NEW YORK WATER RESOURCE RECOVERY FACILITY SELECTS BATCH-STYLE MEMBRANE BIOREACTOR FOR PLANT CONSOLIDATION

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Abstract

Like many other water resource recovery facilities (WRRFs) that discharge to waterways in the Chesapeake Bay watershed, the Northgate WRRF in the Town of Chenango, NY has been required to meet progressively lower effluent nitrogen and phosphorus levels in order to help recover the watershed. In addition, the Town assumed ownership of nearby Chenango Heights WRRF in 2018 to provide resources needed to slow down its deterioration. Determining that they needed a plan to deal with these events, the Town retained the engineering services of Barton & Loguidice, D.P.C (B&L) to evaluate potential alternatives. B&L proposed a Wastewater Treatment and Conveyance Improvements project in which all three of the Town's WRRFs – the Northgate and Chenango Heights plants along with the Town's smallest plant, the Pennview WRRF – will be consolidated into one plant, the larger Northgate facility. To accomplish this, the treatment system at the Northgate plant will have to be upgraded to handle the additional flow and nutrient requirements, and roughly 3 miles of force main piping will have to be added to the existing collection system in order to reroute all of the wastewater flows to the larger plant. It's also important to the Town that the plant upgrades produce the highest quality effluent with the lowest energy and chemical consumption.

Project Background

Existing Facilities

The Town of Chenango, NY is in New York's Southern Tier region, just north of the City of Binghamton. The town has nearly 11,000 residents and over 150 businesses, which generate an average of 0.64 million gallons per day (mgd) of wastewater (2,422 m^3/day). The town's main wastewater treatment plant – the Northgate WRRF - was built in 1993 to treat 0.5 mgd (1,893 m^3/day) and was expanded in 1997 to handle a maximum month flow of 0.8 mgd (3,028 m^3/day). Figure 1 shows the Northgate flow for 2017 - 2020, which averaged 0.6 mgd (2,271 m^3/day).

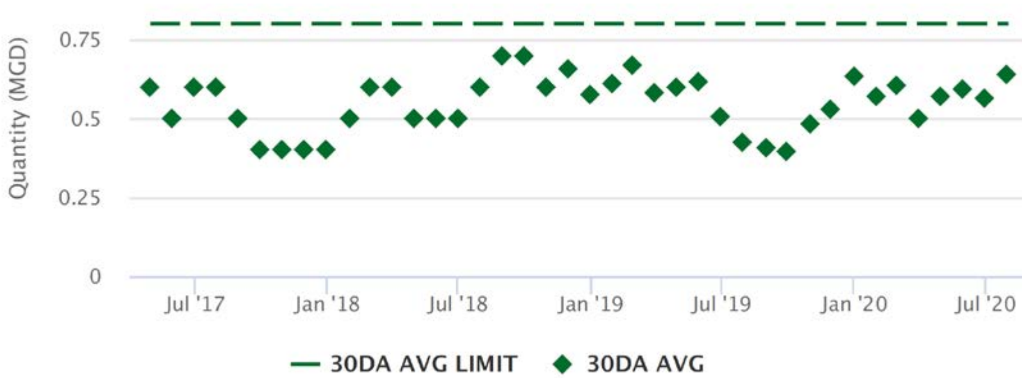

Figure 1 Average Flow at the Northgate WRRF

Figure 2 shows an aerial photo of the existing system at the Northgate WRRF, with the basins and buildings labeled. The main process is a three-basin sequencing batch reactor (SBR): the first two basins were installed in 1991, and the third basin was installed in 1997. In 2001, the facility received an upgrade to its composting facilities, which provided additional solids handling capacity.

