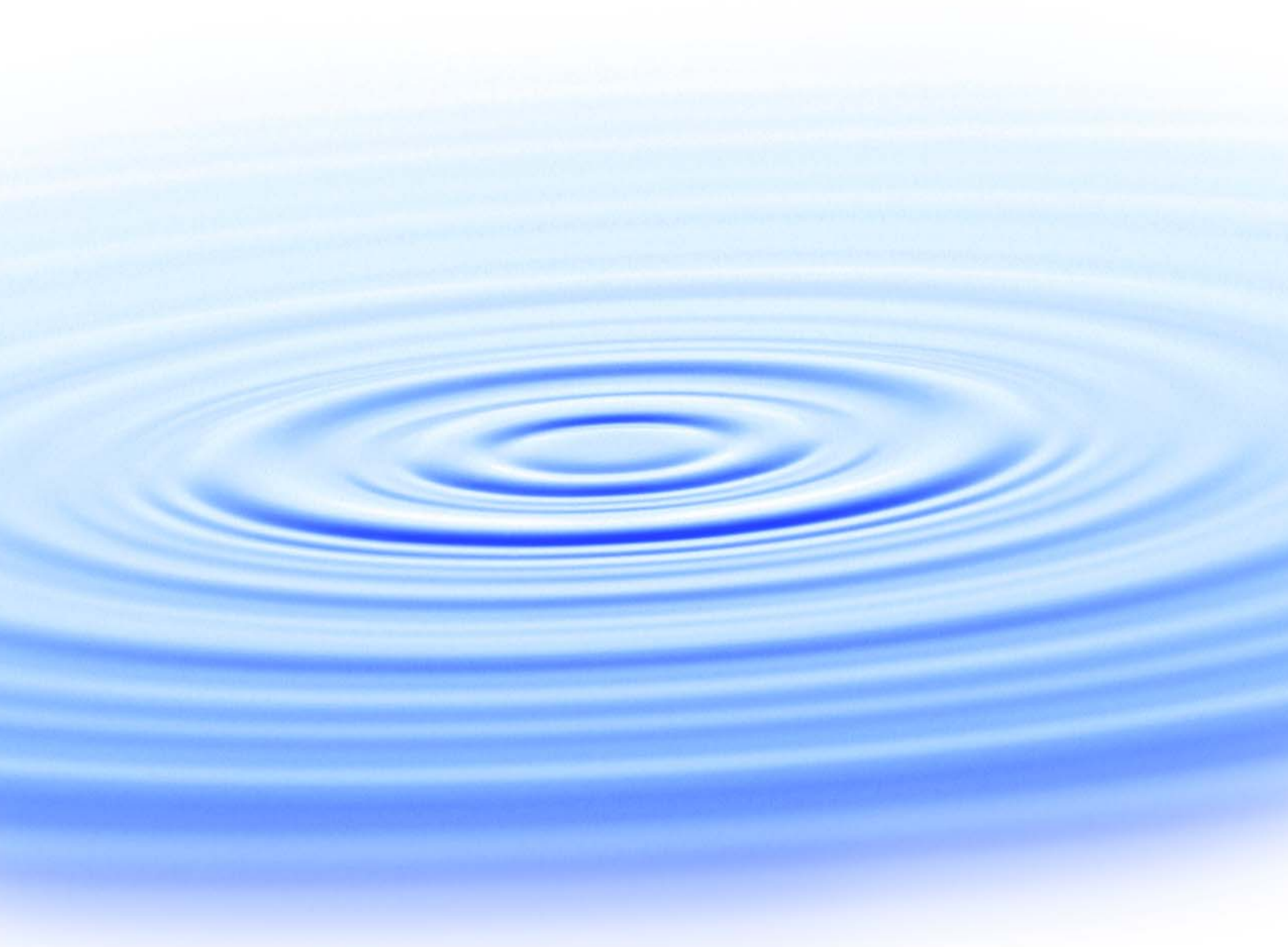
Investigation of Membrane Bioreactor Effluent Water Quality and Technology



WateReuse Research Foundation

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About the WateReuse Research Foundation

The mission of the WateReuse Research Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's subscribers, water and wastewater agencies, and other interested organizations.

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Acronyms and Abbreviations

AOB	ammonia oxidizing bacteria
AOC	assimilable organic carbon
ASP	activated sludge process
BAP	biomass-associated products
BAP_L	biomass-associated products (large)
BAP_S	biomass-associated products (small)
BDOC	biologically degradable organic carbon
BOD	biochemical oxygen demand
BOM	biological organic matter
BPR	biological phosphorus removal
CAS	conventional activated sludge
$CBOD_5$	carbonaceous biochemical oxygen demand (5-day test)
CFU	colony-forming units
COD	chemical oxygen demand
DNA	deoxyribonucleic acid
DO	dissolved oxygen
EBRP	enhanced biological phosphorous removal
EDTA	ethylenediaminetetracetate
EfOM	effluent organic matter
EPA	Environmental Protection Agency
EPS	extracellular polymeric substances
EDC	endocrine disrupting compound
EfOM	effluent organic matter
F/M	food-to-microorganism ratio
FOTE	field oxygen transfer efficiency
GAC	granular activated carbon
gfd	gallon per square foot per day
HRT	hydraulic retention time
K_B	biological degradation constant
k_D	Partition coefficient
K_H	Henry's Constant
kWh	kilowatt hour
lmh	liters per square meter per hour
LRV	log removal value
MBR	membrane bioreactor

MCRT	mean cell residence time
mgd	million-gallons per day
mg/L	milligram per liter
MJ/m^3	millijoule per cubic meter
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
MWH	Montgomery Watson Harza Americas, Inc.
NOB	nitrite oxidizing bacteria
NTU	nephelometric turbidity units
O&M	operations and maintenance
ORP	oxidation reduction potential
P	phosphorus
PAC	Project Advisory Committee
PFU	plaque-forming units
PE	polyethylene
PES	polyethersulfone
PAO	phosphorus accumulating organisms
PHB	polyhydroxybutyrate
PPCP	pharmaceutical and personal care product
PVDF	polyvinylidenedifluoride
Q	flowrate
QA/QC	Quality Assurance/Quality Control
RAS	return activated sludge
RNA	ribonucleic acid
RO	reverse osmosis
SMP	soluble microbial products
SOTE	standard oxygen transfer efficiency
SRT	solids retention time
SS	suspended solids
SNdN	simultaneous nitrification-denitrification
T	temperature
TAC	Technical Advisory Committee
TIN	total inorganic nitrogen
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TMP	transmembrane pressure
TN	total nitrogen
TSS	total suspended solids
UAC	Utility Advisory Committee
UAP	utilization-associated products
VSS	volatile suspended solids
WHO	World Health Organization

Foreword

The WateReuse Research Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities including water professionals, academics, and Foundation subscribers. The Foundation's research focuses on a broad range of water reuse research topics including:

- Defining and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

The Operating Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The Foundation's primary funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and other funding relationships.

The primary objective of this study is to achieve a better understanding of the effluent quality produced from a Membrane Bioreactor (MBR) system as a function of MBR design and operating conditions and how this quality compares with the effluent produced from conventional activated sludge treatment systems.

