CASE STUDY: USING A HIGH STRENGTH MEMBRANE BIOREACTOR FOR AN AFFORDABLE HOUSING PROJECT WITH A STRINGENT TOTAL NITROGEN EFFLUENT STANDARD

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Abstract

Approximately 50 miles south of Boston, the town of Westport, MA sought to develop an affordable housing project with the capacity to treat the wastewater from 50 residential apartments (estimated project daily flow 9,990 gpd). The planning board set an ambitious effluent limit of <5 mg/L Total Nitrogen (TN) and a Net Zero TN at the property line for the 31-acre site due to its proximity to Buzzards Bay. Membranes have been successfully used to consistently treat domestic wastewater to extremely low contaminant concentrations. A membrane bioreactor (MBR) typically combines an ultrafiltration membrane and a suspended growth bioreactor to produce an effluent with low concentrations of pathogens, five-day biochemical oxygen demand (BOD_5) and total suspended solids (TSS).

This case study provides evidence that when commercial-grade effluent filters, flow equalization, supplemental alkalinity and carbon augmentation coupled with drip irrigation to maximize passive nitrogen uptake by plants in the shallow root zone, a stringent total nitrogen effluent concentration is reachable. Noquochoke Village began operation on May 7, 2019. Thus far, the high strength membrane bioreactor has exceeded expectations by producing an average TN of 4.9 mg/L without using a daily operator or requiring repeated modification to the operations. The system has displayed robust performance despite fluctuations in ambient temperature, influent BOD_5 and TSS concentrations and incoming flow volumes.

Introduction

The town of Westport, Bristol County got its name because it was the westernmost port in the original Massachusetts Bay Colony. Rhode Island is located immediately west of the town. Westport was first settled by English colonists in 1670. The mostly residential community with a large farming sector had a population of 15,532 according to the 2010 census (US Census Bureau, 2010).

The Noquochoke Village is located in a secluded wooded setting adjacent to the Noquochoke River and the Forge Pond conservation area. The village is designed consistent with the historical pastoral

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character of Westport to resemble connected farm buildings traditionally found throughout this region of Massachusetts.

The village consists of seven buildings that collectively contain 50 one bedroom to three-bedroom apartments, along with a community center and communal laundry facilities. Housing is concentrated on 8 acres near the entrance to the property. The remaining 23 acres of the site bordering the Noquochoke River is and will remain undeveloped for trails and passive recreation. The compact form of the development coupled with the maintenance of permanent open space are central aspects of the land development strategy called Smart Growth (Handy, 2002).

The watershed containing Noquochoke Village flows to Buzzards Bay in Massachusetts. Buzzards Bay is not only the home waters of the Woods Hole Oceanographic Institution, it is also a National Estuary Program. Established in 1985 as the Buzzards Bay Project, the Nation Estuary Program's mission is to protect and restore water quality and living resources in Buzzards Bay and its surrounding watershed through the implementation of the Buzzards Bay Comprehensive Conservation and Management Plan. Although a total nitrogen limitation of <5 mg/L is not universally required in Massachusetts, it is appropriate in this case (Banta, Gibline, Hobbie and Tucker, 1995).

History of Membrane Bioreactors

Membranes stand out compared to competing technologies for their capacity to retain solids and small particles, producing water suitable for reuse in irrigation and other applications. Membranes allow certain low molecular weight substances to pass through. In the case of wastewater treatment, the aim is for the water to flow through the membrane, holding back undesirable particles on the outside surface of the membrane (Ben Aim and Semmes,2002).

Membrane filtration is now so commonly used by smaller volume municipal and industrial wastewater treatment plants that the process is rapidly reaching the status of a conventional wastewater treatment technology. Municipal and industrial wastewater facilities typically operate under 5-year renewable operating permits. These permits contain discharge concentration limits that must not be exceeded by the facility. Over the last 20 years, local and state Environmental Departments have ratcheted down standards so low for common strength parameters such as TSS and BOD_5 that traditional attached growth plants have difficulty complying with these revised tighter standards (Stephenson, Judd. Jefferson and Brindle, 2000).