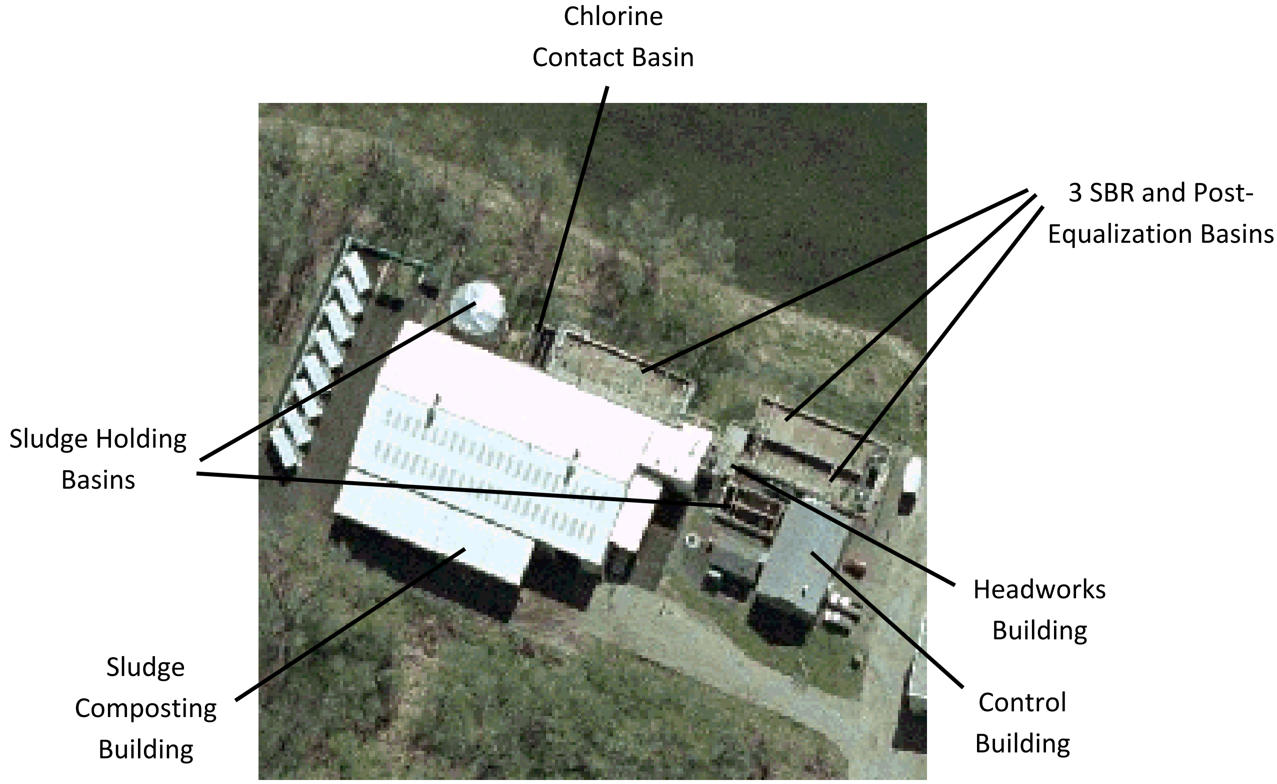

Figure 2 Existing Northgate WRRF Layout

The plant currently has an annual discharge limit to the Chenango River of 27,000 lbs (12,258 kg) total nitrogen (TN) and 1,910 lbs (867 kg) total phosphorus (TP), which equates to 11.1 mg/L TN and 0.78 mg/L TP at the 0.8 mgd design flow. The actual annual effluent TN for 2017 through 2020 averaged approximately 13,000 lbs (5,900 kg), as shown in Figure 3.

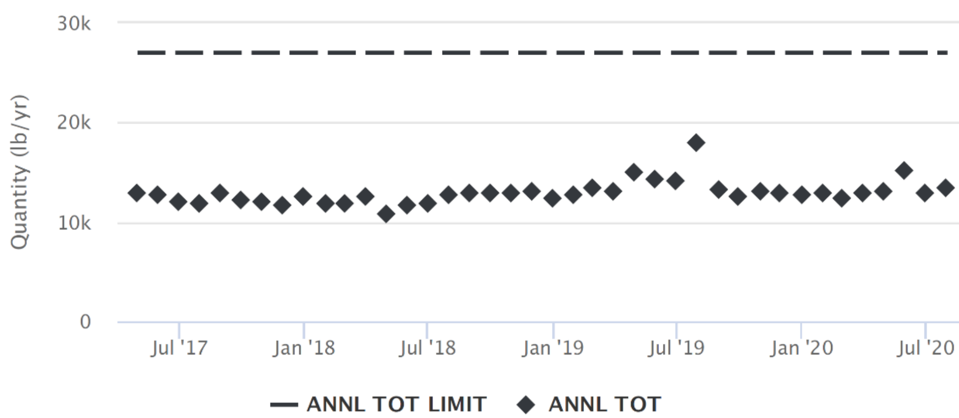

Figure 3 Effluent Total Nitrogen at the Northgate WRRF

The other plant that serves the Town is the Pennview WRRF. This plant is permitted for 0.04 mgd average monthly flow and consists of aeration and solids separation in a steel-tank package plant and chlorine disinfection. Waste solids are transported to the Northgate Plant for conditioning and composting. This package plant treats wastewater from an apartment complex.

The third plant involved in the consolidation is the Chenango Heights WRRF, which is designed to treat 0.05 mgd average monthly flow. This plant uses the same process as the Pennview facility, and also sends its sludge to the Northgate plant for conditioning and composting. The package plant treats wastewater from a Binghamton, NY housing development.

The existing treatment process at the Northgate plant is shown in Figure 4 and consists of pump station, bar screen, grit removal, (3) SBR basins, (2) post-equalization basins, and a chlorine contact system. Waste solids from the SBR are held in a holding tank, thickened in a gravity belt thickener (GBT), aerobically digested, dewatered with a belt filter press (BFP), and composted to achieve Class A biosolids. Supernatant from the GBT and BFP is pumped back to the head of the plant.