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Koch/Puron
Huber
Kruger/Toray
Norit/Parkson
Pall/Asahi Kasei

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- City of Healdsburg, CA, Jim Flugum
- City of Delphos, OH, Kim Riddell
- EFS/IWS Cauley Creek, Duluth, GA, Don Dodson
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- Erftverband, Kaarst, Germany, Christoph Brepols
- United Utilities, Over Kellet, United Kingdom, Richard Ratcliff
- Northern Ireland Water, Loughguile, Northern Ireland, Paul Byers
- Wessex Water, United Kingdom, John Baker
- Waterboard Hollandse Delta, The Netherlands, J.O.J Duin
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Executive Summary

Membrane Bioreactor (MBR) technology has become well established worldwide over the last decade as an activated sludge process option for advanced treatment and recycling of municipal and industrial wastewater. The advantage of MBR technology over a conventional activated sludge (CAS) process derives from the use of a membrane in place of a clarifier and media filtration. The membrane avoids the need for limiting mixed liquor suspended solids (MLSS) concentration in the reactor, which further decouples the volumetric loading rate from the solids separation process and results in consistent removal of colloids and particles within a smaller reactor footprint. The extent to which superior solids separation and the flexibility to operate at higher solids retention time (SRT) coupled with lower hydraulic retention time (HRT) impact other water quality parameters (e.g., microbes, aggregate organics, nutrients, trace organic compounds, and trace metals) is the main focus of this study. MBR water quality performance was assessed through integration of data obtained from peer-reviewed and grey literature, analysis of survey responses obtained from full-scale MBR installations, and development of an MBR predictive model for aggregate organics and trace organic compounds. A worldwide MBR vendor survey was performed prior to the facility survey in order to ensure the selection of representative installations.

The vendor survey clearly demonstrates the growth in application of MBR technology over the past 10 years. A 300% increase in installed cumulative capacity occurred from 2004 to 2008, and the United States presently dominates the growth market. Installations larger than 10 million gallons per day (MGD) are occurring in all regions of the world, and the number of suppliers is expanding. Water quality reliability and footprint restrictions were cited as the major drivers for MBR process selection. The majority of the surveyed installations utilize polyvinylidenedifluoride (PVDF) hollow fiber membranes. The facility survey participants employ SRT design values ranging from 11 to 30 days and 80% of them maintain MLSS values between 4,200–12,000 milligrams per liter (mg/L). The average flux values were reported to be less than 15.5 gallons per square foot per day (gfd) or 26.3 liters per square meter per hour (lmh) for 80% of the surveyed installations, and the ratio of operating flux to design flux ranged from 0.67 to 2.6. MBR systems may utilize more energy than CAS because of the scour air required to maintain the specific flux of the membranes. Surveys reported power requirements of four MBR facilities with approximately 1 MGD (3,785 m^3/day) flow rates ranged from 0.8 to 1.6 kWh/m^3 (2.9–5.8 millijoule per cubic meter (MJ/m^3), which is higher than the 0.7 kWh/m^3 (2.5 MJ/m^3) for a CAS process that included nitrification and filtration (Metcalf and Eddy, 2003). However, the membrane filtration utilized in the MBR process produces better effluent water quality compared to media filtration. It should also be noted that biological process configuration employed to achieve required water quality goals as well as percentage utilization (operating capacity/design capacity) of the facility may also result in different power requirements.

The fate of biodegradable aggregate organics in a bioreactor is dependent on synthesis of active biomass, production of biomass utilization-associated products (UAP), production of extracellular polymeric substances (EPS) that bind to the biomass, or substrate respiration. The key activated sludge operational parameters of an MBR that control removal of aggregate organic matter are SRT, influent chemical oxygen demand (COD) concentration, HRT, and dissolved oxygen (DO). The model developed for this project incorporated the impact of having an immersed membrane in the reactor basin on the disposition of residual

aggregate organic products between the effluent and biosolid phases of the reactor. The model was derived by modifying and then merging the activated sludge design model described by Rittmann and McCarty (2001) with the Laspidou and Rittmann (2002a, 2002b) unified model of EPS, soluble microbial products (SMP), and active and inert biomass. The oxygen demand/process air and power requirements are included in the model but do not include air scour for membrane maintenance. The model demonstrates the relationship between input parameters of SRT, HRT, influent COD, DO, and the fraction of biologically associated products assumed small enough to pass through the membrane and process output parameters of MLSS and COD removal. The model demonstrates that increasing the SRT from 2 to 15 days will increase total biodegradation of organic matter slightly, but no further biodegradation is observed when the SRT increases from 15 to 50 days. Fairly constant effluent COD is also observed when increasing the HRT at constant SRT and influent COD concentration.

Findings from the literature and facility survey showed effluent COD values of 6 to 30 mg/L for municipal sources without industrial input and percentage removals fairly constant of approximately 92 to 93% regardless of operating conditions. Only a change in the influent COD concentration appears to have much influence on the effluent COD. MBR effluent has also been shown to produce lower levels of assimilable organic carbon (AOC) and biologically degradable carbon (BDOC) (Jjemba et al., 2009), which indicates that MBR effluent should be less prone to biological regrowth in reuse distribution systems.

With respect to microbial contaminants, the MBR process produces superior water quality compared to conventional wastewater treatment processes because the membrane provides an absolute barrier to many pathogenic organisms and particulate matter that also increases the efficacy of subsequent disinfection processes. Size exclusion is the predominant removal mechanism for bacteria (i.e., coliforms), but indigenous viruses such as coliphages have also shown good removal that is due to adsorption to the membrane surfaces and membrane attached biofilm as well as adsorption to the sludge. MBR removal of coliphage can be impacted by permeate flux and filtration resistance, feed phage concentration, and MBR operational parameters of SRT, MLSS, and food-to-microorganism ratio (F/M). Literature findings demonstrate 5–6 log removal of coliforms by MBRs, 5–7 log removal of fecal coliforms, and 2.3–4.5 log removal of indigenous coliphages. Total and fecal coliforms have been reported in MBR permeate, but these occurrences are believed to arise from contamination or removal of the dynamic cake layer on the membrane surface or membrane integrity maintenance issues. Facility survey effluent coliform concentrations ranged from <1 colony-forming units (CFU)/100 mL to 53 CFU/100 mL, which should represent approximately 5–6 logs of reduction for typical municipal influent coliform levels.

Facility survey responses showed turbidity effluent values ranging from 0.02 NTU to less than 1 NTU and effluent total suspended solids (TSS) values typically less than the detection limit of 2 mg/L.

Biological nutrient removal (i.e., nitrogen and phosphorous) is achieved in an MBR in the same manner that it is for a CAS system. Anoxic basins are provided for denitrification, and anaerobic selectors are utilized to promote the growth of phosphorous accumulating organisms. Operation at higher SRT is required for stable nitrification because of the slower growth rate of nitrifying organisms compared with heterotrophic organisms. The SRT needed for stable nitrification can range from 6.5 to 20 days, and slower growth can occur because of the presence of inhibitory materials, low temperature, extreme pH, and low DO. Denitrification can be designed with either pre-anoxic, post-anoxic basins or both. Biological

phosphorus removal performance is better at lower SRT values and can also be negatively impacted by addition of electron acceptors (e.g., DO, nitrate, or nitrite) to the anaerobic zone. It is not always possible to meet effluent phosphorus limits through biological treatment alone, and, in these cases, chemical precipitation with lime, alum, or ferric chloride is required alone or in combination with biological phosphorus removal. The literature demonstrates that denitrification efficiency increases as the COD/TKN ratio increases, and a denitrification efficiency of greater than 50% was achieved in every study where this ratio was at least 7. Process configuration is vital to achieving good nutrient removal and especially so for MBR systems where scouring air, used to mitigate membrane fouling, can result in high DO that can transfer to the anoxic/anaerobic basins during mixed liquor transfer. To lessen this impact, many MBR systems are designed with dual recycle configurations or specialized single recycle configurations. Reactor design plays the same important role in MBR configuration as it does in CAS processes. Nutrient performance observed from the literature and facility survey demonstrates that the higher operational SRT of most MBR systems results in high ammonia removal (<0.5 mg/L and greater than 97% removal), whereas nitrate effluent concentrations depend on other parameters that include process configuration, DO concentrations, aerobic-to-anoxic recycle flow-rate, and carbon-to-nitrogen ratio in the feed wastewater. Of four survey facilities designed for total nitrogen removal and reporting nitrate values, effluent nitrate concentrations ranged from 1.5 to 7.5 mg/L and demonstrate how effluent values are dependent on many different parameters. Of seven facilities designed for total nitrogen removal and reporting total nitrogen values, effluent nitrogen concentrations ranged from 3 to 8.3 mg/L with the highest value occurring for a facility with a low COD/TKN ratio. Phosphorus removal data demonstrated the superior performance achieved through chemical treatment (alone or in combination with biological treatment) as compared with biological treatment alone.

