 2. Existing WWTP Layout

Potential Issues with the Existing Design

Because the plant's original discharge permit didn't limit the amount of nutrients in the plant effluent, there were no anaerobic or anoxic zones – only aeration zones. Since low-pressure air was used for both aeration and mixing of the two aeration basins, the air flow could only be throttled to a certain level without running the risk of solids settling on the basin floor. Therefore, during periods of low flow (i.e., during the summer months), much more air was used than was needed for biological treatment, which resulted in higher energy costs and risked the poor settling that often accompanies over-aeration. The lack of an anaerobic zone increased, at times, the population of filamentous bacteria, and periodic chlorination was needed to minimize the filaments and improve settling in the clarifiers.

The high levels of nutrients being discharged to the Potomac River - and eventually reaching Chesapeake Bay – contributed to several issues that occurred in these waterways over time. Excessive phosphorus was causing a condition known as eutrophication, in which the nutrient creates an overabundance of blue-green algae (cyanobacteria) and a subsequent depletion of dissolved oxygen and the marine life that requires it [Kahn and Mohammad (2014)]. In addition, elevated ammonia and nitrate concentrations in the river and bay were approaching levels toxic to many of the fish species that live there. And it wasn't just the marine life that was affected: drinking water supplies with over 10 mg/l nitrates were responsible for a serious sickness called Methemoglobinemia, also known as Blue Baby Syndrome, in which red blood cells can't release as much oxygen as they need to into the body's cells. The map in Figure 3 shows the areas in the U.S. that have the highest probability that the nitrates in their drinking water exceed 4 mg/l; note that the Chesapeake Bay area is one of the several "hot spots" [Nolan (2002)].

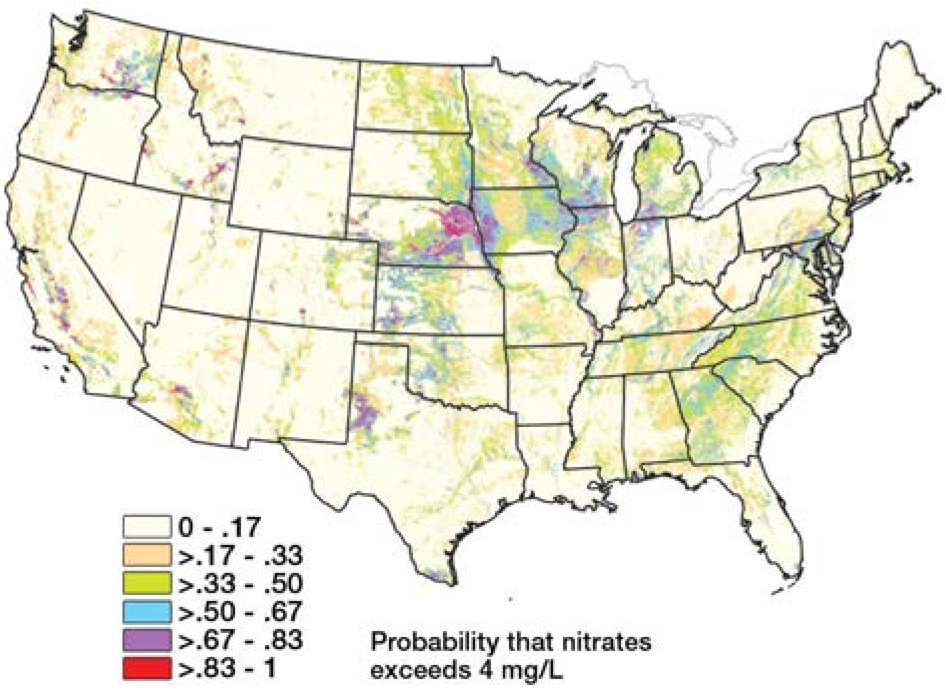

Figure 3. Areas in the U.S. with High Nitrates in their Drinking Water

New Permit Requirements
In response to these issues, the Chesapeake Bay Initiative of 2010 was enacted, requiring the Bay and its connecting waterways to maintain phosphorus and nitrogen concentrations below prescribed levels. As the Shepherdstown plant's NPDES permit approached its 2010 expiration date, the WV Department of Environmental Protection (WVDEP) announced their intention to add effluent nutrient requirements to the upcoming permit. These limits would be in the form of Total Maximum Daily Loads (TMDLs) such that the daily discharge of each nutrient must stay below the specified total amount regardless of the flow. The required TMDLs were set at 20 lbs/day for total nitrogen (TN) and 2 lbs/day for total phosphorus (TP), which equated to 3 mg/l

TN and 0.3 mg/l TP at the new ADF of 0.8 MGD; however, these concentrations would have to be 1.1 mg/l TN and 0.1 mg/l TP at the new MDF of 2.2 MGD in order to stay under the permitted TMDLs.

Plant Improvements

Nitrogen Removal

The WWTP was now faced with the challenge of removing nitrogen to levels below 3 mg/l TN. While they had some success converting the ammonia in the wastewater into nitrate – a process known as nitrification – they would now have to remove the nitrogen completely (denitrify) by converting the nitrate into nitrogen gas, which gets released into the atmosphere. To do this would require an additional step in their activated sludge process – an anoxic zone, where dissolved oxygen is depleted to the point in which the system's microorganisms use the oxygen in the nitrate instead. Figure 4 below shows the complete nitrogen removal process within an activated sludge system.