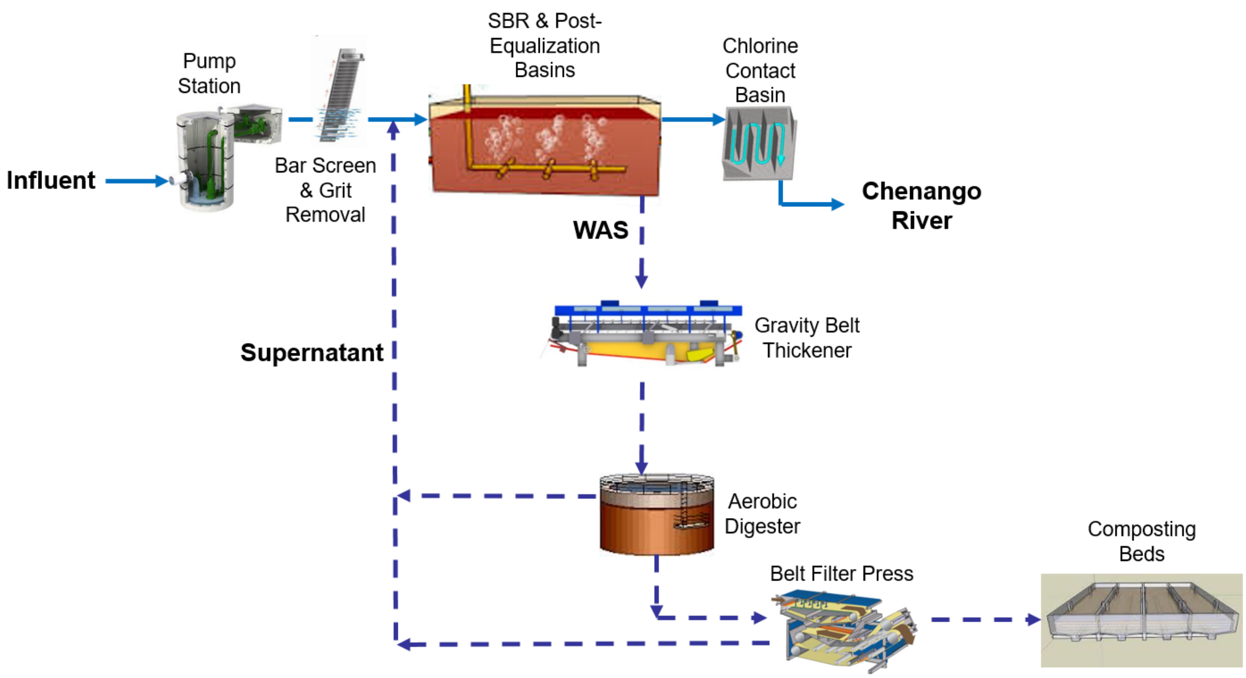

Figure 4 Northgate WRRF Flow Schematic

The Need for an Upgrade

In 2018, the New York State Department of Environmental Conservation (NYSDEC) classified the Northgate plant as a significant contributor of nutrients to the Chesapeake Bay watershed. Guided by the Chesapeake Bay Watershed Initiative (CBWI) of 2010, the NYSDEC required the plant to meet a lower annual phosphorus loading (1,220 lbs per year) by 2025, a 36% reduction. In addition, the design flow will be increased to 1 MGD (3,785 m^3/day) to accommodate the flows that will be redirected from the Pennview and Chenango Heights plants. At the new flow, the average effluent phosphorus concentration will be 0.4 mg/L. While the total maximum daily load (TMDL) for nitrogen will remain the same (27,000 lbs per year), the average effluent nitrogen concentration will drop to 8.9 mg/L at the new flow, a 20% reduction. Taking into consideration that the digester and belt press supernatant - a little over 9% of the total flow - will be recycled back to the plant headworks, the required nutrient concentrations will be even lower.

Over the past several years, the plant has experienced a significant increase in organic and nutrient loading, a result of new/repaired collection systems providing less infiltration, and environmentally-friendly toilets, showers, and appliances using less water. The current SBR system volume is insufficient to achieve the lower nutrient limits at the extra flow/loadings, but the plant doesn't have the space to add basins.

Plant Improvements

The Northgate plant was now faced with the challenge of removing phosphorus and nitrogen to as low as 0.4 and 8.9 mg/L, respectively, increasing capacity, and treating higher organic and nutrient loading. To do this, several process improvements would have to be made.

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. To minimize the amount of chemical used, it's best to remove as much phosphorus biologically prior to adding chemical; without a tertiary filtration step, however, most systems don't have a good way to do this and end up adding the chemical before biological phosphorus removal (BPR) is complete, resulting in less-than-optimal chemical usage.

During BPR, special bacteria in the anaerobic zone 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 [Seviour (2003)]. 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).

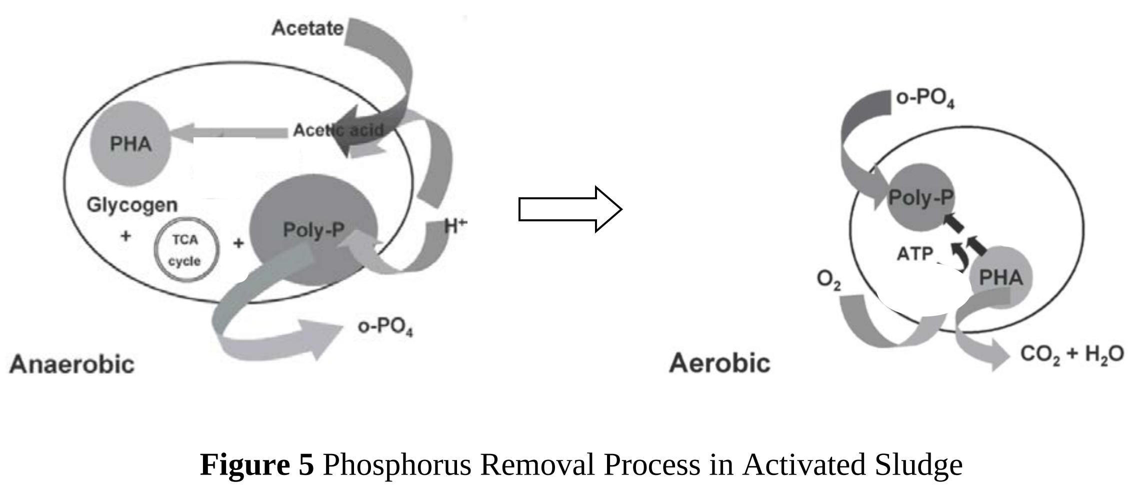

Figure 5 Phosphorus Removal Process in Activated Sludge

To cultivate healthy PAOs, the solids retention time (SRT) is 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.