The removal of trace metals is believed to be equivalent for MBR and CAS systems based on data reported in the literature. Data across a number of studies indicate that the only consistent trend in metals removal is that it is most effectively achieved through efficient solids separation, and that this represents the primary advantage offered by the MBR. As such, MBRs achieve average metals removals that are consistently but not dramatically higher than the ranges reported by the CAS: 64 to 92% versus 51 to 87%, with no more than a 55% decrease on average in effluent concentration. The slightly greater removal attained is attributable to the additional suspended solids retention attained by the membrane process. In either case, further removal of metals would demand a tertiary process for removal of the dissolved material. Of the 19 plants that completed the facility survey, only 3 facilities had metals permit requirements, and all reported meeting their effluent water quality goals.

Compounds of most concern within the trace organic compounds category are potential endocrine disrupting compounds, pharmaceuticals, and personal care products. These compounds are removed in an activated sludge process through volatilization, sludge adsorption, or biodegradation fate processes. The MBR model for aggregate organics described earlier was combined with a fate model for organic micropollutants in a steady state CAS (Lee et al., 1998) to develop a MBR model for micropollutants. Utilizing this model, scenarios were run for different input combinations of trace organic compound fate constants and different MBR operating conditions for SRT and MLSS. The model outputs demonstrate little additional removal of trace organic compounds amenable to biodegradation or volatilization by operating an MBR beyond the stable nitrification SRT of 20 days. Furthermore, trace organic compounds removed via adsorption will show best removal for SRT values lower than 10 days. The majority of trace organic compounds presently being studied are removed primarily through biodegradation rather than volatilization or sorption,

and because of this the higher aeration rates and better solids separation of an MBR should provide no benefit in the removal of these compounds as compared with a CAS. This model prediction has been supported with side-by-side comparison studies of MBR and CAS systems that demonstrate equivalent performance when they are operated at similar SRT conditions.

The primary advantage of an MBR over a CAS system is the superior and more consistent removal of particulate and colloidal compounds (e.g., coliforms, indigenous coliphage TSS, and turbidity) and the ease in which higher SRT conditions, which promote greater reduction of aggregate organics, nutrients, and organic micropollutants, can be achieved within constrained site locations. MBR effluents should also result in less re-growth within reuse distribution systems because of their lower concentrations of AOC and BDOC content. Reactor design is an important consideration in nutrient control systems in order to minimize oxygen carryover to anoxic and anaerobic zones, and innovations in membrane flux maintenance systems that minimize reliance on air scour will reduce energy usage.

The MBR model utilized in the project was developed by first modifying and then adjoining the Rittmann and McCarty (2001) activated sludge design model with the Laspidou and Rittmann (2002a, 2002b) unified model of EPS, SMP, and active and inert biomass. The modifications account for differences in the solids separation component of the CAS processes (settling tank) compared to MBRs (low pressure membranes). The second step of model development extended the basic model to incorporate the fate of trace organic compounds through an adaption from Lee et al. (1998), who considered the fate of trace organic compounds in a steady state CAS.

The MBR model in its present form is a research tool that provides a foundation for further development in understanding how the membrane separator can enhance the effluent quality as performance and design variables are modified. The existing model clarifies that the influent COD concentration and the membrane's ability to separate the large biomass-associated products (BAP_L) are the key parameters responsible for changes in the effluent COD. Design of membranes with better BAP_L separation characteristics may result in lower effluent COD but may increase membrane fouling rate. Regarding trace organic compounds, the model clearly demonstrates the limitations to achievable removal as a function of a particular compound's kinetic coefficients for adsorption, volatilization, and biodegradation. Better understanding of how membranes retain BAP and how MLSS components control trans-membrane flux and oxygen transfer will aid in future enhancements to the model and in further optimizing MBR process performance.

Chapter 1

Introduction

1.1 Background

Membrane Bioreactor (MBR) technology has become well established worldwide over the last decade as an activated sludge process option for advanced treatment and recycling of municipal and industrial wastewater. The MBR process utilizes low-pressure membrane filters that are submerged within or adjacent to the conventional activated sludge (CAS) reactor, which eliminates the need for a secondary clarifier or tertiary filters. The membrane avoids the need for limiting MLSS concentration in the reactor, which further decouples the volumetric loading rate from the solids separation process and results in consistent removal of colloids and particles within a smaller reactor footprint. The industry has other well documented advantages of MBR technology as compared to CAS processes that include production of more consistent and superior effluent water quality, increased operational flexibility, increased automation capabilities, and ease of expansion/retrofit for increased capacity. Although the effluent water quality of MBR processes has been reported to be superior to that of CAS systems, largely attributed to the membrane barrier, the water quality performance of pilot- and full-scale MBR processes indicate varying degrees of performance with respect to microbes, nutrients, aggregate organics, trace organic compounds, and trace metals. It is, therefore, important to gain insight into the specific removal mechanisms associated with the MBR process for different contaminants as well as learning what design and operational factors can impact performance. Such an understanding will aid in further optimizing MBR design and operational strategies in order to support more stringent future water quality regulations and the need to reduce energy consumption and greenhouse gas emissions.

The main advantage of MBR technology is that it can consistently produce high quality effluent that facilitates a wide range of water reuse applications. In the United States and in the absence of federal reuse regulations, the Environmental Protection Agency (EPA) first released guidelines for water reuse in 1980. These were revised in 1992 and updated in 2004 (U.S. EPA, 2004). The document provides a compilation of effluent water quality requirements mandated by the different states and demonstrates through case studies and literature review, the potential of water reuse to address water resource shortages and the need to acquire further treatment technology performance data, particularly for trace organic compounds. Several states with increasing water shortage (e.g., California) have adopted water recycling criteria that include effluent quality limits and monitoring criteria for indirect potable reuse applications that are applied on a case-by-case permit basis. Guidelines from other international agencies such as the World Health Organization (WHO) specify effluent quality and treatment process criteria for potable municipal reuse. All of these guidelines recognize the need for stringent effluent limits as public concern mounts over the unknown health impacts of residual wastewater-derived compounds.

There is a significant amount of reported research on the application of MBR technology for municipal wastewater treatment that includes literature reviews, case studies, bench and pilot-

scale testing, MBR system comparisons, and full-scale demonstrations. MBR research has focused on

- Impact of bioreactor conditions on membrane fouling
- Comparison of operational performance and characteristics of MBR systems from multiple suppliers including different configurations
- Membrane cleaning regimes and fouling control strategies
- MBR effluent water quality and performance modeling
- Pilot-scale evaluations of MBR to remove nutrients and trace organic compounds commonly found in reclaimed water
- Optimization of MBR energy consumption
- Mixed liquor characteristics and MBR sludge dewatering
- Capital and O&M costs

None of the studies have tried to synthesize the data presented in peer-reviewed and grey literature with data acquired from surveys of full-scale plant operations or with the development of any mechanistic models for prediction of effluent water quality as a function of MBR operational characteristics. Theoretically, there are several ways in which the membrane component of an MBR system should enhance effluent water quality as compared to CAS. First, contaminants removed by size exclusion should not pass an intact membrane. Also, the MBR is not susceptible to carryover of solids (microbes and organic matter) into the effluent because of upsets in the biological process as can occur in the CAS process. Furthermore, the membrane can provide partial retention of organic macromolecules, such as biomass-associated products (BAP) that come from the hydrolysis of extracellular polymeric substances (EPS) (Laspidou and Rittmann, 2002a, 2002b). This retention of larger organic molecules by the MBR process could lead to lower effluent soluble COD concentration than can be achieved with the CAS process. Last, there might be differences in the microbial populations of MBRs versus CAS systems because of higher solid carryover for CAS that could contribute to changes in the system performance.