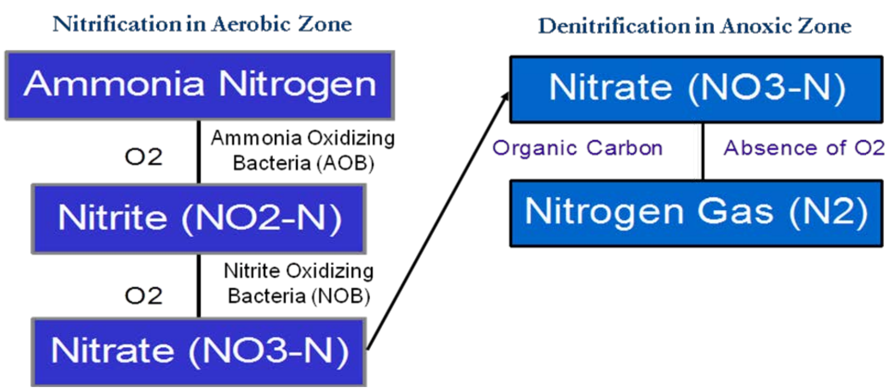

Figure 4. Nitrogen Removal Process in Activated Sludge

As noted in the figure, complete nitrogen removal requires dissolved oxygen (O2), Ammonia Oxidizing Bacteria (AOB), Nitrite Oxidizing Bacteria (NOB), organic carbon, and an anoxic zone void of O_2. To cultivate healthy AOB and NOB in the system, the sludge age – or solids retention time, SRT – must be longer than for most of the other bacteria in the system; during the colder Shepherdstown winters, this should be at least 7 days. In addition, the lower the desired nitrogen level, the more organic carbon will be needed; at levels below 5-6 TN, the amount of carbon left in the wastewater after it has been oxidized in the aerobic (nitrification) zone is typically not enough, and supplemental carbon must be added.

Phosphorus Removal

Phosphorus removal occurs two ways in an activated sludge system - biologically and/or chemically – both of which are followed by some type of settling and/or filtration. Attaining the 0.3 mg/l TP required at average flow will probably require both methods. To achieve biological phosphorus removal (BPR), the plant would have to include a second additional step to the process – an anaerobic zone completely depleted of available oxygen (including nitrates). In this zone, special bacteria called Phosphorus Accumulating Organisms (PAOs) release phosphate (PO_4) into the reactor to obtain the energy they need to consume volatile fatty acids (VFAs, such as acetic acid) and store them in the cell as poly-L-hydroxyalkanoates (PHA); this process is illustrated on the left side of Figure 5. Then, when oxygen is reapplied within the aerobic zone, these same bacteria are capable of consuming excessive amounts of PO_4, including that contained in the influent wastewater; this process is known as "luxury uptake" (shown on the right). In a typical BPR system, 3-5% of the biomass will be made up of phosphorus.

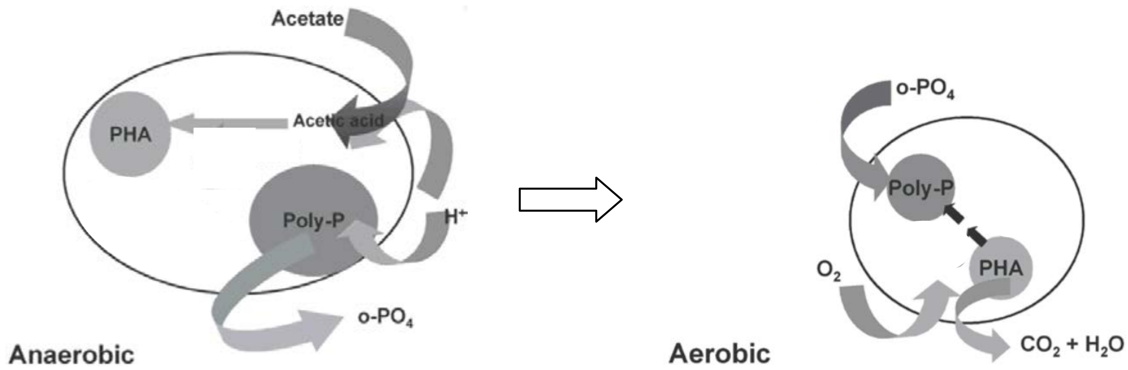

Figure 5. Phosphorus Removal Process in Activated Sludge [Seviour (2003)]

As indicated, biological phosphorus removal requires PAOs and an anaerobic zone containing VFAs followed by an aerobic (O_2-laden) zone. To cultivate healthy PAOs, the SRT should be even longer than that used for nitrification, typically between 15 and 25 days. To make sure there are enough VFAs in the anaerobic zone, this step is usually performed first in the process so that the VFAs in the raw wastewater can be used.