Using a membrane bioreactor treatment train in place of a municipal-sized activated sludge plant provides several notable advantages. Two advantages will be highlighted here. First, because the membrane bioreactor operates most efficiently at approximately three times or higher the mixed liquor suspended solids content of activated sludge plants, the size of the aeration zone can be substantially smaller (Figure 1). Secondly, the membrane bioreactor replaces the functions of three different unit processes in the activated sludge plant: clarification (labelled settler in Figure 1), sand filtration and disinfection.

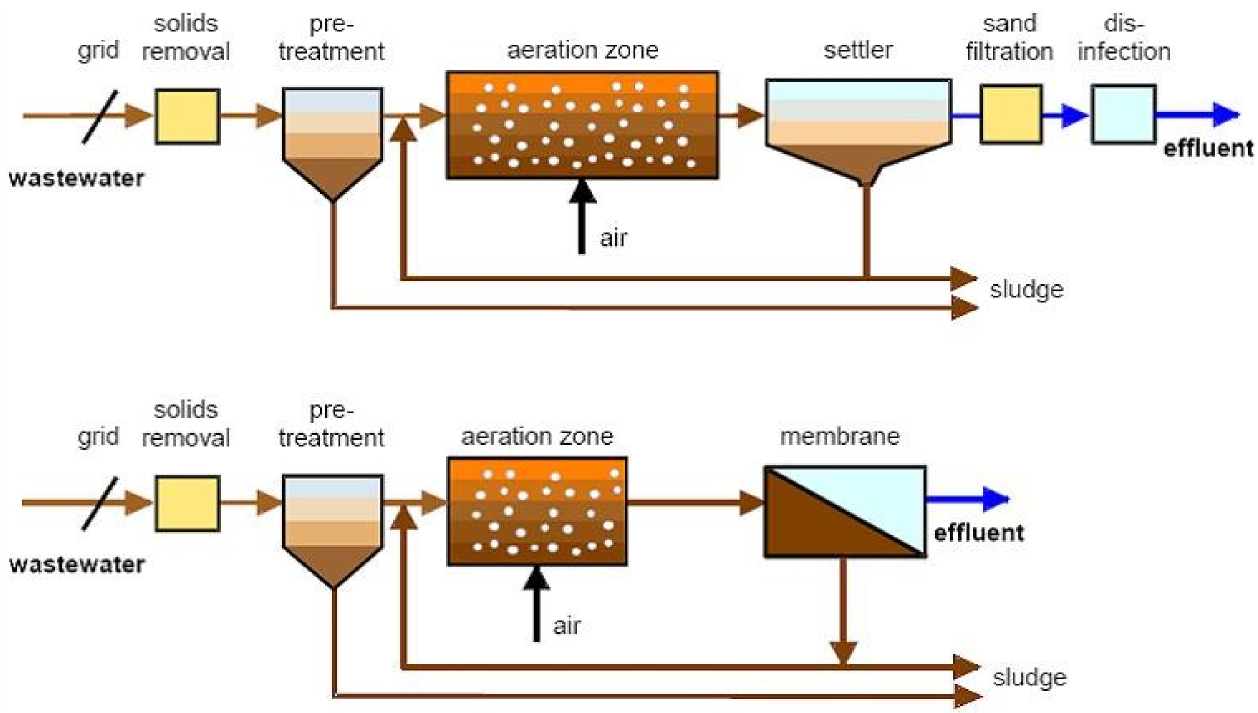

Figure 1. Comparison of treatment trains activated sludge process (above) versus membrane bioreactor (below) IN: Wikipedia, accessed using term Membrane Bioreactor 7/2/2021

Design concept of BioBarrier®

BioMicrobics® developed the BioBarrier membrane bioreactor in 2007. The technology was initially developed to allow water reuse projects to be permitted. The technology was first certified in 2011 under NSF/ANSI Standard 350 Onsite Residential and Commercial Water Reuse Treatment Systems (2021).

The heart of membrane technologies is the membrane material. The membrane in this technology has a pore size of 0.03 μm. This pore size qualifies as ultrafiltration (Figure 2). Bacteria and large viruses are retained (prevented from passing) by this membrane, while water, salts and dissolved materials pass through the pores (Figure 3).

