Presented at 2007 Virginia AWWA/WEA Water JAM

THE DESIGN ELEMENTS OF STATE-OF-THE-ART TREATMENT TECHNOLOGY: MBR WASTEWATER TREATMENT SYSTEMS

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Abstract

The Virginia Water Quality Improvement Act of 1997 was enacted in response to the need to finance the nutrient reduction strategies being developed for the Chesapeake Bay and its tributaries. Pursuant to the Act, the Commonwealth established in the State treasury a special permanent, nonreverting fund known as the "Virginia Water Quality Improvement Fund." Legislation passed during the 2006 legislative session (SB644 – Watkins) amended the Water Quality Improvement Fund with respect to several issues. Notably, SB644 included a change to the numerical concentration limits in grant agreements so that they are based upon the technology installed at the facility ("technology-based limits"). To further facilitate and assure an equitable grant process, DEQ developed guidance memorandum (GM) #06-2012. Both the GM and the waste load allocation regulation (9 VAC 25-820-10) currently define "state-of-the-art nutrient removal technology" as technology that will achieve an annual average total nitrogen effluent concentration of 3 mg L^{-1} and an annual average total phosphorus effluent concentration of 0.3 mg L^{-1}, or equivalent load reductions in total nitrogen and total phosphorus through recycle or reuse of wastewater as determined by the Department. The proven technologies for compliance with this definition include biological nutrient removal with supplemental carbon and phosphorus removal by using a physiochemical precipitation process. A membrane bioreactor (MBR) is a wastewater treatment process that can be coupled with a biological nutrient removal and physiochemical process to meet the need for supporting the Water Quality Improvement Act. Currently, the team comprised of HRSD, DEQ and McKim & Creed has identified the minimum design requirements of a MBR Wastewater Treatment System to comply with the permitted effluent requirements for the wastewater system and the current state-of-the-art nutrient removal requirements for nitrogen and phosphorus limits. This paper will address the fundamental design requirements needed for the MBR wastewater treatment system's compliance with the regulated effluent limits and include a discussion of technical issues that were accounted for in the process analysis. The paper will also include a discussion of biological modeling as a means to help evaluate the design criteria. The information presented in this paper should help engineers, regulatory agencies, and owners address the minimum requirements for initiating a MBR wastewater treatment system.

Introduction

The Virginia Water Quality Improvement Act of 1997 was enacted in response to the need to finance the nutrient reduction strategies being developed for the Chesapeake Bay and its tributaries. Pursuant to the Act, the Commonwealth established in the State treasury a special permanent, nonreverting fund known as the "Virginia Water Quality Improvement Fund." Legislation passed during the 2006 legislative session (SB644 – Watkins) amended the Water Quality Improvement Fund with respect to several issues. Notably, SB644 included a change to the numerical concentration limits in grant agreements so that they are based upon the technology installed at the facility ("technology-based limits"). To further facilitate and assure an equitable grant process, DEQ developed guidance memorandum (GM) #06-2012. Both the GM and the waste load allocation regulation (9 VAC 25-820-10) currently define "state-of-the-art nutrient removal technology" (SOA) as technology that will achieve an annual average total nitrogen effluent concentration of 3 mg L^{-1} and an annual average total phosphorus effluent concentration of 0.3 mg L^{-1}, or equivalent load reductions in total nitrogen and total phosphorus through recycle or reuse of wastewater as determined by the Department. The proven technologies for compliance with this definition include biological nutrient removal with supplemental carbon and phosphorus removal by using a physiochemical precipitation process. The membrane bioreactor (MBR) was a wastewater treatment process that can be coupled with biological nutrient removal and physiochemical process to meet the need for supporting the Water Quality Improvement Act (WQIA).

Given the King William Wastewater treatment plant, located in King William County, Virginia, provides service to several small commercial establishments, a car wash, and residential dischargers, a need was identified to expand the existing facility as a small wastewater system. Currently, the flow is about 15,000 gallons per day and has been identified to be expanded to 100,000 gallons per day for service to primarily residential growth. Due to the stringent environmental regulation, conventional waste activated sludge wastewater treatment plants may not provide the level of treatment required to comply with 3 mg L^{-1} nitrogen and 0.3 mg L^{-1} phosphorus in the effluent. Coupled with the need for meeting the new WQIA discharge limits was the need for: handling variable flow; providing a reasonable economic solution; success in treating high ammonia wastewater; and satisfying the potential relocation of the treatment works, thus involving an abandonment of the existing treatment plant site in the future. A project goal was established to deploy a SOA treatment system that would comply with these conditions through use of a MBR wastewater treatment system.