For a BPR system to be effective, it's not enough for the biomass to remove most of the phosphorus from the wastewater; the final effluent must have in it as little biomass as possible, measured as total suspended solids (TSS). This is accomplished by clarification and/or filtering. Table 1 shows the effluent phosphorus (P) that corresponds to four different effluent TSS values, assuming 3-5% of the TSS is P and there is no soluble P left in the water. The table also shows the technologies that are typically used to achieve these values. Because the Shepherdstown plant must achieve TP values as low as 0.1 mg/l (at MDF), it made sense that they seriously consider installing a microfiltration (MF) or ultrafiltration (UF) low-pressure membrane system.

Table 1 Correlation between Effluent TSS and P in BPR Systems

	Effluent TSS (mg/l)	P in Effluent TSS (mg/l)
	15	0.45 - 0.75
Clarifier →	10	0.3 - 0.5
Tertiary Filter →	5	0.15 - 0.25
MF/UF →	2	0.06 - 0.10

Chemical phosphorus removal, on the other hand, is accomplished by adding a metal salt to the influent or aeration basin. This chemical reacts with the phosphate in the water to form a compound that is only slightly soluble such that most of it can be removed through subsequent settling and/or filtering. For instance, the iron in ferric chloride will react with the phosphate in the water to form ferric phosphate, which is almost completely undissolved at pHs between 6.8 and 7.4 (refer to Figure 6).

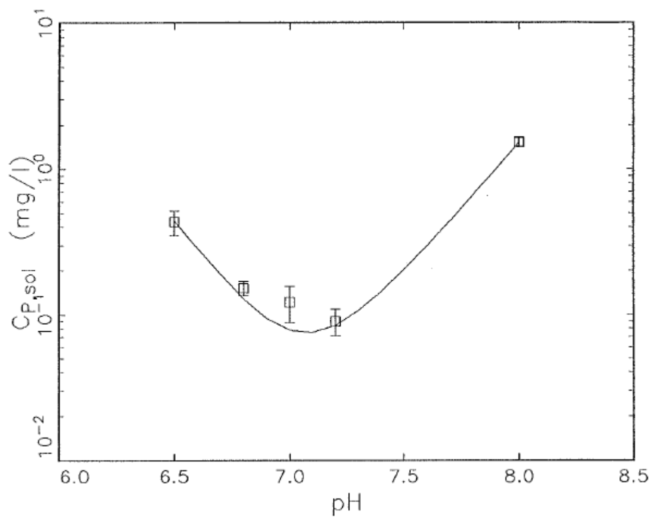

Figure 6. Solubility of Ferric Phosphate in Water [Jenkins (1991)]

Capacity Increase
The Shepherdstown plant had at least three options for increasing the plant throughput to double the ADF and nearly triple the MDF:

1. Add 2 -3 more aeration basins and clarifiers, making them identical to the existing equipment.
2. Convert the existing suspended growth activated sludge system to some type of fixed-growth system, which would allow the existing aeration basins to handle the increased loading. This option would require the addition of 2 -3 more clarifiers identical to the existing clarifiers.
3. Convert the existing system to a membrane bioreactor (MBR) system, which would allow the existing aeration basins to handle the increased loading. In this option, the existing clarifiers would no longer be needed as the membranes would filter out all of the solids.

Other Considerations
Besides the new flow and effluent requirements, the Town used several additional criteria to determine how to expand their plant:

- Footprint – the expanded system should have as small of a footprint as possible, which meant reusing as much of the existing structures and equipment as was practical.
- Chemical Usage – the effluent nutrient limits should be met with as little supplemental carbon and metal salt addition as possible.
- Flexibility – the system should be flexible to handle the large swings in hydraulic and organic loadings that occur due to the large difference between summer and school-year flows.
- Ease of Operation – the existing system was fairly simple to operate, and the Town wanted the same from the expanded system.

Selected System

After looking at the various options, the Town and their engineer, Chapman Technical Group, chose to go with an MBR. This would allow them to not only meet the upcoming nutrient limits, but also to achieve the increased capacity in the existing aeration basins without adding several more basins or clarifiers, thus achieving their goal of a small footprint. The only choice remaining, then, was to the type and brand of MBR that would best meet all of their criteria - including low chemical usage, high flexibility, and simple operation – and do so economically.

By early 2010, the town had narrowed the choice down to two specific hollow-fiber MBR systems, one a flow-through system and one a batch system. The construction contract went out for bid in July, and was awarded to Alvarez Contractors in September. Alvarez chose to go with the batch system, the Aqua-Aerobic® MBR, and the system was procured, installed, and started up by May of 2012.

In the batch configuration, only one of the two system bioreactors receives the flow of raw wastewater, while the biomass in the second bioreactor is continuously recirculated through four membrane tanks, with high-quality permeate pulled through the hollow-fiber membranes using vacuum pumps (refer to Figure 7). The recirculation flow is designed to keep the biomass concentration in the membrane tanks from getting too high (> 12,000 mg/l), which lowers the flow through the membrane and could result in irreversible fouling.