In this technology, the membrane material is used to form parallel sheets. Multiple sheets are placed in parallel inside a plastic container called a cassette. Cassettes can be stacked on top of each other for high flow systems. Cassettes are immersed and wastewater is allowed to flow into the open spaces between sealed pockets of sheets. Vacuum is used to remove liquids that have passed through the membrane, called permeate, out of the treatment tank. Sheets to which vacuum will be applied are sealed to form a pouch or packet with a discharging vacuum tube.

Over time, particles begin to accumulate on the membrane surfaces. If these particles are not quickly removed from the membrane surface, they will form a microbial film, thereby reducing the membrane's efficiency. In this technology's case, coarse bubble diffusers (called BioRobic®) are placed at the base of each cassette stack. Large air bubbles have higher buoyancy and escape the diffuser at high velocity. As they pass through stacks of cassettes, the bubbles continuously scour the membrane surfaces and prevent biofilms from forming on the membrane's surface.

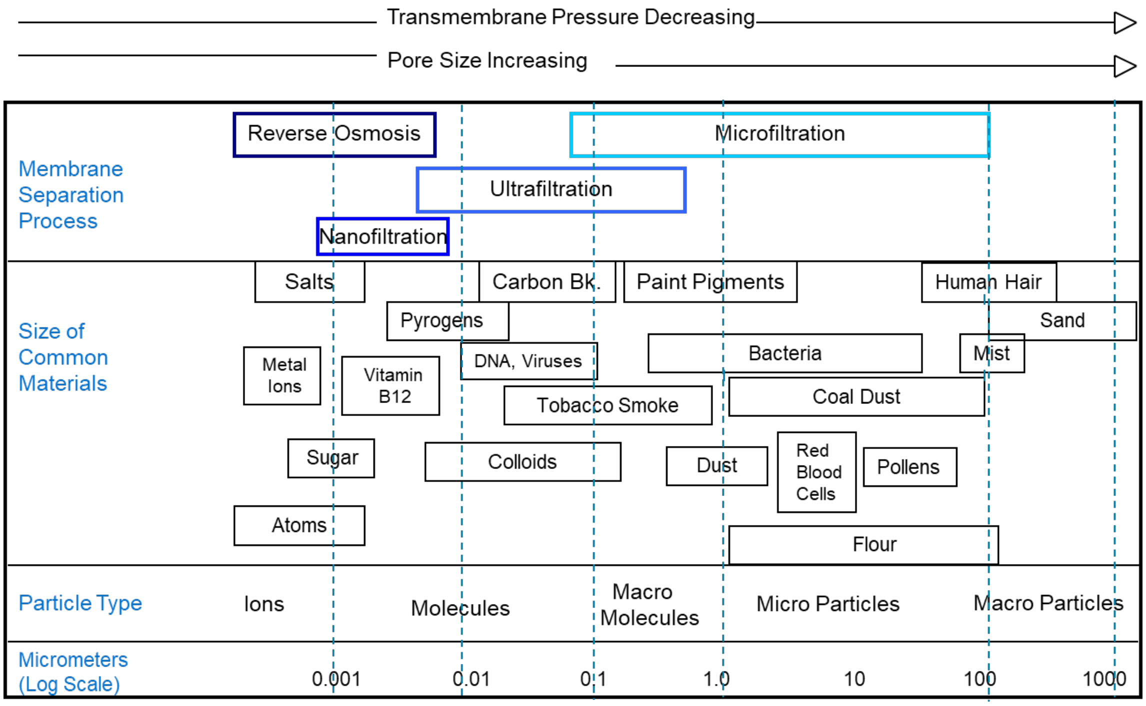

Figure 2. Sizes of various common materials compared to effective ranges of Microfiltration, Ultrafiltration, Nanofiltration and Reverse Osmosis membrane separation processes.