In a typical BPR system, 3-5% of the biomass will be made up of phosphorus; therefore, once the biomass removes most of the phosphorus from the wastewater, the biomass must be settled or filtered out such that the effluent contains less than the permitted amount of phosphorus. Assuming 3% of the biomass is phosphorus, the Northgate effluent will have to contain no more than 8 mg/L of suspended solids in order to achieve the required 0.4 mg/L phosphorus.

In contrast, chemical phosphorus removal is performed by reacting soluble phosphorus with a metal salt, forming a compound that is only slightly soluble such that most of it can be removed through subsequent settling and/or filtering. For instance, the aluminum in aluminum sulfate (alum) will react with the phosphate in the water to form aluminum phosphate, which is almost completely undissolved at pHs between 6.7 and 7.1, as shown in Figure 6.

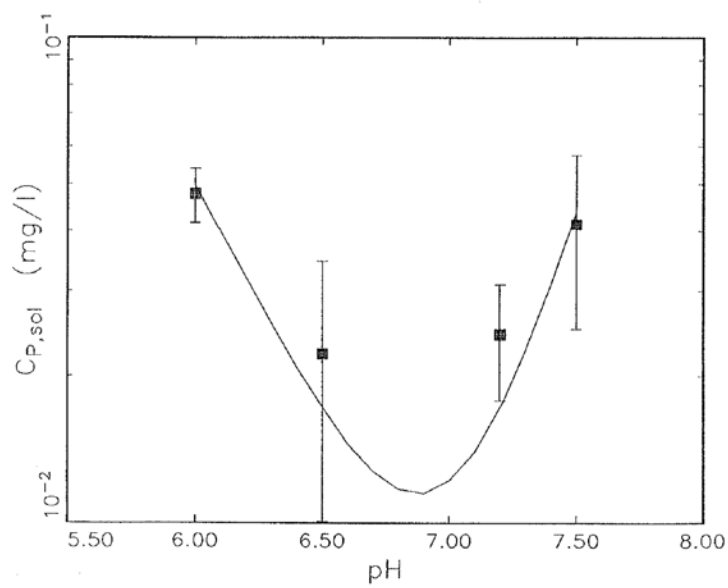

Figure 6 Solubility of Aluminum Phosphate in Water [Jenkins (1991)]

Attaining the 0.4 mg/l TP required at average flow will probably require both biological and chemical removal. To achieve maximum BPR at the higher loadings, the plant would have to:

1. Increase retention time in its anaerobic zone so that it's long enough to completely deplete the available oxygen (including nitrates).
2. Operate at an SRT that favors the development and maintenance of a healthy population of PAOs.
3. Settle or filter the effluent to consistently achieve less than 8 mg/L TSS.

Nitrogen Removal

Nitrogen removal in an activated sludge plant is a two-step process, as shown in Figure 7. The first step is nitrification of the ammonia in the raw wastewater, where ammonia oxidizing bacteria (AOB) convert the ammonia to nitrite (NO_2) and nitrite oxidizing bacteria (NOB) convert the nitrite to nitrate (NO_3), both in the presence of oxygen. The second step is denitrification, where heterotrophic bacteria use the oxygen in the nitrate, converting it to nitrogen gas, which is released to the atmosphere; for this to happen, there must be an adequate supply of organic carbon and a lack of dissolved oxygen.

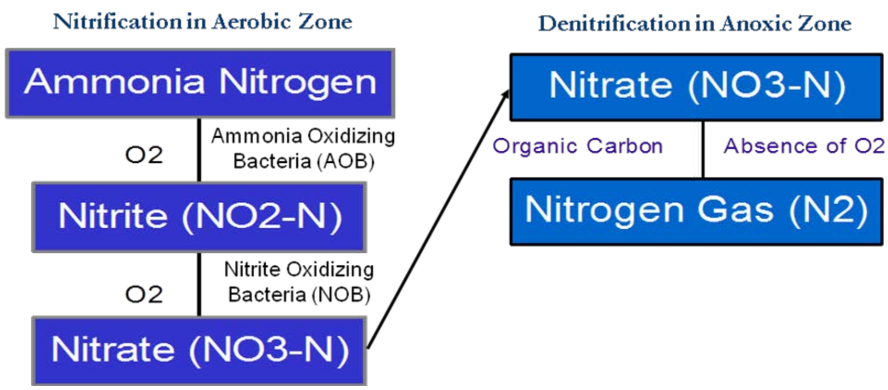

Figure 7 Nitrogen Removal Process in Activated Sludge

To cultivate healthy AOB and NOB in the system, the SRT must be longer than for most of the other bacteria in the system; during the colder New York winters, this should be at least 7 days. In addition, the lower the desired nitrogen level, the more organic carbon will be needed; at very low levels, 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.

Capacity and Loading Increase

To increase the average design flow from 0.8 mgd to 1 mgd at the Northgate plant, the plant will have to either increase the biomass in the existing SBR basins, or add basins. Unfortunately, the biomass concentration in the SBR is limited to a maximum of about 4,000 mg/L TSS; above this level, the biomass may not settle well, resulting in higher effluent TSS. In addition, the increase in organic and nutrient loading will require additional aeration for organic consumption and nitrification, extra anaerobic time for phosphorus release, and more anoxic time for denitrification.