The MBR wastewater treatment system has gained wide use in the US (Yang *et al.*, 2006) and its application would achieve the desired performance based on the influent conditions and wastewater characteristics. Previous study for small wastewater treatment systems indicated that the MBR wastewater treatment systems were economical and could meet variable influent characteristics, performance objectives, and site constraints (Cole, 2002). The MBR treatment system has been demonstrated to: reduce BOD greater than 98% (Kishino *et al.*, 1996); reduce COD 84% (Fan and Haung, 2002), 94% (Bracklow *et al.*, 2007) (Wang *et al.*, 2005), 95% (Rosenberger *et al.*, 2002), 97% (Badani *et al.*, 2005) (Atiga *et al.*, 2005) to 98% (Al-Malack *et al.*, 2007); produce a consistent NH_4^+-N^+ removal rate 91% (Wang *et al.*, 2005), 94% (Kishino *et al.*, 1996), 98% (Fan and Haung, 2002), and 99% (Gao *et al.*, 2004a); exhibit a consistent nitrate removal for wastewater through denitrification (Wasik *et al.*, 2001), 60% denitrification (Yamamoto *et al.*, 1989), 74% TN removal (Wang *et al.*, 2005), and 82% nitrogen removal (Rosenberger *et al.*, 2002); provide 5-log removal of E. *coli* (Ottoson *et al.*, 2006); and eliminate greater than 97% phosphorus (Bracklow *et al.*, 2007). MBR performance for wastewater containing ammonia was found to be completely converted NH_4^+-N to NO_3^--N as compared to a conversion rate of 95% for conventional activated sludge processes (Gao *et al.*, 2004b).

Due to differences in MBR wastewater treatment systems' manufacture, membranes, site and operational constraints, several objectives were identified for the design of the King William Wastewater treatment system. The key objective was to identify design elements for the MBR wastewater treatment system that would provide reasonable result toward accomplishing the established project goal.

Technical Evaluation

Because there were multiple MBR wastewater treatment systems capable of complying with the project, the design elements were divided into three primary categories. These were use of existing facilities, treatment performance, and portability.

Existing Facilities

The MBR SOA treatment system criteria considered the maximum use of existing treatment facilities. These considerations included a systematic evaluation of the condition of the existing facility from the plant intake to the existing outfall, Figure 1. Beginning at the plant intake, existing course screening works were identified and these screens were identified to remain. The gravity pipe located from the intake works to the existing treatment facilities was checked to confirm future capacity.

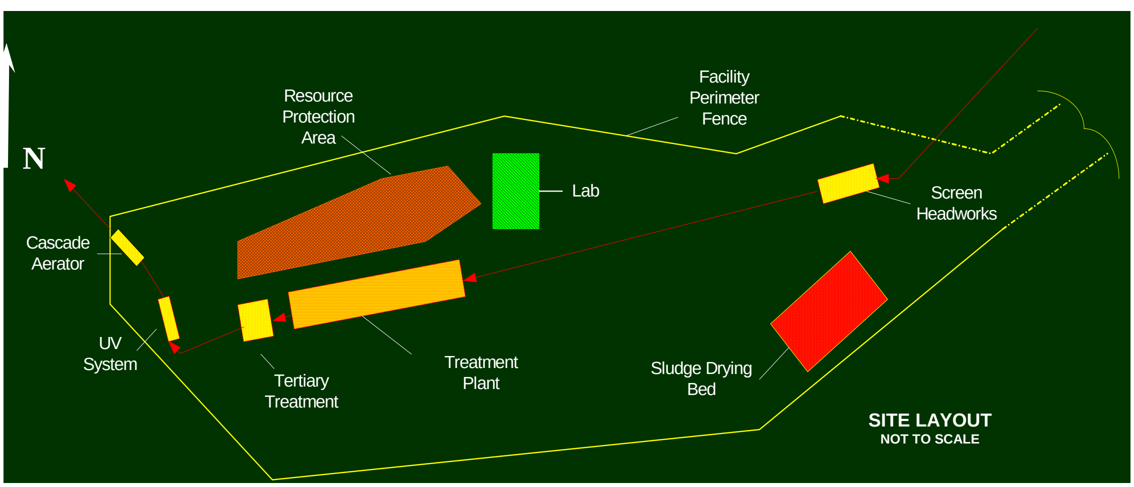

Figure 1. Existing Wastewater Treatment Facility Schematic Diagram
Diagram By: Yasuhito Kai, Nicole Turnbull, John Donohue, Ram Prasad
Civil and Environmental Engineering Dept., Old Dominion University, Norfolk, May 2004