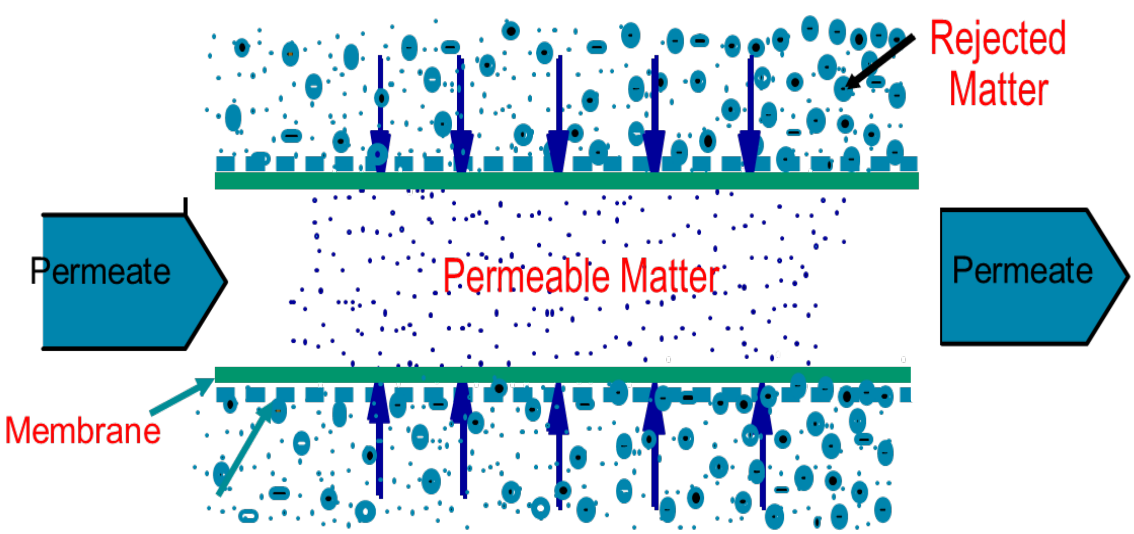

Figure 3. Cross-section view of parallel sheets of immersed membrane showing permeate and rejected matter

Methods

The high strength membrane bioreactor system (HSMBR) for Noquochoke Village was designed by Phil Cordeiro of Allen & Major Associates, Inc. The design was based on both hydraulic and organic considerations. The designer's decision to categorize the wastewater as high strength is supported by the lower infiltration and inflow in decentralized collection systems as compared to gravity sewer (Sample, Fox and Galbraith, 2014; Tchobanoglous, 2002). The treatment train is shown in Figures 4 and 5. Specific design enhancements are the use of MicroC® as a carbon source for more complete denitrification, addition of alkalinity (not used currently), addition of commercial grade effluent filters (SaniTEE®), addition of flow equalization tanks (cast in-place tanks), creation of two parallel treatment trains for easier servicing of the HSMBRs, and the addition of GeoFlow® drip irrigation fields to maximize passive nitrogen uptake by plants in the shallow root zone.

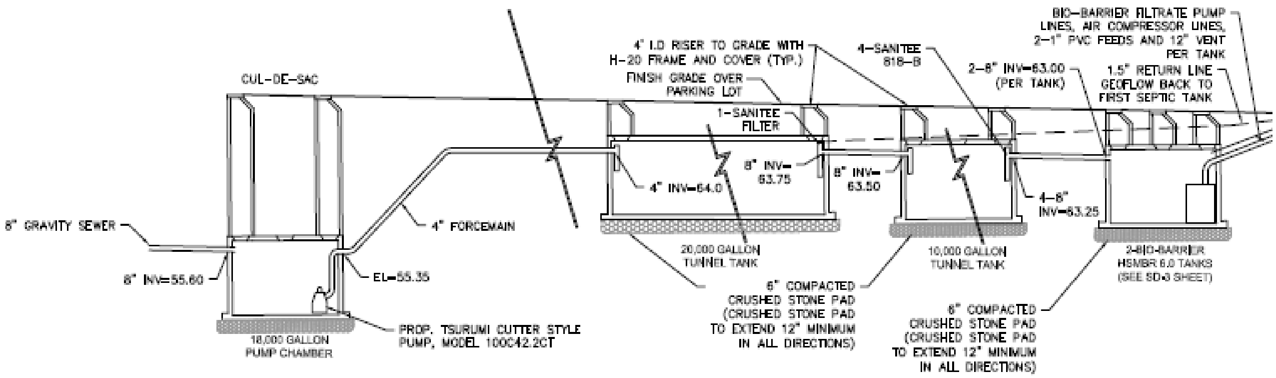

Figure 4. First half of treatment train at Noquochoke Village (Cul-de-sac pump chamber to HSMBRs)