Other Considerations

Besides meeting the new nutrient and capacity requirements, there are several additional criteria that must be considered:

- Power Usage – the system must treat the additional capacity and achieve the required effluent quality with minimal power usage.
- Chemical Usage – the effluent nutrient limits should be met with as little supplemental carbon and metal salt addition as possible.
- Footprint – the expanded system should have as small of a footprint as possible, which means reusing as much of the existing structures and equipment as is practical.
- Ease of Operation – the consolidated system should be fully automated and fairly simple to operate.

- Flexibility – the system should have the flexibility to handle large swings in hydraulic and organic loadings.

Upgrade Options

It quickly became apparent to B&L that the existing SBR system would not be able to handle the 25% increase in capacity and meet the stricter effluent requirements that will be on the 2026 National Pollutant Discharge Elimination System (NPDES) permit. In lieu of this, the following options were considered:

1. Add a fourth SBR train.
2. Convert the SBR system to an aerobic granular sludge (AGS) process.
3. Convert the SBR system to a flow-through membrane bioreactor (MBR) system.
4. Convert the SBR system to a batch-type MBR system.

Option 1: Adding a Fourth SBR Train

This option involves adding a fourth SBR/post-equalization basin and, if needed, extra aeration capacity. It may also require adding a tertiary filter to assure the effluent TSS is consistently below the 8 mg/L needed to stay under the 0.4 mg/L TP limit. The big advantage to this option is ease of operation, which will stay the same. However, there simply is not room at the site to add a fourth basin, much less tertiary filters; therefore, this option is not a viable alternative.

Option 2: Converting the SBR to an AGS Process

This option involves growing the biomass into granules that settle much faster than typical activated sludge; therefore, the biomass concentration in the basins can be increased such that the system can treat more flow in the same footprint. During the initial evaluation process, however, B&L determined that the AGS process – though the least power-intensive option – would not be able to treat the 3.1 mgd peak hourly flow within the current footprint using the existing tanks.

Option 3: Converting the SBR to a Flow-Through MBR

This option involves filtering the biomass with low-pressure membranes, which eliminates the settling and decant steps used in the SBR process. As with the AGS option, the biomass concentration in the basins can be increased in order to handle higher flows through the existing basins. A schematic of a typical flow-through MBR for biological nutrient removal (BNR) is shown in Figure 8. The influent wastewater first mixes with flow from the anoxic basin, providing additional VFAs for the PAOs in the anaerobic basin, which release phosphorus under the oxygen-free conditions. The wastewater then flows into the anoxic basin and combines with nitrates recycled from the aerobic basin; heterotrophic bacteria in the anoxic basin convert the nitrates into nitrogen gas. The denitrified wastewater then flows into the aeration basin, where luxury uptake, nitrification, and organic consumption occur. The treated wastewater is then recycled through the membranes, where vacuum pumps draw solids-free water through the small pores of the membranes, discharging it to the downstream disinfection system.

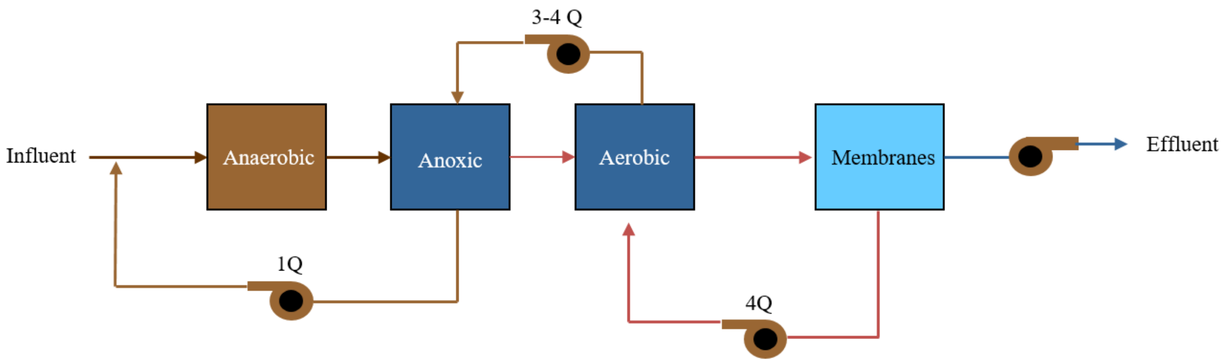

Figure 8 Typical Flow-Through MBR for Biological Nutrient Removal

One membrane system provider, Aqua-Aerobic Systems, Inc. (AASI) offers an alternative flow-through MBR configuration, shown in Figure 9. This configuration has the same quantity of basins and total volume as the conventional flow-through MBR, but the aerobic and anoxic zones occur in the same basin, which has separate aeration and mixing devices; both are used during the aerobic phases, and only the mixer is used during the anoxic phases. This allows sequencing multiple times between the aerobic and anoxic phases – the traditional system can only sequence once or twice – which facilitates the denitrification process. Because the return activated sludge (RAS) is not sent to the aeration basin (as it is in the conventional MBR), there is a pre-anoxic phase to remove the oxygen put into the water during the membrane air scour. An adjustable portion of the deoxygenated RAS provides VFAs to the anaerobic basin, while the remainder of the flow returns to the aerobic/anoxic basin. Note also that two of the recycle loops have been eliminated; the RAS pump provides the VFAs for the anaerobic basin, and the nitrates created during the aerobic phases are made available for the subsequent anoxic phases without the need for external recirculation.