1.2 Study Objectives

The primary objective of this study is to achieve a better understanding of the effluent quality produced from an MBR system as a function of MBR design and operating conditions and how this quality compares with the effluent produced from CAS treatment systems. The primary objective was met by performing the following set of tasks:

- Comprehensive analysis of MBR effluent quality and operational data collected from a wide variety of sources that included peer-reviewed and grey literature of pilot studies and full-scale plant operations;
- Comprehensive analysis of data obtained through surveys of vendor suppliers and operating full-scale installations; and
- Synthesis of data obtained for aggregate organics and trace organic compounds with the predictions of a mechanistic MBR model developed to simulate different operating scenarios.

The literature survey focused on grey and peer-reviewed papers published during the past 5 years to identify removal mechanisms and removal efficiencies with respect to a wide range of contaminant types including particulates, aggregate organics, microbes, nutrients, trace

organic compounds, and trace metals. The vendor survey included eight MBR manufacturers representing the majority of the worldwide market of suppliers offering MBR systems for municipal applications. The vendor survey was intended to capture general information such as the location and capacity of operating and planned installations, plant startup year, drivers for MBR process selection, and the use of the MBR product water. The worldwide installation survey was designed to capture information related to operation, design, water quality performance, and lessons learned. The installations survey was launched on the worldwide web and targeted plants within the United States, European Union, and Asia Pacific region. Last, the project team worked closely with Arizona State University to simulate different scenarios using a model developed in tandem with this project to further understand how changes in operation and design of the MBR process and pollutant characteristics can impact water quality performance for aggregate organics and trace organic compounds.

Overall objectives of the study were to

- Assess the current market trends of MBR technology
- Determine the current expectations of MBR effluent water quality
- Evaluate and identify operational and design factors that can impact MBR effluent quality
- Assess the removal efficiency of MBR for various contaminants including nutrients and emerging contaminants
- Capture global water quality performance data of municipal MBR installations
- Identify knowledge gaps related to MBR technology for the treatment of municipal wastewater
- Simulate model scenarios to assess the impact of operating and design conditions on MBR effluent water quality performance

1.3 Organization of the Report

In order to address and discuss each of these research objectives, this report is subdivided into chapters:

- **Chapter 2** provides a description of the study research approach including literature review, vendor survey, full-scale utility survey, and computational model development. The methodology and data consolidation procedure utilized in each of the previously mentioned tasks are summarized.

- **Chapter 3** presents an overview of the MBR technology. The data of this chapter were consolidated from a survey of MBR vendors and a representative group of full-scale MBR plants. The results of the survey are characterized based on the following categories: number of installations, regional distribution, market share by the vendors, drivers for MBR selection, membrane material composition and configuration, and bioreactor operating conditions.

- **Chapter 4** summarizes the performance of the MBR system based on the effluent water quality parameters that are categorized into different groups such as aggregate organics, microbial contaminants, particulates, nutrients, trace metals, and trace organic compounds. For each group of parameters, the performance of the MBR processes were evaluated based on removal mechanism

and removal observed from available model prediction, literature review, and full-scale operational data survey. This chapter also summarizes the impacts of key operational issues on the effluent water quality performance of the MBR process and describes key differences between MBR and CAS processes.

- **Chapter 5** presents and discusses conclusions obtained from this study and recommendations for filling identified knowledge gaps and areas of uncertainty regarding process performance characteristics.

Chapter 2

Research Approach

The research approach consisted of a literature review, survey of MBR manufacturers and suppliers, survey of full-scale plants, and analysis of MBR operations on the removal of aggregate organics and trace organic compounds through development of a mathematical model. The methodology, data consolidation, and model development approaches used in the study are presented in this chapter.

2.1 Literature Review

2.1.1 Methodology

Active research on MBR process capabilities has resulted in a large quantity of peer-reviewed and grey literature on the application and performance of this technology. The objective of this task was to conduct an MBR technology literature review targeted on summarizing what is known or demonstrated about the technology's water quality performance aspects as reflected in effluent concentrations and characteristics. On the basis of this review, the following information was extracted and synthesized for subsequent use in development of the full-scale facility survey questionnaire and development of the aggregate organics and trace organic compounds predictive model:

- Removal mechanisms cited for each target contaminant group
- Assessments of relevant design and operational parameters impacting mechanistic performance
- Global trends in MBR system implementation and performance expectations
- Summary of water quality performance characteristics and range of operating characteristics
- Identification of readily discernable relationships between effluent quality performance and operational design characteristic
- Identification of knowledge gaps

The selection of literature for review and inclusion in this study was made in accordance with the following criteria:

- Findings during the 5-year period between 2004 and 2008
- Utilization of keyword search criteria of publications and conference proceedings
- Review of reference list by the TAC/PAC for inclusion of missing critical publications

The following keywords were used to find papers related to MBR effluent water quality: MBR, water reuse, MBR nutrient removal, MBR metals removal, MBR organic removal, MBR microbial removal, MBR removal mechanisms, micropollutants, microcontaminants,

PPCP, pharmaceuticals, personal care products, compounds of emerging concern, nitrogen, and phosphorus.

2.1.2 Data Consolidation

The critical findings of each reviewed publication were compiled. The information captured included:

- Contact information for primary author
- Citation
- Time frame when work was conducted
- Location of study
- Scale of study (i.e., bench, pilot, demo)
- Project objectives
- Water quality (i.e., influent and effluent concentrations)
- MBR system design parameters

2.2 Vendor Survey

2.2.1 Methodology

Rapid growth in the worldwide MBR market has resulted in several MBR manufacturers and system suppliers marketing their system for municipal wastewater treatment. In order to characterize the full-scale municipal MBR installations worldwide with capacity greater than or equal to 1 MGD, eight MBR vendors were invited to participate in a vendor survey. This included all of the top MBR technology suppliers other than Mitsubishi Rayon, who is known to be active mainly in the Far East with more than 2000 installations worldwide. The eight vendors that participated in the vendor survey were:

- GE/Zenon
- Kubota/Enviroquip
- Siemens
- Koch/Puron
- Huber
- Kruger/Toray
- Norit/Parkson
- Asahi Kasei/Pall

Each of these vendors was asked to provide key information about their installations, which included:

- Name/location of the MBR installation
- Capacity of the installation (average daily flow)
- Startup year
- Driver behind selecting the MBR process over a CAS process

2.2.2 Data Consolidation

Each participating MBR vendor was sent a survey questionnaire soliciting information about their installations. These data were incorporated into one common file in order to maintain consistency in data analysis among the different vendors. All survey questions were carefully worded to avoid ambiguity in vendor responses; for example, when asked for capacity, each vendor was specifically asked to provide "average annual daily flow" in order to avoid ambiguity with other flow designations.

2.3 Facility Survey

2.3.1 Methodology

The facility survey was conducted to collect background, design, operational, and water quality information from selected full-scale MBR installations treating municipal wastewater. The basis of the survey was a questionnaire that was also later used as a template to develop a Web-based survey. The survey was intended to capture six classes of information on full-scale MBR installations:

- Background information
- Preliminary and primary treatment
- Bioreactor design and operational characteristics
- Membrane design and operational characteristics
- Water quality goals/performance
- Lessons learned

A complete version of the questionnaire is provided in Appendix A. The survey was launched in draft form on the Internet using an online survey (www.zoomerang.com).