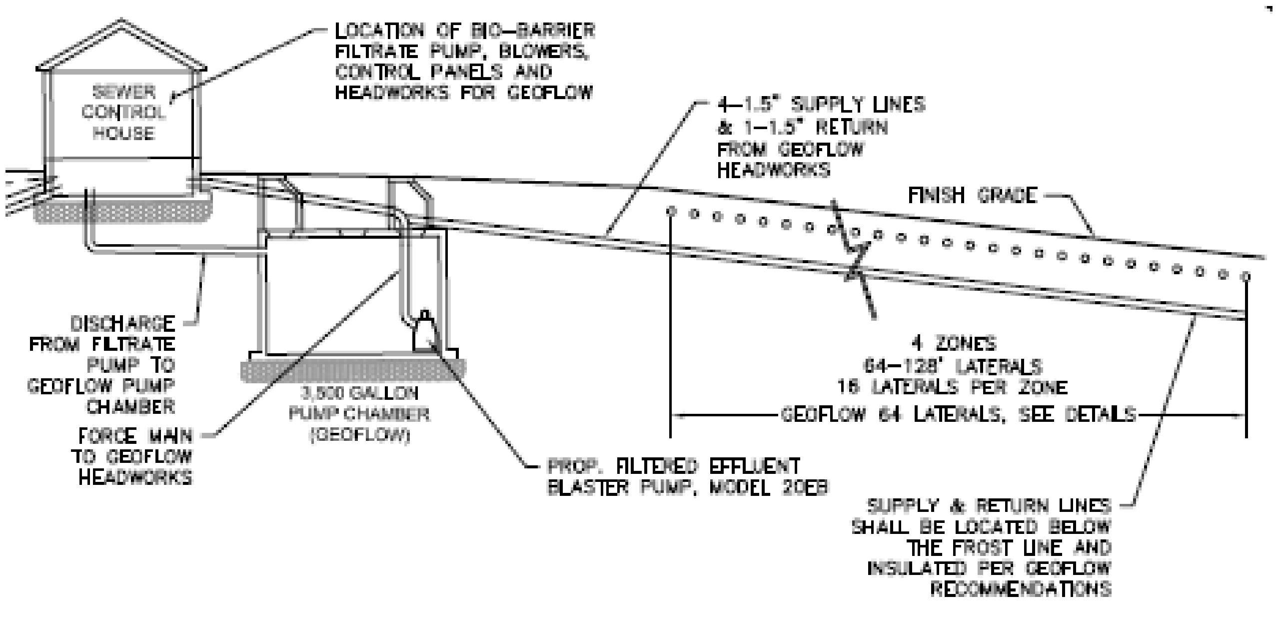

Figure 5. Second half of treatment train at Noquochoke Village (Sewer control house to drip fields)

Photographs of the system are provided in Figures 6 to 19.

Figure 6. 20,000-gallon cast in-place tank installation

Figure 7. Two of four SaniTEE® effluent filters installed in 10,000-gallon cast in-place tank


Figure 8. 10,000-gallon cast in-place tank (right) splits into two identical HSMBR treatment trains


Figure 9. Eight HSMBR cassettes stacked 2 high. Curved pipe is vacuum connection to cassettes.


Figure 10. Coarse bubble aeration early in system operation

Figure 11. HSMBR after pumping out excess solids and cleaning in place

Figure 12. Coarse bubble aeration of HSMBR with ~10,000 mg/L MLSS

Figure 13. Installed tanks with access lids to grade, (foreground parallel treatment trains)