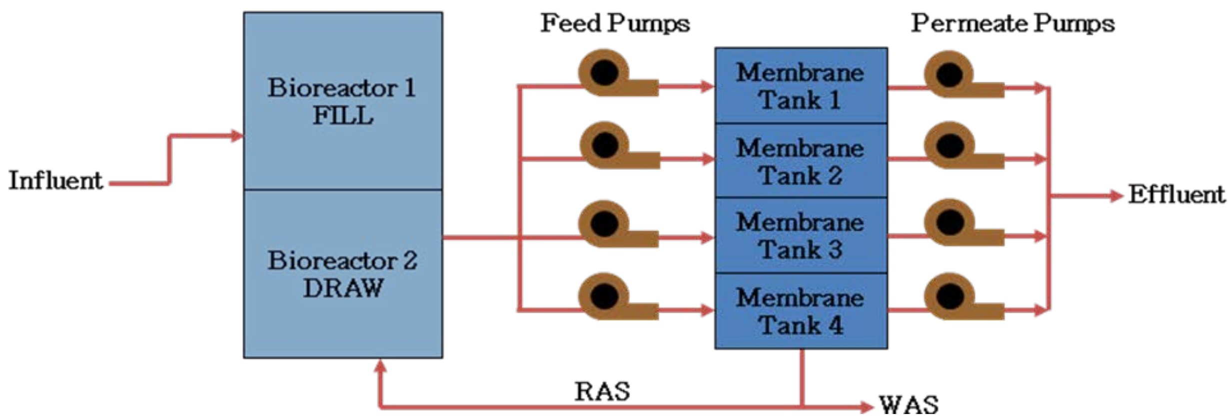

Figure 7. First Half-Cycle of Batch MBR Operating Sequence

Mixers in the bioreactors keep the contents continuously agitated, while the aeration system in each basin is throttled to maintain a residual dissolved oxygen of 2 mg/l during the aeration steps and turned off periodically to achieve anoxic and anaerobic conditions. If needed, carbon and/or alum are added to each bioreactor near the end of its Fill step after the system has removed the bulk of the nutrients biologically. To maintain the sludge age that is optimum for nutrient removal, waste activated sludge (WAS) is occasionally removed from the trough that returns the recycled activated sludge (RAS) to the bioreactor that is feeding the membrane tanks. Timers in the programmable logic controller (PLC) are used to set the duration of the anaerobic, aeration, and anoxic steps to obtain the desired effluent quality.

The batch MBR operating sequence is made up of two timed half-cycles, each set for 1.2 hours at influent flows up to the MDF of 2.2 MGD. After the first half-cycle times out, the second half-cycle begins, in which the bioreactors alternate steps; mixed biomass will now be drawn from Bioreactor 1 and recirculated through the membranes, and raw wastewater will begin to fill Bioreactor 2 (refer to Figure 8). Once the second half-cycle times out, the entire cycle will be repeated.

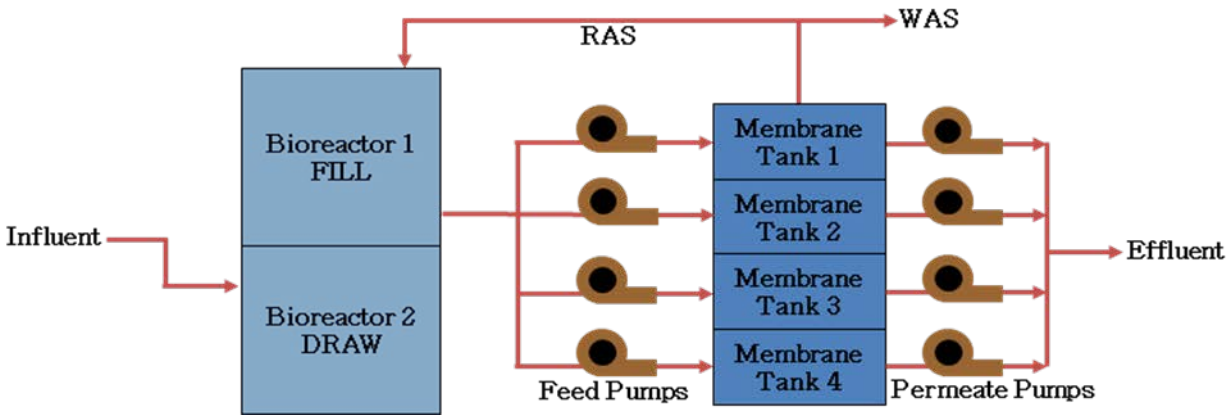

Figure 8. Second Half-Cycle of Batch MBR Operating Sequence

Each of the four membrane tanks contains (5) submersible 500 m^2 ultrafiltration (UF) modules. Each module contains thousands of hollow fibers constructed of polyvinylidene diflouride (PVDF) that filter the wastewater using an outside-to-inside flow path, enabling the membrane to handle solids concentrations as high as 14 g/l (refer to Figure 9).