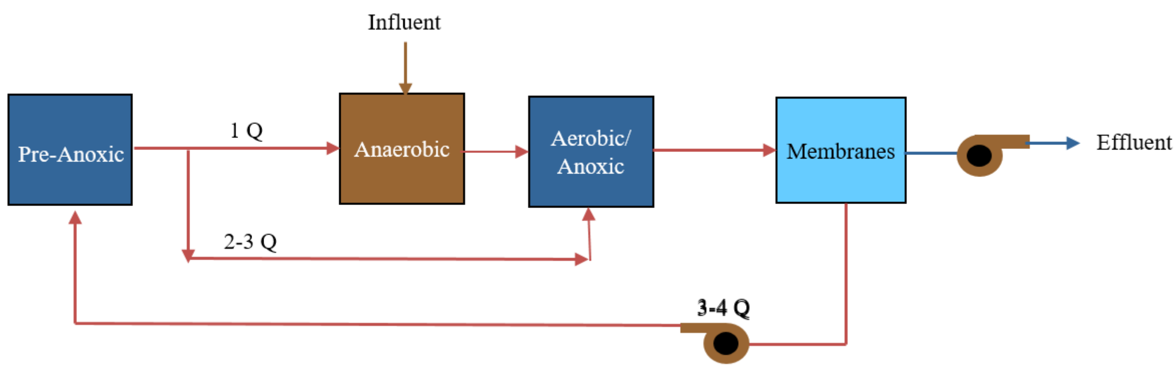

Figure 9 AASI Flow-Through MBR for Biological Nutrient Removal

Not only do the multiple anoxic and aeration phases result in very low effluent nitrogen, but they do so with very little (if any) supplemental carbon. The reason for this is that supplemental carbon is only added to the basin after all of the carbon in the wastewater has been consumed by the biomass, as evidenced by a leveling off of the nitrate concentration; if the basin nitrate level is below the effluent requirement –for the Northgate expansion, this is 8.9 mg/L at the average flow – no additional carbon will be needed. Figure 10 illustrates this; the aeration system turns on and off as indicated, alternating between aerobic and anoxic phases, with carbon added to the final anoxic phases if the nitrogen concentration in the basin is still above the required effluent limit. This approach is much more flexible than the conventional flow-through MBR because the quantity and duration of the anoxic and aerobic phase are adjustable with timers in the system's programmable logic controller (PLC). In addition, the basin's final nitrogen concentration can be increased during periods of low flow because the goal is to meet the required TMDL, not a specific TN concentration; this approach – known as tailored nutrient management [Vuono, (2012)] – results in very low carbon usage.

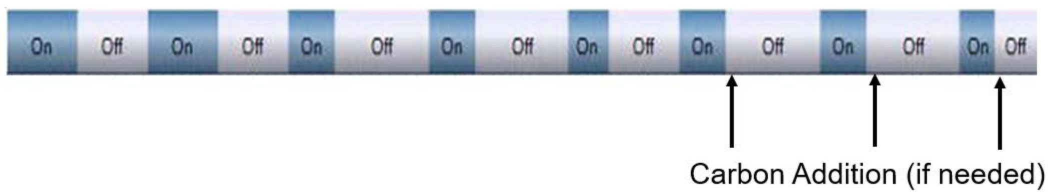

Figure 10 Carbon Addition to the Aerobic/Anoxic Basin

Option 4: Converting the SBR to a Batch-Style MBR
In contrast, all of the treatment phases - anaerobic, anoxic, and aerobic - occur in the same basin in a batch-style MBR – shown in Figure 11. In this configuration, all of the phase volumes are adjustable with timers in the PLC. Because this MBR is a batch system, it requires at least two bioreactors: one filling with a batch of wastewater, and the other sending its batch through the membranes. In the case of the Northgate plant, the third bioreactor will be neither filling nor discharging, but rather alternating between aerobic and anoxic phases to reduce the nitrogen as much as possible prior to discharge.

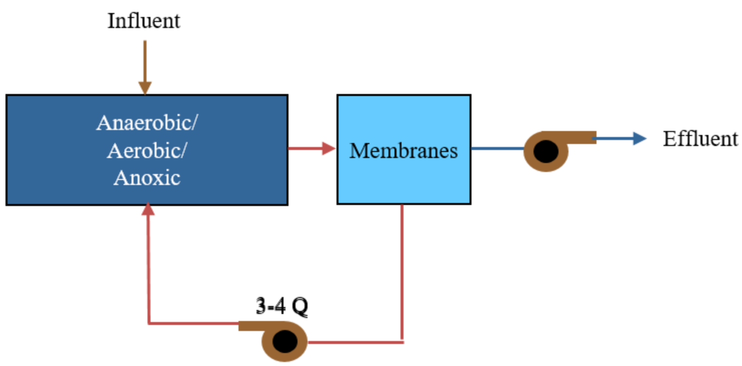

Figure 11 Typical Batch-Style MBR for Biological Nutrient Removal

Figure 12 shows a typical 3-bioreactor batch MBR with BNR. Each bioreactor will sequence through its Mix Fill, React Fill, React, and React Draw modes and back into Mix Fill, staying in each mode for the preset cycle time. Because there will always be a bioreactor in React Draw, flow through the membranes will be continuous.

The batch-style has all of the advantages of the AASI flow-through MBR – low effluent nutrients, minimal carbon usage, half the recycle pumps, and increased flexibility - but with several additional benefits. Most notable is its built-in equalization: peak hourly flows are equalized in the filling bioreactor such that additional membranes are not needed.