Figure 14. Sewage control house

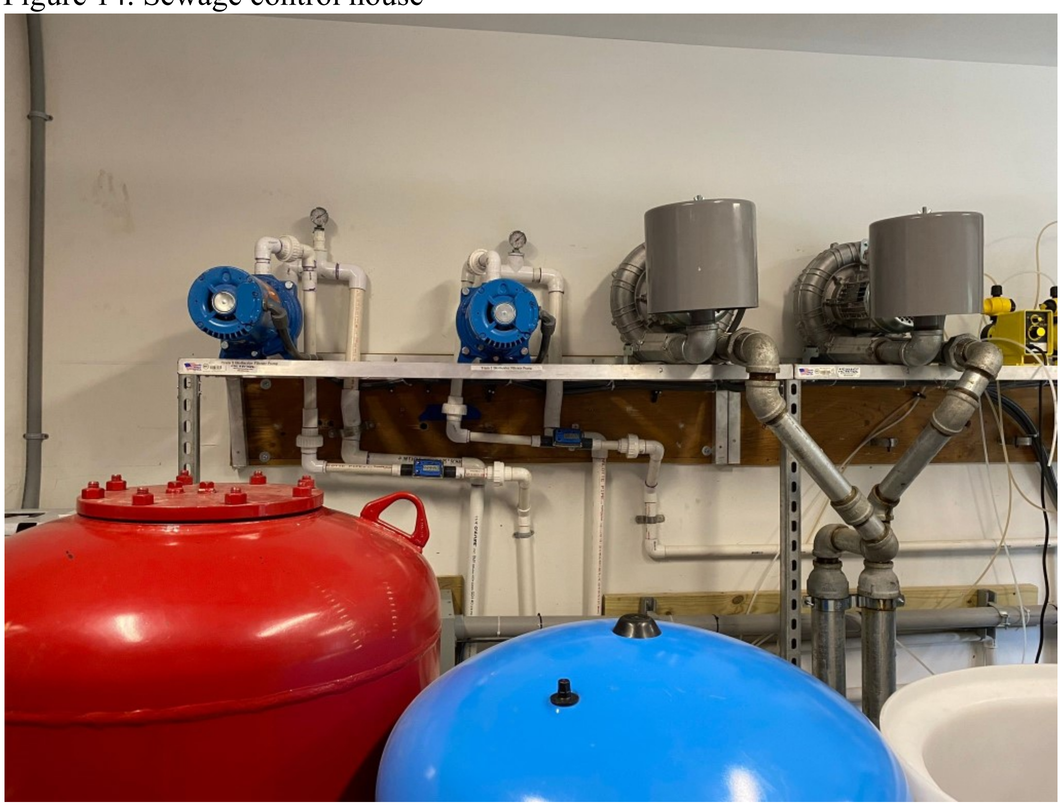

Figure 15. On wall inside sewage house 2 vacuum pumps, 2 linear blowers for coarse bubble diffusers

Figure 16. MicroC® supply delivered by yellow chemical feed pumps on wall

Figure 17. View of Noquochoke Village from across the street.

Figure 18. Permeate discharging to drip dose tank

Figure 19. Geoflow® drip line feeding header and footer installed below freeze depth

Statistical Considerations

The samples collected during this study should not be considered to be true replicates. They are more properly classified as repeated measures (Sokal and Rohlf, 1981). A helpful analogy about the statistical limitations of pseudoreplicates is found in Sherman, 2014.

As researchers increasingly investigate trace substances in the world's soil, air and water, they repeatedly find concentrations that are lower than the limits deemed reliable enough to report as a numeric value. As effluent limitation standards become more stringent and equipment manufacturers respond to the opportunity to provide products meeting these standards, the likelihood of encountering concentrations below detection limits will increase.

Nondetectable results from an analytical laboratory analysis indicate sample results less than the detection limit for the parameter in question. On the one hand, it would be unjustified and overly optimistic to assume that all nondetectable sample results are assumed absent (zero) for a specific parameter. It would also be inconsistent with the use of the best available science to assign the detection limit as the value of all nondetectable sample results. Such a method would produce a mean concentration that is biased high and confidence limits that were biased low.

The objective for data below laboratory detection limits is to make transparent, accountable and scientifically defensible decisions regarding assessing non-detectable results before (a priori) such samples arrive in a laboratory. In this case, nondetectable data were reported in Table 3 as half the detection limit. Additional options for handling such data are found in USEPA, 2006.