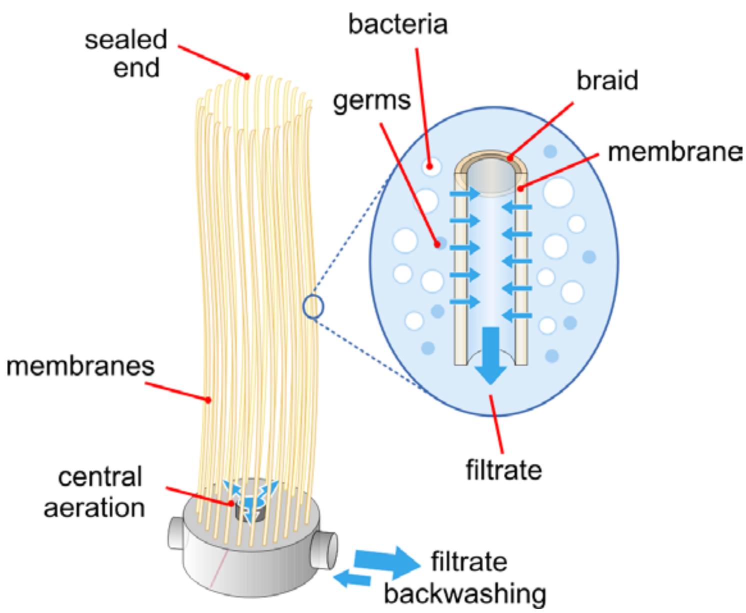

Figure 9. Hollow-Fiber Bundle in the Batch MBR

Air is injected into the middle of each fiber bundle to keep the solids from plugging the membrane. The fibers are vertical with sealed, free-floating tips at the top end to minimize the collection of hairs and other debris. These two features make the membranes very resistant to fouling and sludging; therefore, air scour need only be alternated between the four membrane tanks under most conditions. To maintain low trans-membrane pressures (TMP), the permeate flow is occasionally reversed to backwash the membrane pores, cleaning out solids not being removed by the air scour. A small dose of sodium hypochlorite is injected daily into the backwash flow to remove organic foulants and disinfect the membrane. About once every quarter, citric acid is injected to control inorganic fouling.

Another feature that is unique to the batch system is the ability to turn off all of the membrane pumps and blowers during bioreactor anoxic conditions at flows less than ADF. On flow-through MBRs, the RAS is continuously recirculated back to the bioreactors, even during low flows; because the oxygen in the RAS (from the air scouring of the membranes) will disrupt the anoxic zone, a separate pre-anoxic zone must be used on flow-through systems to allow the biomass to consume the oxygen in the RAS prior to the anoxic zone. This extra zone is not required for the batch system, as illustrated in Figure 10.

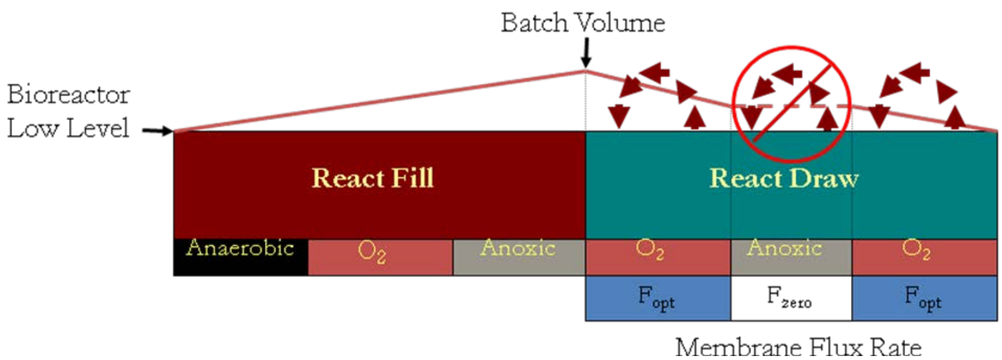

Figure 10. Batch MBR Steps at Flows below ADF

In this scenario, the permeate pumps will be set for the optimum flux (F_{opt}), which is the flow needed to treat a batch at ADF. Because the influent flow is below ADF, there will be a period of time that the permeate pumps turn off – flux will be zero (F_{zero}) – as well as the air scour blowers and the feed pumps. The PLC will time this no-flow (relaxation) period with the anoxic zone in the bioreactor, since there is no RAS flow (shown as red arrows) and, therefore, no oxygen returning to the bioreactor that could inhibit the ability to achieve a true anoxic condition.

Results and Discussion

Effluent Nutrient Levels

During 2013 and 2014, the batch MBR system consistently produced an effluent with nutrient levels below the permitted TMDL requirements, with only a few minor excursions in total nitrogen. The average TMDL for this period was 12.4 lbs/day TN and 0.48 lbs/day TP, which are 38% and 76% below their required TMDL, respectively. As of this writing, the single best month was May of 2014, which produced the results shown in Table 2. The TMDLs for this month were 3.3 lbs/day TN and 0.13 lbs/day TP.

Table 2 System Performance for May 2014

PARAMETER	INFLUENT	EFFLUENT
Average Flow, May 2014 (MGD)	0.2765	0.2765
Average Monthly BOD_5 (mg/l)	233	1.4
Average Monthly TSS (mg/l)	150	< 1.5
Average Monthly TN (mg/l)	27	**1.43**
Average Monthly TP (mg/l)	4	**0.055**

To accomplish this, the system has been operated to achieve low nutrient concentrations during the highest-flow season (when the university is in session) and higher nutrient concentrations during the lowest-flow season (summer months). Figures 11 and 12 show this "tailored water" approach, where the anoxic/anaerobic time and carbon/alum dose can be tailored (adjusted) to achieve the desired nutrient concentrations and TMDLs for each particular season.