Prior to launching the MBR survey, the project team developed a list of 43 facilities to invite to participate in the survey that were believed to be representative of the larger list of worldwide municipal MBR installations reported in the vendor survey. This was accomplished by targeting plants that had a broad range of characteristics with respect to items such as

- Location (U.S., EU, Asia Pacific)
- Capacity
- Years in operation
- Membrane supplier
- Membrane and biological process configuration

In addition, the survey was intended to capture specific plants that could provide information related to key challenges that MBR systems will most likely face in the near future including the following:

- Need to meet low nutrient (nitrogen and phosphorus) requirements (including dissolved organic nitrogen)
- Need for membrane integrity testing (to ensure consistent virus removal)
- Impact of energy/carbon footprint on effluent water quality

- Impact of temperature feed water on water quality performance
- Need to remove endocrine disrupting compounds (EDC) and personal care products and pharmaceuticals (PPCP)
- Impact of peak flow on water quality performance
- Impact of effluent biological organic matter (BOM) including assimilable organic carbon (AOC) and biologically degradable organic carbon (BDOC) on microbial quality of reuse distribution systems

The target list of plants for participation in the survey was developed as follows:

- Preliminary list of facilities assembled based on review of plant lists obtained from the vendor survey
- Requested list of facilities operated by the project's UAC Feedback from TAC and PAC on additional facilities to be targeted based on their contacts with operating MBR plants and considerations of future key challenges facing MBR technology

As a result, 43 full-scale MBR plants were directly invited to participate in the survey. Each plant name, location, startup year, design, capacity, and membrane vendor is provided in Table 2.1.

Table 2.1. Full-Scale MBR Facilities Invited to Participate in the Web-Based Facility Survey

No.	Plant Name	Location	Plant Start Up	Design Capacity (MGD)	Vendor
1	Kellets	European Union	2005	0.5	Zenon
2	North Head	Asia Pacific	2006	0.5	Siemens
3	Coppermine WRF	United States	2008	1	Enviroquip/Kubota
4	Ootmarsum	European Union	2007	1	Norit
5	Pumpkinvine Creek WRF	United States	2004	1	Enviroquip/Kubota
6	James Creek	United States	2006	1	Enviroquip/Kubota
7	LACSD	United States	2006	1	GE/Zenon
8	Brookyln Dagger STP	Asia Pacific	2008	1	GE/Zenon
9	Arenas de Iquna	European Union	2006	1.1	Huber
10	City of Corona	United States	2001	1.1	GE/Zenon
11	Tulalip WWTP	United States	2003	1.2	Enviroquip/ Kubota
12	Aquafin Schilde	European Union	2004	1.5	GE/Zenon
13	McFarland Creek, WWTP	United States	2006	1.8	Enviroquip/Kubota
14	Crescent City	United States	2008	1.9	Siemens
15	Martins Way Reclamation Plant	United States	2006	2	Siemens
16	Dundee WVVTP	United States	2005	2	Enviroquip/Kubota
17	Winlock WWTP	United States	2008	2	Enviroquip/K ubota
18	Fowler WRF, Forsyth County	United States	2004	2	GE/Zenon
19	Calls Creek	United States	2004	2	Siemens
20	Victor Harbor	Asia Pacific	2005	2.3	Kubota
21	American Canyon	United States	2002	2.5	Zenon
22	Heenvliet	European Union	2006	2.5	Toray
23	Buxton	European Union	2004	2.6	Zenon
24	Dover WWTP	United States	2008	3	Enviroquip/Kubota
25	South China WWTP	Asia Pacific	2008	12	Puron
26	Swanaqe	European Union	2000	14	Kubota
27	Ballyclare	European Union	2005	3.5	GE/Zenon
28	Bullhead City WWTP	United States	2007	16	Siemens
29	City of Delphos	United States	2006	3.8	Enviroquip/Kubota
30	Healdsburg WWTP	United States	2008	4	Siemens
31	Palm Jumeriah	Asia Pacific	2006	4.8	Kubota
32	Varsseveld	European Union	2005	4.8	GE/Zenon
33	Cauley Creek	United States	2002	5	GE/Zenon
34	Broad Run Water Reclamation Facility	United States	2008	5	GE/Zenon
35	Cairns Northern Plant	Asia Pacific	2008	5.1	GE/Zenon
36	Ulu Pandan	Asia Pacific	2006	6	GE/Zenon
37	Cleveland Bay, Townsville	Asia Pacific	2007	7.6	GE/Zenon
38	Traverse City	United States	2004	8	GE/Zenon
39	Tempe, Arizona	United States	2006	9	Zenon
40	City of Redlands	United States	2004	9.5	Zenon
41	Brescia	European Union	2003	11	Zenon
42	Gippsland Water Factory	Asia Pacific	2009	11.6	Siemens
43	Nordkanal	European Union	2004	11.9	GE/Zenon

2.3.2 Data Consolidation

The raw data received from the online facility survey was consolidated and organized into one database in order to assess specific trends with respect to operations and water quality performance, energy consumption, and whether the distribution of facility characteristics were representative of the industry based on information received from the vendor survey. The data consolidation was performed in a manner to meet the following objectives:

- Assess the overall "representativeness" of the facility that responded to the survey by comparing general trends identified to that of the worldwide installation lists generated as part of the vendor survey.
- Identify water quality performance trends by sorting reported water quality performance data for targeted contaminants into groups with respect to factors identified in the literature that can impact removal efficiencies.
- Assess the overall energy requirements reported by the plants.
- Identify overall trends of reported factors that can impact water quality and operation based on reported lessons learned.
- Identify upper and lower limits of key operating data and influent water quality data to include in the model-run scenarios.

General water quality performance and design/operational factors impacting MBR effluent quality for key contaminant types (i.e., particulates, microbial, aggregate organics, nutrients, trace organic compounds, and trace metals) were documented and identified in the literature survey. One objective of consolidating the data collected from the facility survey was to compare some of the water quality trends gleaned from the literature survey to what is being observed by actual operating plants. A general method of approach was to sort the effluent water quality reported by the participating facilities into specific categories related to reported operational and design factors known to impact removal of the targeted contaminants. A description of the data consolidation method used to achieve this objective for each contaminant type is as follows:

- Assess the range of average effluent concentrations along with maximum values of contaminants reported by all facilities.
- For facilities that reported effluent concentrations higher than expected, assess available information reported from the facility with regard to factors that could possibly impact effluent water quality including membrane integrity and membrane fouling control.
- Summarize reported lessons learned regarding facility operations and performance.

2.3.3 QA/QC Procedure

The project team implemented the following QA/QC procedures to ensure the reported responses from the facility survey were accurate, complete, and representative of MBR installations used for municipal wastewater treatment:

2.3.3.1 Development of Questionnaire

- Draft Questionnaire reviewed by TAC and PAC
- Draft Questionnaire expanded and revised based on TAC/PAC comments

2.3.3.2 Development of Web Survey

- Web support team converted Excel-based questionnaire to an online survey.
- Project team performed internal beta test of the survey and corrected deficiencies.
- Members of the UAC were sent the survey for completion and requested to provide input on areas that required clarity and whether they experienced any functionality issues when accessing the survey.
- Input from the UAC was reviewed and necessary clarification was made to the survey prior to launching it to the outside group of targeted participants.

2.3.3.3 Data Collection

- Initial survey target list was derived from worldwide list of MBR facilities provided by eight vendors in order to achieve representative sampling group.
- Initial survey target list was modified per comments received from TAC/PAC review.
- Project team followed up with contact calls to invited participants and leveraged contacts of the TAC/PAC in order to fulfill 40% completeness objectives for participation.
- Survey responses that were not received via the Web were manually entered and reviewed by the project team.
- Submitted surveys were reviewed on an individual basis to check for data consistency.
- Data inconsistencies were corrected based on follow-up phone calls for clarification.