Results

The influent was grab sampled by Analytical Balance Corporation of Middleboro, MA from the 10,000-gallon cast in-place tank prior to effluent filtration twelve times from June 2019 to July 2021. The pandemic had a substantial impact on the frequency of influent sampling as six influent sampling events out of eighteen total site visits were eliminated due to COVID concerns. Influent results are given in Table 1.

The influent had an average flow of 4,724 gallons per day with the first five months having less flow as residents were being added to the community. The average BOD concentration was ~350 mg/L. The average TSS concentration was higher at ~510mg/L. The average TN concentration was ~105 mg/L. These influent concentrations combined are within the concentration ranges of a high-strength wastewater.

Table 1: Influent samples

Noquochoke Village		1163 American Legion Hwy. Westport MA				Dual 6.0-N HSMBR	
Raw Influent Data							
Date	daily flow (gpd)	BOD_5 (mg/L)	TSS (mg/L)	TN (mg/L)	Alk. (mg/L $CaCO_3$)	pH (unitless)	
7/21/2021	5588	196	54	48	290	6.6	
6/28/2021	6315	216	2110	264	394	6.5	
5/25/2021	4591	1150	1780	168	395	6.6	
4/30/2021	4570	390	310	97.3	371	6.6	
3/16/2021	4901	COVID	COVID	COVID	COVID	COVID	
2/12/2021	5133	COVID	COVID	COVID	COVID	COVID	
1/22/2021	4970	COVID	COVID	COVID	COVID	COVID	
5/28/2020	5515	COVID	COVID	COVID	COVID	COVID	
5/1/2020	3878	COVID	COVID	COVID	COVID	COVID	
4/1/2020	4975	330	56	86.5	345	6.9	
2/28/2020	7932	31.3	88	30.48	167	6.9	
1/27/2020	6202	COVID	COVID	COVID	COVID	COVID	
12/18/2019	6491	146	70	75	284	6.8	
11/22/2019	5068	408	140	90.4	337	6.5	
10/29/2019	3255	403	848	118.45	286	6.9	
8/30/2019	2530	295	54	97.3	329	6.9	
7/29/2019	1822	520	590	146	333	7	
6/28/2019	1289	105	16.5	36.7	202	7.3	
min value	1289	31.3	16.5	30.48	167	6.5	
max value	7932	1150	2110	264	395	7.3	
average	4,723.6	349.2	509.7	104.8	311.1	6.8	
median	4972.5	312.5	114	93.85	331	6.85	
std. dev	1678.4	290.0	720.3	64.8	70.5	0.2	
n (pseudo)	18	12	12	12	12	12	
Notes							
COVID = influent samples were not taken this month							

The same third-party laboratory grab sampled effluent at the dose tank for the Geoflow® drip system (see Figure 18). The table shows unmodified results from the project. One influent sampling date was cancelled due to COVID concerns. Substantial non-detect data were found with BOD_5 and TSS parameters. The results are shown without statistical evaluation in Table 2.

Table 2: Unmodified effluent data

Noquochoke Village		1163 American Legion Hwy. Westport MA				Dual 6.0-N HSMBR	
Raw Effluent Data							
Date	daily flow (gpd)	BOD_5 (mg/L)	TSS (mg/L)	TN (mg/L)	Alk (md/L $CaCO_3$).	pH (unitless)	
7/19/2021	5588	<4	<4	4.25	56.9	7.4	
6/28/2021	6315	<4	<4	2.9	73.6	7.2	
5/25/2021	4591	<4	<4	0.92	85.9	7.5	
4/30/2021	4570	<4	<4	5.28	43.5	7.5	
3/16/2021	4901	<4	<4	9.33	97.1	7.5	
2/12/2021	5133	<4	<4	7.15	69	7.5	
1/22/2021	4970	<4	<4	2.41	78	7.5	
5/28/2020	5515	<4	<4	3.9	63.7	7.5	
5/1/2020	3878	<4	<4	8.83	63.5	7.4	
4/1/2020	4975	<4	<4	3.64	80.6	7.7	
2/28/2020	7932	<4	<4	3.59	81.4	7.4	
1/27/2020	6202	COVID	COVID	COVID	COVID	COVID	
12/18/2019	6491	4.4	<4	5.43	81	7.7	
11/22/2019	5068	<4	<4	1.68	260	7.8	
10/29/2019	3255	<4	<4	1.9	108	7.9	
8/30/2019	2530	<4	<4	3.91	229	8.1	
7/29/2019	1822	<4	<4	6.8	94.2	7.8	
6/28/2019	1289	<4	<4	10.65	56.6	7.6	
Notes							
COVID = effluent samples were not taken this month							