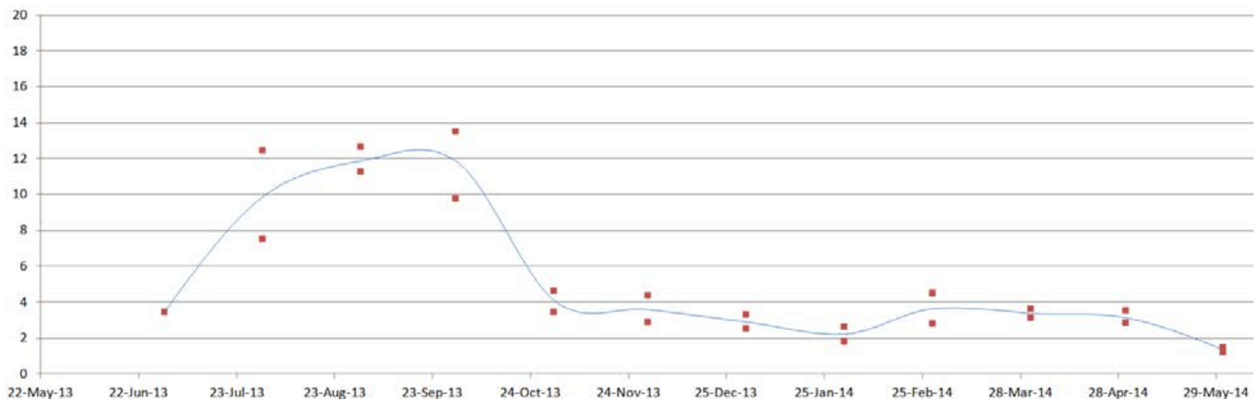

Figure 11. Effluent TN Concentrations Tailored to Achieve Required TMDL, mg/l

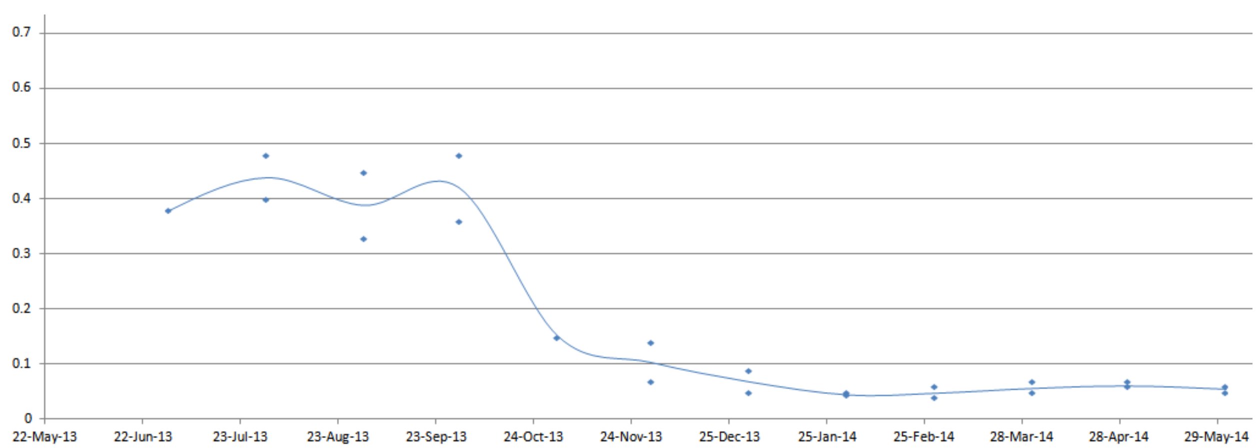

Figure 12. Effluent TP Concentrations Tailored to Achieve Required TMDL, mg/l

During the summer, less chemical can be added to the system and the aerobic time can be lengthened, resulting in a savings in both chemical expense and blower energy costs. The figures show the effluent nutrient concentration plotted for a one-year period, with two data points for each month and a curve showing the approximate monthly average values.

There are several reasons for the system's success in nutrient removal:

1. No "short-circuiting" – as shown earlier in Figures 7 and 8, the contents of the bioreactor in its Fill step are not being recirculated through the membranes; therefore, there is no possibility of the nutrients in the raw wastewater getting into the membrane permeate.
2. Multiple anoxic "zones" – the mixing and aeration equipment in each bioreactor are separate from each other, such that anaerobic, aerobic, and anoxic conditions can be achieved in each basin simply by leaving the mixer running and turning on and off the aeration blowers. Blower timers in the PLC allow the system to alternate between aerobic and anoxic periods up to five different times, allowing the total nitrogen level in the basin to drop lower than for flow-through systems with one or two anoxic basins.
3. Adjustable anaerobic, aerobic, and anoxic "volumes" – because these functions all occur in the same basin, their retention volumes can be adjusted with timers in the PLC, something that's not possible with the fixed-volume basins on a flow-through system. Figure 13 shows the relative concentrations for nitrate-nitrogen (NO_3-N) and phosphate-phosphorus (PO_4-P) during consecutive steps in the batch cycle, as well as the oxidation-reduction potential (ORP) of the wastewater. The graph shows that the P in the basin is still climbing at the end of the anaerobic step; therefore, extending this step will probably increase the phosphorus released and ultimately decrease the effluent P.