2.3.3.4 Data Consolidation

- Conversion tables were used to normalize reported data to common units.
- Identified outliers were verified through follow-up calls with survey participants.
- Outliers were verified, flagged as suspect, or removed from the database as appropriate.
- Plots prepared in Excel using data extracted from the .survey were compared for consistency with plots generated directly using Web-survey tools.
- Trends observed from the facility survey were compared to those derived from the literature and model output and reviewed by TAC if conflicting trends were identified.
- All survey data were checked and verified by follow-up phone calls.

2.3.3.5 Data Presentation

Presentation figures and tables summarizing information received from the facility survey were checked and revised by the project team, TAC, and PAC.

2.4 Model Development for Aggregate Organic and Trace Organic Compounds

2.4.1 Mechanistic Principles Utilized

The MBR model was developed in two discrete steps. The first step modified the existing conventional activated sludge model developed by Rittmann and McCarty (2001) to form a

basic MBR model to predict the fate of aggregate organics. The key modifications to the original model account for differences in the solids separation component of the CAS processes (settling tank) compared to MBRs (low pressure membranes). The second step in the model development extended the basic model to incorporate the fate of trace organic compounds.

2.4.1.1 MBR Model for Aggregate Organics

The project team developed the MBR model by modifying and then adjoining two existing models—the activated sludge design model described by Rittmann and McCarty (2001) and Laspidou and Rittmann's (2002a, 2002b) unified model of extracellular polymeric substances (EPS), soluble microbial products (SMP), and active and inert biomass.

A reliable MBR model requires an accurate mathematical representation of the relationships between EPS, SMP, and active and inert biomass. Laspidou and Rittmann successfully developed a model that quantifies a unified theory that they developed for EPS, SMP, and active and inert biomass (Laspidou and Rittmann, 2002a, 2002b). Their approach classifies the solid species as bacteria, EPS, and residual inert biomass and the soluble species as original substrate, utilization-associated products (UAP), and biomass-associated products (BAP).

On entering the reactor, the original substrate may take four possible paths:

- Synthesis of active biomass
- UAP production, which once produced, is released to the aqueous solution surrounding the cell
- Production of EPS that is a non-active solid
- Substrate respiration, where remaining electrons are sent to an electron acceptor to generate energy

Active biomass is oxidized by endogenous respiration, resulting in the formation of residual inert biomass. The hydrolysis of EPS produces BAP. Because BAP and UAP are biodegradable, a portion of their electrons can be consumed by bacteria, serving as "recycled" substrate, whereas the remaining electrons are devoted to the acceptor for energy generation. The project team modified the equations Laspidou and Rittmann used to describe the aforementioned relationships in order to suit the structure of the MBR and then included these equations in the MBR model.

The absence of a settling tank and the inclusion of an immersed membrane in the reactor basin required the activated sludge model to be modified to represent an MBR process. Because activated sludge solids are too large to pass through the membrane, no solids are present in the effluent, and all solids must leave the system as wasted sludge. Thus, no biomass, whether volatile, active, or inert, is found in the effluent. Only soluble material can pass through the membrane, such as remaining influent soluble BOD, COD, and the portion of SMP that is small enough to pass through the membrane. UAP readily passes through the membrane, whereas only a fraction of small BAP, referred to as BAP_s is small enough to permeate ultrafiltration and microfiltration membranes. The fraction of BAP_s that can pass through the membrane is assumed to be 50%, although this value can be adjusted in the model. The remaining 50% of the BAP_s that is not present in the effluent is wasted from the system, along with large BAP (BAP_L).

The oxygen demand and power required were also modeled. The oxygen supply rate is the difference between the input (influent) and output (effluent and waste) oxygen demand, as shown in the following:

Input oxygen demand = $QS0 + 1.42QXi0 = Q(S0 + 1.42\ Xi0)$ (1)

Output oxygen demand = $Qe(S + SMPeffluent) + 1.42(XvV/\theta x) + Qw(SMPwasted)$ (2)

Oxygen supply rate = input oxygen demand – output oxygen demand (3)

$SMP_{effluent}$ consists of UAP and BAP_S, whereas SMP_{wasted} consists of UAP, BAP_S, and BAP_L.

where, Q is the influent flow-rate
S^o is the influent substrate concentration
Xi^0 is the inert solids concentration
Q^e is the effluent flow-rate
S is the effluent substrate concentration
X_v is the MLVSS concentration [ML^{-3}]
V is the volume containing X_v [L^3]
θ_x is the solids retention time [T]
$SMP_{effluent}$ is the effluent soluble microbial products
Q^w is the waste sludge flow-rate.

To calculate the power requirement, the oxygen supply rate is divided by the field oxygen transfer efficiency (FOTE), which is represented mathematically as

$$FOTE = SOTE * 1.035^{T-20} * \alpha * (\beta c_l^* - c_l)/9.2\ mg/L \quad (4)$$

where SOTE is the standard oxygen transfer efficiency, (kg O_2/kWh)
T is the reactor temperature (C)
c_l^* is the liquid phase oxygen concentration in equilibrium with bulk gas phase at temperature T(mg/L)
c_l is the liquid phase bulk oxygen concentration (mg/L)
β is a correction factor to better represent wastewater oxygen solubility
α is a correction factor to better describe the aeration capacity in a volume of wastewater.

Studies have shown that α decreases as MLSS concentration increases (Schwarz et al., 2006). To address this issue, the project team used the following equation to determine the α value for a given MLSS (Schwarz et al., 2006):

$$\alpha = e^{-0.08788MLSS} \quad (5)$$

where MLSS is in units of grams per liter (g/L).

The other factors in the FOTE equation were selected for typical wastewater conditions (Rittmann and McCarty, 2001) and do not vary with different MLSS concentrations. Once α was determined and FOTE calculated, the power requirement was determined by dividing the oxygen supply rate by FOTE and using the appropriate unit conversion factors.

The model is set up using non-steady state mass-balance equations, initialized with reasonable starting values for all components, supplied accurate parameter values for organic

substrate (BOD_L) utilization and metabolism of heterotrophic bacteria, and solved in an Excel spreadsheet program until the output represents steady state condition. The outputs include:

- Effluent concentrations of S, UAP, BAP_S, COD, and BOD_L
- Waste solids rates for active VSS, residual (inert VSS), EPS, VSS (= the sum of the first three), inorganic SS, and total SS (= the sum of VSS and inorganic SS)
- Oxygen-supply rate and power needed to provide this supply.

2.4.1.2 MBR Model for Trace Organic Compounds

The following development for trace organic compounds was adapted from Lee et al. (1998), who considered the fate of trace organic compounds in a steady state CAS. The model was designed to handle trace organic compounds that can be biodegraded as secondary substrates, volatilized to the gas phase because of aeration, and sorbed to biomass. The sorbed trace organic compounds are removed with wasted biomass. Micropollutant mass that is not removed by one of these mechanisms passes through to the effluent. This approach can be adapted readily for inorganic micropollutants, such as metals and nanoparticles, which usually can be represented by sorption to the biomass. The most difficult aspect of model application is obtaining accurate kinetic and partitioning constants for biodegradation, volatilization, and sorption.

The steady state mass balance given here is the core of the model.

$$0 = \text{Advection In} - \text{Advection Out} - \text{Volatilization} - \text{Sorption} - \text{Biodegradation} \quad (6)$$

The advection terms are the products of the flow rate in or out of the system and the concentration of pollutant in that flow.

$$\text{Advection In} = Q^0 C^0 \quad (7)$$

$$\text{Advection Out} = Q^e C + Q^w C \quad (8)$$

where Q^0 is the influent flow rate
Q^e is the effluent flow rate
Q^w is the waste flow rate

These flow rates are in units of $[L^3T^{-1}]$. In the case of the MBR, the advection into the system is the influent flow rate multiplied by the influent contaminant (trace organic compound) concentration, whereas the advection out of the system is the product of the effluent flow rate and effluent concentration plus the product of the waste flow rate and the wasted concentration, which is taken to be the same concentration as that in the effluent. The user of the model must input the influent flow rate; the model will then calculate the effluent and waste flow rates. C^0 is the influent concentration of a target compound, whereas C is the effluent soluble concentration, both in units of $[M^cL^{-3}]$. The influent contaminant concentration must be specified by the user, after which the effluent concentration is calculated by the general fate model using eq. 6 and the mechanistic representations shown in the following.