In table 3 on the next page, all non-detect data were substituted with half the detection limit. In other words, all <4 values were replaced by 2 mg/L before statistical evaluation began. This one of the options provided by USEPA (2008) and the author it found to be more reasonable than accepting the detection limit as the inputted values. In other words, all <4 values could conceivably be replaced with 4 mg/L. Similarly, the author was equally unwilling to replace all the <4 values with 0 mg/L. The average total nitrogen for the HSMBR is 4.9. All values for this parameter were detectable.

Table 3: Effluent data with non-detect data substituted as half the detection limit.

Noquochoke Village		1163 American Legion Hwy. Westport MA				Dual 6.0-N HSMBR	
Effluent non-detect data substituted to half the detection limit							
Date	daily flow (gpd)	BOD_5 (mg/L)	TSS (mg/L)	TN (mg/L)	Alk. (mg/L $CaCO_3$)	pH (unitless)	
7/19/2021	5588	2	2	4.25	56.9	7.4	
6/28/2021	6315	2	2	2.9	73.6	7.2	
5/25/2021	4591	2	2	0.92	85.9	7.5	
4/30/2021	4570	2	2	5.28	43.5	7.5	
3/16/2021	4901	2	2	9.33	97.1	7.5	
2/12/2021	5133	2	2	7.15	69	7.5	
1/22/2021	4970	2	2	2.41	78	7.5	
5/28/2020	5515	2	2	3.9	63.7	7.5	
5/1/2020	3878	2	2	8.83	63.5	7.4	
4/1/2020	4975	2	2	3.64	80.6	7.7	
2/28/2020	7932	2	2	3.59	81.4	7.4	
1/27/2020	6202	COVID	COVID	COVID	COVID	COVID	
12/18/2019	6491	4.4	2	5.43	81	7.7	
11/22/2019	5068	2	2	1.68	260	7.8	
10/29/2019	3255	2	2	1.9	108	7.9	
8/30/2019	2530	2	2	3.91	229	8.1	
7/29/2019	1822	2	2	6.8	94.2	7.8	
6/28/2019	1289	2	2	10.65	56.6	7.6	
min value	1289	2	2	0.92	43.5	7.2	
max value	7932	4.4	2	10.65	260	8.1	
average	4,723.6	2.1	2.0	4.9	95.4	7.6	
median	4972.5	2	2	3.91	80.6	7.5	
std. dev	1678.4	0.6	0.0	2.8	58.6	0.2	
n (pseudo)	18	17	17	17	17	17	
Notes							
nd= not detected < data converted to 0.5 detection limit					**(<4 reported as 2)**		
COVID = effluent samples were not taken this month							

Discussion

Reviewing the data in Table 3, alkalinity and Total Nitrogen appear to have a worrisome correlation. With a few exceptions, whenever the alkalinity was 81 mg $CaCO_3$/L or less, the TN was above 4 mg/L. Alkalinity is a measure of the pH buffering ability of a liquid. Nitrifying bacteria consume approximately 7.1 pounds of alkalinity per pound of ammonia converted to nitrate. The loss of alkalinity must be considered serious as the nitrifying bacteria are inhibited by acidic conditions (Oakley, 2005). The author has recommended small amounts of alkalinity be added to the system (target effluent alkalinity above 100 mg $CaCO_3$/L) in hopes of continuing the attainment of stringent total nitrogen concentrations for the project.

Conclusion

This HSMBR system has shown robust performance for the last 2+ years. Operation and maintenance have been limited to pumping out excess solids and cleaning the membranes using in-place procedures every six months. This fall, a thorough cleaning of the membranes is planned.

This experience to date gives hope that achieving stringent total nitrogen effluent limits is possible for membrane-based decentralized wastewater technologies when design enhancements and reliable operation and maintenance services are included with the system.

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