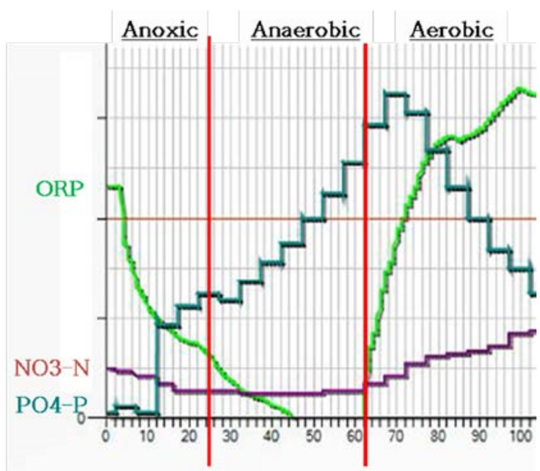

Figure 13. Relative Nutrient Concentrations During Consecutive Steps in the Batch MBR

4. Effective Chemical Usage – Carbon and alum are added to the system when and where they can be most effective. The best strategy for this is to remove as much of the nutrient as possible/practical prior to adding the chemical; not only does this result in lower chemical usage, but also in lower effluent nutrient levels.

   Each chemical will enable removal of a certain percentage of the nutrient in the basin; the lower the initial nutrient level, the lower the final nutrient level. For instance, if alum addition at a specific alum:P ratio will leave soluble only 10% of the phosphate in the basin, and the initial phosphate level is 4 mg/l, the final phosphate level will be 4 x 0.1, or 0.4 mg/l. If, however, BPR has lowered the basin phosphate to 1 mg/l prior to alum addition, the final phosphate level will be 1 x 0.1, or 0.1 mg/l. Figure 14 shows where in the batch MBR cycle biological nutrient removal (BNR) occurs, as well as when in the cycle are the best times for chemical addition.

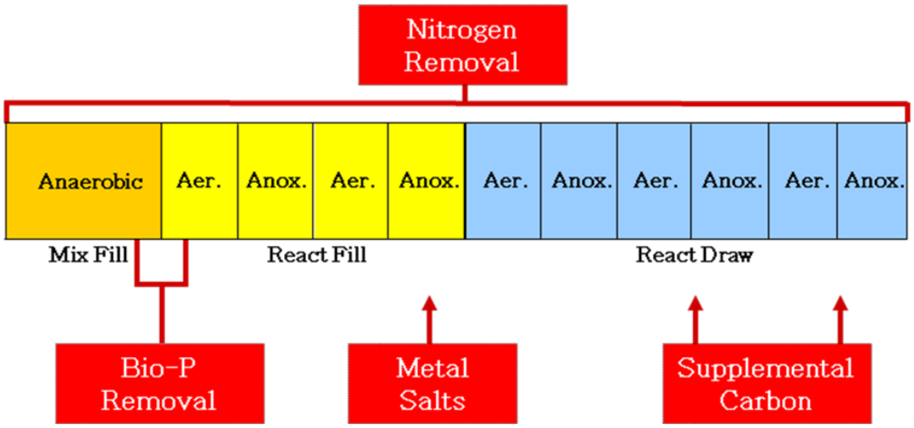

Figure 14. Optimum Chemical Injection Locations in the Batch MBR Cycle

Treatment Capacity

While the MBR will provide the additional capacity required, the actual flows since system startup have been far below the design capacity of 0.8 MGD ADF (refer to Figure 15 for the flows over a one-year period). There are three data points on the graph for each month, with the curve showing the average daily flow for that month.

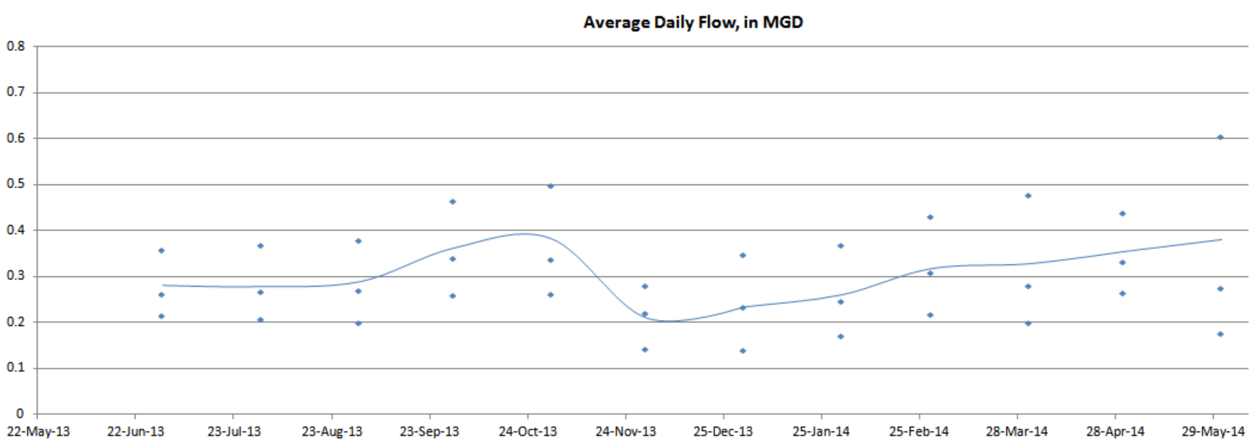

Figure 15. System Flows over a One-Year Period

Because the anaerobic, aerobic, and anoxic retention volumes can easily be adjusted in the PLC (refer again to the discussion concerning Figure 13), the batch MBR system is more flexible in handling flow variations than its flow-through counterpart. In addition, the bioreactor in its Fill step performs some equalization of the influent flow such that the membranes are designed for the maximum batch volume in lieu of the peak hourly flow; therefore, the system can handle higher peak flows, though this has yet to be tested on the Shepherdstown plant.