The existing 25,000 gallon per day wastewater treatment plant was a conventional waste-activated treatment plant built and installed in ground. The existing treatment plant was evaluated for 1) use during construction of the new MBR facilities, 2) material condition, and 3) future use. Based on assessment of the existing facility, it was determined that its best value for use was that of an equalization facility. The MBR SOA system can normally tolerate variable flows and loading rates (Stepehson *et al.*, 2000) and does not normally require flows equalization; however, the perceived advantage for use of the existing treatment plant as tankage was included, Figure 2.

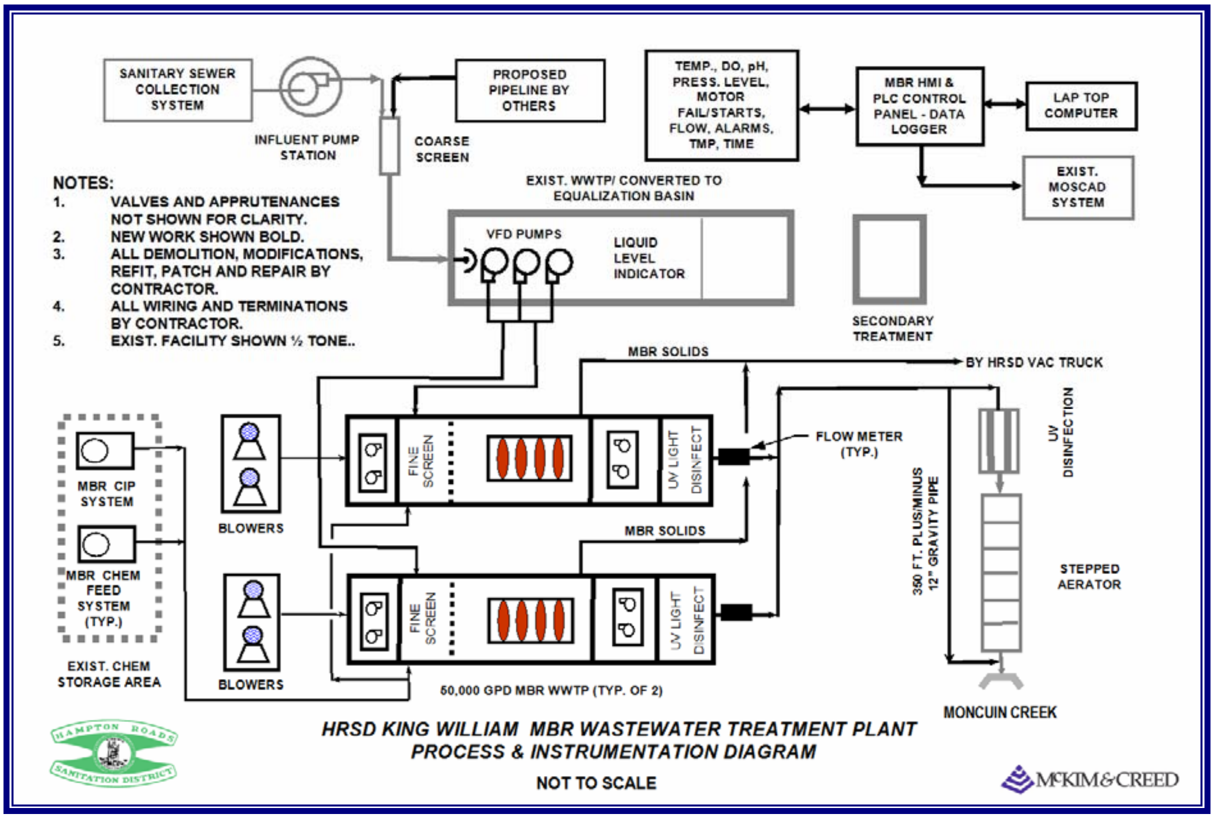

Figure 2. MBR Process Schematic.