The volatilization term is comprised of two parts: volatilization at the surface of the water in the reactor and volatilization to bubbles in diffused aeration. The mathematical equation representing these phenomena is:

Volatilization = $(k_La_c)_{sur}CV + Q_ACH_C$ (9)

where $(k_La_c)_{sur}$ is the surface gas transfer rate coefficient [T^{-1}]
V is the volume being aerated [L^3]
Q_A is the aeration gas volumetric flow rate [L^3T^{-1}]
H_C is the Henry's constant for that compound in units L^3 water (L^3 gas)$^{-1}$, and
$(k_La_c)_{sur}$ and Q_A are calculated within the model, the calculations of which are described in the following two paragraphs, whereas V and H_C are specified by the user for the system and the target compound, respectively.

Because a total gas transfer rate coefficient generally is measured in the field and not quantitatively differentiated into its surface and bubble components, the portion of the rate that is due to surface gas transfer, $(k_La_c)_{sur}$, and the portion that is due to gas transfer from aeration bubbles, $(k_La_c)_{bubble}$, must be separated. The model does this by computing the surface gas transfer rate coefficient based on the work done by Kyosai and Rittmann (1991), where the ratio of $(k_La_c)_{bubble}$ to $(k_La_c)_{sur}$ for four different volatile organic compounds was found to be about 2. Thus, given a user-input value for the total gas transfer rate, k_La_c, the aforementioned ratio to approximate $(k_La_c)_{sur}$ is assumed to be about 1/3 of the total gas transfer rate coefficient, with $(k_La_c)_{bubble}$ being 2/3.

The model determines the aeration gas volumetric flow rate, Q_A [L^3T^{-1}], using the power requirement equation given in *Wastewater Engineering* (Tchobanoglous et al., 2003). Rearranging the power equation to solve for the weight of the flow of air, w [MT^{-1}], gives

$$w = \frac{29.7neP_w}{RT\left(\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right)} \quad (10)$$

where n is 0.283 for air
e is the compressor efficiency, usually between 0.7 and 0.9
P_w is the power requirement for aeration [kW] that is calculated in Stage One of the model
R is the gas constant [kJ/mol-K]
T is the inlet (atmospheric) temperature
p_1 is the inlet pressure [atm]
p_2 is the outlet pressure [atm]

Once w is calculated, Q_A can be determined as follows:

$$Q_A = \frac{wRT}{p_1} \quad (11)$$

Assuming adsorption is at equilibrium (Lee et al., 1998; Rittmann and McCarty, 2001), the sorption term is the product of the sludge-wasting rate and the concentration of the compound in the wasted sludge.

Sorption = X_vVK_pC/θ_x (12)

where X_v is the MLVSS concentration [ML^{-3}]
V is the volume containing X_v [L^3]

K_p is the linear partitioning coefficient of the target compound [L^3M^{-1}]
θ_x is the solids retention time [T]

X_v is calculated in Stage One of the model from the non-steady state discretized equations once they reach steady state. θ_x is also calculated in Stage One.

The final term in the mass balance is that of biodegradation. It is assumed that contaminant biodegradation is first-order in C, because the concentration of the contaminant is low, and in X_a, which assumes secondary utilization (Lee et al., 1998; Rittmann and McCarty, 2001):

$$\text{Biodegradation} = k_b X_a C V \tag{13}$$

where k_b is the mixed second-order rate coefficient [$L^3M^{-1}T^{-1}$]
X_a is the concentration of active biomass degrading the contaminant [ML^{-3}]

X_a is calculated in Stage One, although the user must enter the value for k_b into the model.

After substituting the fate terms given earlier (eq. 9–13) into eq. 6, eq. 6 can be rearranged to solve for the effluent concentration, C, of the target compound. The following equation results:

$$C = \frac{C^0}{\frac{Q^e}{Q^0} + \frac{Q^w}{Q^0} + \left(k_L a_c\right)_{sur}\theta + \frac{Q_A H_C}{Q^0} + \frac{X_v K_p \theta}{\theta_x} + k_b X_a \theta} \tag{14}$$

where, θ is the hydraulic retention time [T].

After calculating the effluent concentration of the contaminant, we can compute the fraction of its removal as follows:

$$x = \frac{\left(C^0 - C\right)}{C^0} \tag{15}$$

Finally, comparing the contaminant mass flows for each fate term, we can generate fractions of fate mechanisms to input mass flows, which demonstrate the significance of each fate mechanism in the removal of the compound from wastewater. The rate terms are eq. 9, eq. 12, and eq. 13, and they use C from eq. 15.

2.4.2 Model Scenarios Considered

The model can be modified at some future date to consider biological nitrification and denitrification processes through the incorporation of autotrophic ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) biomass. For this study, simulations were performed for the heterotrophic model in order to gain insight into the impact that various operating conditions have on MBR aggregate organic and trace organic compound effluent water quality. Input parameters to the model include user-defined characteristics such as SRT, reactor volume, HRT, DO, temperature, and influent COD concentration. As part of the

facility survey data consolidation, the reported upper and lower limits of these parameters were identified for incorporation into the model scenarios simulated as part of this study. The range of values for key model input parameters as obtained from the facility survey are presented in Table 2.2. The water quality predictions using the model were produced for different scenarios and are presented in Chapter 4.

Table 2.2. Range of Model Input Parameters as Obtained from the Facility Survey

Parameter	Range of Values
Influent COD (mg/L)	109–600
MLSS (mg/L)	4,200–12,000[1]
HRT (hours)	3–20
SRT (days)	11–30[2]

[1] 80% of respondents fell within this range.

[2] SRT as high as 50-days used for model input.

Chapter 3

Overview of MBR Technology

Surveys of MBR manufacturers and full-scale installations were conducted. The objective of the vendor survey was to characterize the current status of MBR installations regionally and globally. Full-scale facilities were surveyed to compile process information and operational and water quality data from a representative set of operating MBR systems. This chapter summarizes the current state of knowledge of MBR installations with an emphasis on number of installations, design capacity, market share, and key operational parameters.

3.1 Number and Capacity of MBR Installations

Driven by stricter water quality regulations and increasing water reuse applications, the number of MBRs implemented has seen significant growth over the last few years. This section provides an overview of the number and capacity of currently installed MBR plants.

3.1.1 Results of Vendor Survey

3.1.1.1 Global Distribution

MBR technology has seen significant growth over the past decade because of more stringent water quality regulations and increasing implementation of water reuse applications. Figure 3.1 shows the cumulative number of municipal MBR installations from 1998 to 2011 with design capacity greater than or equal to 1 MGD (3,785 m3/d). As of February 2009, 166 municipal MBR installations were in operation or under contract worldwide, and according to data collected from the eight major MBR vendors, 98 of these are presently in operation. Only 149 installations are shown in Figure 3.1 because the start-up year could not be discerned for 17 installations. The most significant growth in MBR installations was observed over the period from 2004 to 2008—a 250% increase occurred in the number of MBR installations worldwide. The total number of MBR installations (including ones with design capacity of less than 1 MGD) probably exceeds 5000, and the global MBR capacity exceeds 1200 MGD (4,542,494 m3/d).