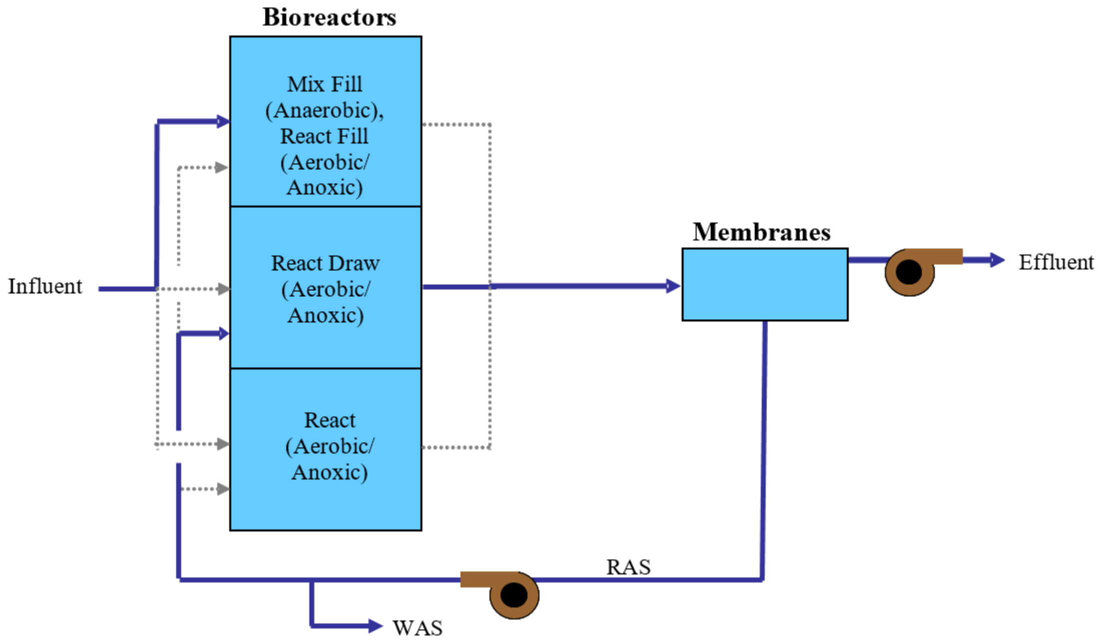

Figure 12 Flow Schematic for a Three-Bioreactor Batch-Style MBR with BNR

Another advantage to the batch-style MBR is that it minimizes metal salt usage. The reason for this is that chemical is only added to the basin after as much phosphorus as possible has been removed biologically, as illustrated in Figure 13. At the end of React Fill, the phosphate level is measured, and the proper amount of metal salt is added to convert the phosphate to an insoluble form, which is removed by the membrane during React Draw; if the basin phosphate level is already below the effluent TP limit –for the Northgate expansion, this is 0.4 mg/L at the average flow – no metal salt will be needed. For the batch-style MBR, tailored nutrient management applies to both the nitrogen and phosphorus: the basin's final nitrogen and phosphorus concentrations can be increased during periods of low flow and the system can still meet the required TMDLs.

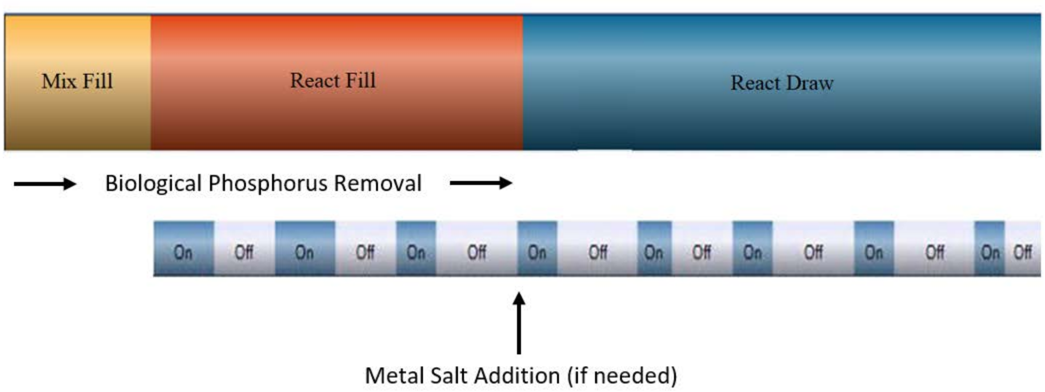

Figure 13 Phosphorus Removal in a Batch-Style MBR

One other major advantage of the batch-style MBR is that the flow through the membranes can be regulated based on the size of the batch being filtered. This enhanced flux approach allows the flow through the membranes to be set at the highest flux they can handle, with the flow turned off when the discharging bioreactor is in its anoxic phases; this allows the bioreactor to become anoxic much faster and saves power because the RAS pump, air scour blowers, and vacuum pumps can be turned off at these times.

As noted earlier, the bioreactors in the batch-style MBR have a variable level, with each bioreactor at its low level just prior to entering its Mix Fill phase. In contrast, the bioreactors in a flow-through MBR are always at the same level. This is a disadvantage for the batch-style MBR because the bioreactors will have to be slightly larger to handle the same flow. However, the level in the batch bioreactors can be lowered during periods of low flow, resulting in a much larger turndown capability than in flow-through MBRs.