The existing sand drying beds were not considered to be needed for solids handling, as operations intended to use trucks for hauling solids on a routine biweekly basis. Other existing facilities that would not be needed for the MBR system included use of the existing UV disinfection system, sand filters located downstream of the wastewater treatment plant, and the aeration steps located ahead of the outfall. The concrete-stepped aerator would be converted to a flow chamber for use as a compliance monitoring sample point that helped to improved hydraulic performance at increased plant flow. Outfall piping was checked to confirm that the line was suitable for future flows.

Treatment Performance

The treatment performance of the MBR to meet the project goal was identified by indicating the criteria for effluent limits. MBR systems have been proven successful to meet stringent effluent requirements and this has been demonstrated by reuse requirements (Ernst *et al.*, 2007) that exceed wastewater permit requirements and wastewaters that contain surfactants (Dhouib *et al.*, 2005). The MBR wastewater treatment system design elements include those parameters in Table 1 for the limits for wastewater effluent:

Table 1
MBR System Effluent Parameters

Parameter		Value	Remarks
Daily flow, gpd	Initial Start-Up Flow	30,000	
	Average Daily Flow	100,000	
	Maximum Daily Flow	200,000	
	Peak Hourly Flow	250,000	
$cBOD_5$, mg L^{-1}	Influent:	208 to 674	(Carbonaceous BOD)
	Effluent	≤ 10 (Monthly Average)	
	Effluent	≤ 15 (Weekly Average)	$cBOD_5$ must be reduced by at least 85% of influent.
TSS, mg L^{-1}	Influent	218 to 744	
	Effluent	≤ 10 (Monthly Average)	
	Effluent	≤ 15 (Weekly Average)	TSS must be reduced by at least 85% of influent.
Dissolved Oxygen, mg L^{-1}	Influent (Estimated)	Zero	
	Effluent	≥ 5.0	
pH	0 to 14 S.U		
	Influent	6.8 to 7.5	
	Effluent	6.0 to 9.0	
E. *Coli*, n/100 mL	Influent	Unknown	
	Effluent	126 (geometric mean)	
Nitrogen, mg L^{-1}	Influent		
	TKN	25.9 to 186	
	TKN (average)	71.3	
	NH_3	7.5 to 74.6	
	NH_3 (average)	40	
	Effluent	≤ 3.0 (Monthly Average)	Permitted value
	Effluent	≤ 4.5 (Weekly Average)	
Total Phosphorous, mg L^{-1}	Influent	5.9 to 41.1	
	Influent (average)	10.4	
	Effluent	≤ 0.3	Permitted value
Temperature, °C	Influent	12 to 25	
	Effluent	Ambient	

Alkalinity, mg L^{-1} as $CaCO_3$	Influent	117 to 362
	Influent (average)	264.9
	Effluent	75

The system configuration to meet these effluent limits generally consisted of two individual 50,000 gallon per day MBRs, including all biological tanks, membrane operating tanks, influent screening and an UV disinfection system. The MBR system was identified to contain membrane tank with manifolds and supports for containing the membranes and the membranes comprised of either proprietary, PVDF, or polyethylene materials with a pore size not more than 0.1 micron or as required to meet the project conditions. The system would also be required to contain a filtration manifold, air manifold and mixed liquor manifold. Each of the membrane tanks was to be large enough to contain the required number of membranes, sized to remove the membranes for replacement or service, and be separated from the remainder of the process volume for the required biological reactions. The membrane tanks could form part of the aerobic biological treatment volume. The mixed liquor was identified to be fed to the membrane tanks from the remainder of the biological system along with air. The MBR system configuration was typical in that all membranes were connected to a common permeate header and pumps, with permeate ultimately passing through the membranes to the existing wastewater plant outfall. The system also included in-place chemical cleaning with the needed piping and valves to allow automatic flushing of all membrane manifolds and appurtenances with cleaning chemicals. Automation in the system's control and monitoring functions was devised to assist in the reduction of staff time on site.

Computer Modeling

Many designs and processes are possible and the calculations used to support these designs can be complex. To help develop a systematic method for interpretation of the processes with their respective calculations and results, computer modeling was used. This computer modeling includes all major unit processes, calculations, and results indicating influent data and compliance with effluent requirements. Computer software such as *BioWin*™ (version 2.2) by EnviroSim Associates Ltd. uses a general Activated Sludge/Anaerobic Digestion model which is referred to as the BioWin General Model. The model includes 50 state variables and 60 process expressions where these expressions are used to describe the biological processes occurring in activated sludge and anaerobic digestion systems and several chemical precipitation reactions. Although the model was not calibrated, the model helps to provide a benefit for use in prediction of the system performance, future operations and decision making. The arrangement processes unique to the *BioWin*™ computer model would be similar to Figure 3.