Chemical Usage

The average daily chemical usage at the Shepherdstown plant is 6 gallons of MicroC carbon supplement and 10 gallons of 48% aluminum sulfate (alum), though this varies depending on the season (refer to the earlier discussion on the "tailored approach"). To see how the carbon usage compares with other batch systems, Table 3 lists several batch systems with their effluent nitrogen limits and their carbon-to-nitrogen (C:N) ratios with and without carbon addition. Note that the far right column for the Shepherdstown plant (4.44) is slightly better than the average ratio of all the batch systems shown (4.66); this means that the plant uses a little less carbon than the other plants to remove the same amount of nitrogen.

Table 3 Carbon Usage on Batch Systems

Plant Name	Design Effluent TN (mg/l)	% of Design Load BOD	Design C:N Ratio	Current C:N Ratio (no Carbon)	Current C:N Ratio (w/ Carbon)
Key Largo, FL	3	31.5%	5.00	4.69	4.90
Huntington, NY	4	66.8%	4.50	4.03	4.20
Dale Service Section 1, VA	8	47.1%	4.41	4.00	4.71
Dale Service Section 8, VA	8	47.1%	4.41	4.00	5.03
Shepherdstown, VA	3	49.1%	10.37	4.28	4.44
Averages	**5.2**	**48.3%**	**5.74**	**4.20**	**4.66**

In comparison, Table 4 lists several flow-through systems with some of the same information. Note on this table that the average C:N ratio for these plants (8.06) is considerably higher than the average for the batch systems.

Table 4 Carbon Usage on Flow-Through Systems

Plant Name	Design Effluent TN (mg/l)	Current C:N Ratio (w/ Carbon)	Biological Process
Alexandria Renew WRF, VA	3	7.8	5 Stage Bardenpho
Central Johnston, NC	3.7	10	Activated Sludge with denite filter
Henrico County, VA	5	7.90	5 Stage Bardenpho
Lee County, FL	3	4	Activated Sludge with denite filter
Lott WWTP, WA	10	4.75	4 stage bardenpho
Western Branch WWTP, MD	3	13.90	4 anoxic, 8 aerobic reactors
Averages	**4.6**	**8.06**	---

With respect to the alum dosage, the average influent phosphorus concentration has been 4.9 mg/l; therefore, the 10 gpd of alum used calculates to be 0.3 lbs of Al per lb of P. This dosage is way below even the stoichiometric value. The reason for this is because the alum isn't added until the end of the Fill step so that as much P as possible has first been removed biologically (refer again to Figure 14). In comparison, testing was done on a similar batch system with ultrafiltration membrane to achieve less than 0.066 mg/l, and approximately 2 lbs of Al was added per lb of influent P [Holland (2014)].

The main reason that chemical usage is low on the batch MBR system is due to the placement of the chemical injection points in the batch cycle, as described above. The capability to adjust the anaerobic, aerobic, and anoxic retention volumes using the PLC timers provides the flexibility needed to optimize BNR. Doing so leaves a minimal amount of nutrients in the basin, resulting in only small amounts of chemical to achieve the balance of the removal needed.

Conclusions

Based on over two years of operation, there are several conclusions that can be derived from the performance of the batch MBR at Shepherdstown, WV:

1. The average Total Mass Daily Load (TMDL) for this period was 12.4 lbs/day Total Nitrogen (TN) and 0.48 lbs/day Total Phosphorus (TP), which are 38% and 76% below their required TMDL, respectively. The main reasons for this are:
   - No possibility of raw wastewater "short-circuiting" to the membrane permeate.
   - Multiple anoxic steps in the PLC that allow the TN level in the basin to drop lower than for flow-through systems, which typically have only one or two anoxic basins.
   - Adjustable anaerobic, aerobic, and anoxic steps in the PLC that enable fine-tuning of the biological nutrient removal (BNR).
   - Flexibility to add chemicals at the point in the batch cycle where the nutrient levels are lowest and the chemicals will have the greatest affect.
2. Like other MBR systems, the membranes replace the clarifiers, allowing the biomass concentration in the bioreactors to be nearly tripled, resulting in a corresponding capacity increase. But unlike flow-through MBRs, the batch system is more flexible in handling flow variations and equalizes the peak hourly flows so these don't pass through to the membranes.
3. Carbon usage was only 4.44 lbs per lb of influent nitrogen, a value that is slightly less than other batch systems but about 45% less than on flow-through systems. One reason for this is the "tailored approach", which adjusts the system timers and carbon usage to achieve only the nutrient concentrations needed to meet the TMDL during the plant's two different seasonal flow demands.
4. Alum usage was only 0.3 lbs Al per lb of influent phosphorus, a value that is much less than other systems, both flow-through and batch. Besides the tailored approach, removing as much P as possible biologically before adding the alum greatly reduces the amount of alum needed to achieve the same P removal.

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