Option Evaluation

Each MBR option was then evaluated based on the criteria given earlier:

- *Nutrient Removal* - Both flow-through and batch-style MBRs are capable of achieving the required effluent nutrient levels.
- *Capacity and Loading Increase* – All of the MBR options can handle the increased capacity and loading; however, the flow-through MBR option is able to handle slightly higher flows and loadings since the entire volume of the bioreactors is used at all times, a result of operating at a constant level.
- *Power Usage* – Power usage was estimated for each MBR option and compared with the actual power used by the existing SBR system, also referred to as the Cyclic Activated Sludge System (CASS). Table 1 gives the results of this comparison [Bottar (2021)].

Table 1 Estimated Energy Usage Comparison

Process Option	Proposed Daily Electrical Consumption (kWh/day)[1]	Proposed Annual Electricity Cost[2]
Existing CASS	2,086	$60,000
Batch MBR	2,385	$70,000
Flow Thru MBR	4,319	$126,000

[1]These values were provided by the equipment vendor for each technology based on average day flow rate.
[2]These costs are based on $0.08/kWh.

The power consumption of the existing system is based on the current design flow of 0.8 mgd, while the MBR estimates are based on the future average flow of 1 mgd; assuming a linear increase, the CASS consumption at 1 mgd will be about 2,608 kWh/day, or 9.3% higher than the batch MBR estimate. One reason for this may be that the CASS uses its aeration system for both oxygen delivery and mixing such that it can only be turned down so far and keep the basin properly mixed.

Also, note that estimated power consumption for the batch-style MBR is considerably lower than that of the flow-through MBR; this is due mostly to the fact that the batch option equalizes the peak hourly flow in the bioreactors, minimizing the required membrane area.

- *Chemical Usage* – For the reasons given earlier, the batch MBR is estimated to use less metal salt and supplemental carbon than a flow-through MBR. Table 2 shows that lower carbon usage is not unique to MBRs; in this study, the batch systems required an average of 44% less carbon than the flow-through systems [Holland (2015)]. This same study also found that the batch systems used, on average, 85% less aluminum-based coagulant than were used on the flow-through systems.

Table 2 Comparison of Carbon Usage in Batch and Flow-Through Systems Engaged in BNR

Plant Name	Design Effluent TN (mg/l)	Current Carbon –to-Nitrogen Ratio	Biological Process
Batch Systems			
Key Largo, FL	3	4.90	SBR
Huntington, NY	4	4.20	SBR
Dale Service Section 1, VA	8	4.71	SBR
Dale Service Section 8, VA	8	5.03	SBR
Shepherdstown, WV	3	4.44	Batch MBR
Riverhead, NY WRRF	3	3.69	Batch MBR (no supplemental carbon)
Average	**5.2**	**4.49**	
Flow-Through Systems			
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
Average	**4.6**	**8.06**	

- *Footprint* – Both MBR options will be able to achieve the necessary capacity and treatment in the existing basins; however, the flow-through MBR will be able to handle slightly higher flows since its constant level allows the entire bioreactor volume to be used at all times. The AASI MBRs - both flow-through and batch - have two less pump stations than the conventional flow-through MBR; therefore, the latter will occupy the most space.
- *Ease of Operation* – Both the flow-through and batch-style MBRs will be fully automated. The batch system, however, will require fewer modifications to the current system.
- *Flexibility* – Because all of the phase times can be adjusted in the PLC, the chemical dosing can be varied with the nutrient concentrations in the bioreactors, and the minimum bioreactor levels can be lowered, the batch-style MBR is the most adaptable to changing conditions.

Since the main advantages of the batch system – lower power/chemical usage, ease of operation, and flexibility – outweighed the disadvantage of slightly less future capacity, B&L recommended that the Town proceed with the batch-style MBR.

Implementation

The Town asked the system provider to generate plans and specifications that could be used to select an installation contractor. In late 2020, this document package was provided to B&L, who used it to create the documents for the contractor bid. The project was advertised in late 2021, with six contractors responding. All of the bid prices were within 9% of each other, with the two lowest bids within 0.2%; however, all bids were over the monies that had been budgeted for the project, presumably because of the significant increases in materials and transportation costs following the COVID-19 pandemic. As a result, the Town board voted to delay the project for at least a year in hopes of better costs once the economy returns to pre-pandemic levels. In late 2022, the MBR system provider was asked to update their pricing in anticipation of a re-bid in early 2023.

Conclusions

The Town of Chenango, in concert with its engineer, Barton & Loguidice (B&L), has decided to close its deteriorating Chenango Heights water resource recovery facility (WRRF) and divert wastewater from this facility as well as from the Town's Pennview facility to their Northgate WRRF. Because Northgate's existing SBR system does not have the volume required to handle the additional flow and meet the 2025 total phosphorus limit of 1,120 lbs (506 kg) per year, the Town decided to upgrade the plant to a membrane bioreactor (MBR); this eliminates the need for clarification, which allows the plant to operate at much higher biomass concentrations. B&L evaluated both flow-through and batch-style MBRs, concluding that both will meet the required flow and nutrient requirements, but that the batch-style MBR will do so using approximately 45% less power, 44% less supplemental carbon, and 85% less aluminum-based coagulant. In addition, the batch system allows operators to adjust the retention times in the anaerobic, anoxic, and aerobic phases to adapt to changes in influent flows and loadings. Bids were then solicited for installing the batch-style MBR system, but all came in higher than anticipated; therefore, the Town board voted to postpone the project until 2023 in hopes that costs will return to pre-pandemic levels by then. At the time of this writing, project costs are being updated. The next step will likely be for the Town and B&L to work with the MBR system supplier as well as the other equipment vendors to find areas where costs can be reduced.

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