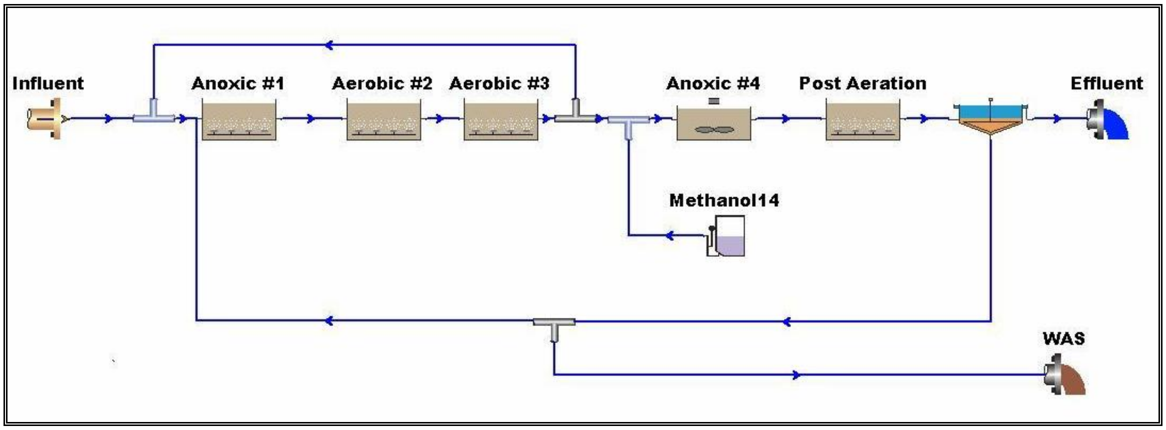

Figure 3. Typical process arrangement *BioWin™* computer model for MBR wastewater treatment system. Courtesy of Reid Engineering Company, Inc. (540-371-8500).

Portability

The existing activated sludge wastewater treatment plant was constructed circa 1999. The facility with lands are currently leased from the County. The site was small and limited in the amount of space that could be built out. The site, however, was found to be of an adequate size to accommodate an initial 100,000 gpd MBR treatment facility suitable for a design life expectancy of 20 years with an expansion of an additional 100,000 gpd MBR treatment plant. Future flows to the treatment plant beyond 200,000 gpd will require expansion beyond the capability of the existing site to support any further expansion. Should the plant require additional space for expansion, the new MBR treatment plant will be relocated. As a design element to the project, the MBR wastewater treatment system was required to incorporate portability. The portable nature of the MBR wastewater treatment facility generally included removing all primary systems. This portability was also demonstrated by the methods used for installation, Figure 4.

Figure 4. Portability of the MBR Wastewater Treatment System as Demonstrated by Installation Method.

Conclusions

The design elements identified for a MBR wastewater treatment system were found successful for facilitating start up and operation of the facility, and for meeting the intended wastewater effluent quality objectives and results. All effluent requirements identified have been satisfied. Use of existing treatment facilities have been found to enhance operation of the MBR system. In addition to compliance with stringent regulatory discharge requirements, the significant benefit gained from the use of MBR treatment system was project schedule. The total duration from project conception to substantial completion was approximately 11 months. Other inherent value of the MBR treatment system was the portability of the system that was also identified as critical toward the system's total suitability for use. As the MBR treatment system effluent quality has been found to exceed regulatory requirements and project expectations, the system can be relocated in the future for use at other locations as a satellite or scalping plant.

Throughout the project development, from initial conception, design, shop drawing review, to installation, it was noted that a strong team comprised of the Owner (HRSD), Engineer (McKim & Creed, PA), Regulatory Authority (DEQ), Contractor (MEB), and MBR Equipment Manufacturer (Heyward, Inc.) was critical toward the project's overwhelming success. In particular, open communications and a willingness to participate in value engineering by all team members turned this very good project into an excellent project.

The design elements selected for the MBR wastewater treatment system resulted in a system that met and exceeded the established project objectives and goal. The benefits gained from use of an MBR SOA system will improve our environment and help meet regulatory requirements well into the future.

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