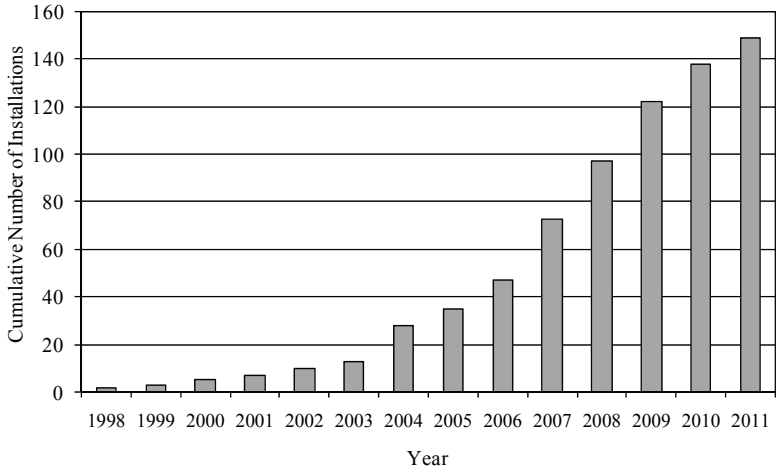


Figure 3.1. Cumulative number of surveyed MBR installations (≥1 mgd capacity).

Figure 3.2 shows the cumulative capacity of MBR installations from 1998 to 2011. As of February 2009, the cumulative capacity of MBR installations, which are either in operation or in design phase, was calculated at 679 MGD (2,570,295 m3/d). Over the period of 2004–2008, a 300% increase in cumulative capacity of MBR installations was observed.

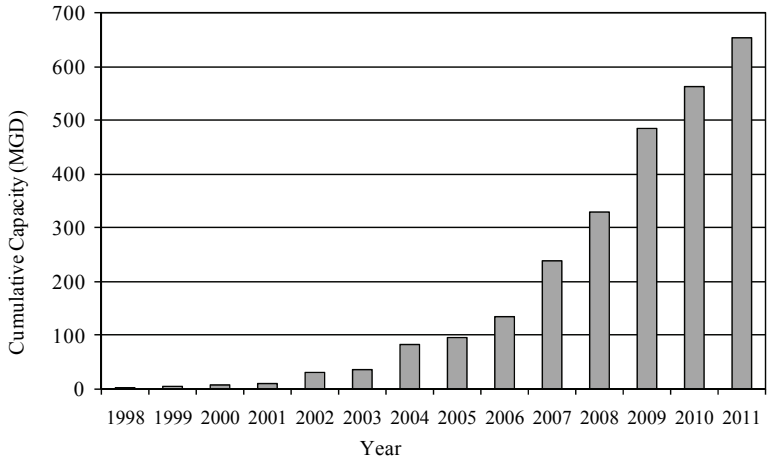


Figure 3.2. Cumulative capacity of surveyed MBR installations (≥1 mgd capacity).

The distribution of MBR installations based on design capacities is shown in Figure 3.3. The majority (73%) of municipal MBR installations were designed to treat less than 5 MGD (18,927 m3/d) of flow. Even though the percentage of installations with capacity greater than

5 MGD is relatively low (27%), a steady growth in large MBR installations occurred in recent years. The number of MBR installations with capacity of 1–5 MGD, 5–10 MGD, and greater than 10 MGD (37,854 m3/d) are 110, 25, and 15, respectively. Table 3.1 and Table 3.2 show some of the largest MBR plants either in operation or under contract.

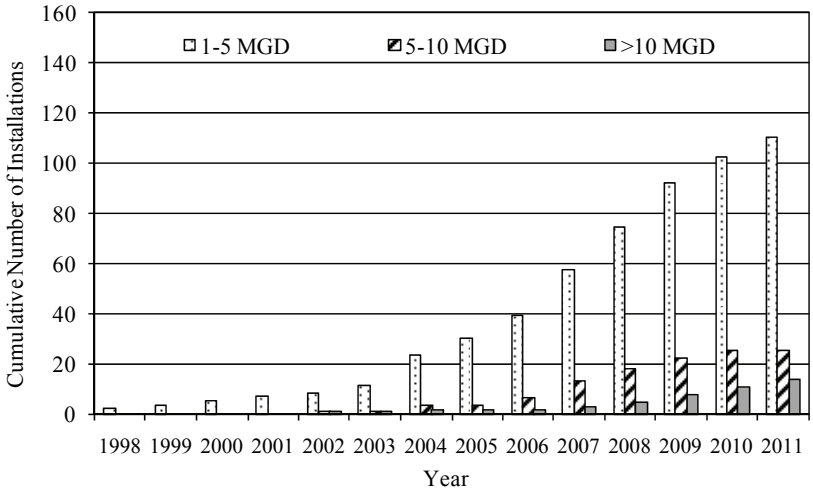


Figure 3.3. Cumulative number of surveyed MBR installations by capacity.

Table 3.1. Five Largest MBR Installations Currently in Operation

Name/Location	State	Country	Capacity (MGD)	Start-up Year
Lusail	Lusail	Qatar	15.9	2007
Bei Xiao He	Beijing	China	15.9	2008
Nordkanal	Nordrhein-Westfalen	Germany	11.9	2004
Brescia	Verziano	Italy	11.1	2002
Tempe-Kyrene	Arizona	USA	9.0	2006

Table 3.2. Five Largest MBR Installations Currently Under Contract

Name/Location	State	Country	Capacity (MGD)	Start-up Year
Jumeirah Golf Estates	Dubai	UAE	60.0	2009
Brightwater	Washington	USA	39.0	2011
City of North Las Vegas	Nevada	USA	25.0	2012
Al Ansab	Muscat	Oman	20.6	-
Yellow River	Georgia	USA	18.3	2011

3.1.1.2 Regional Distribution

Figure 3.4 shows the global distribution of worldwide MBR installations among four different regions. The majority of the installations were in the Americas (56%) followed by Europe (24%), Asia-Pacific (19%), and Africa (1%). In order to understand the growth of MBR technology in these regions, the data collected for MBR installations was further distributed by start-up year from 1998 to 2011. As shown in Figure 3.5, a significant growth in full-scale MBR installations (with capacity greater than or equal to 1 MGD) was observed in the Americas and Europe starting in 2004, whereas substantial growth in the Asia-Pacific region was observed only since 2007. Figure 3.6 shows the municipal MBR installations (greater than 1 MGD) in the United States, with 21 out of 50 states showing at least one MBR installation and California, Georgia, Washington, Arizona, and Florida showing 19, 12, 10, 8, and 6 installations, respectively.

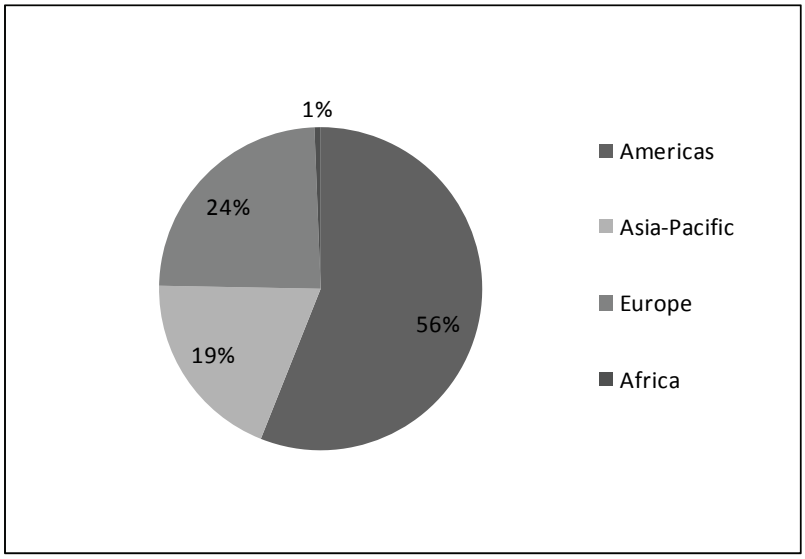


Figure 3.4. MBR installations by region.

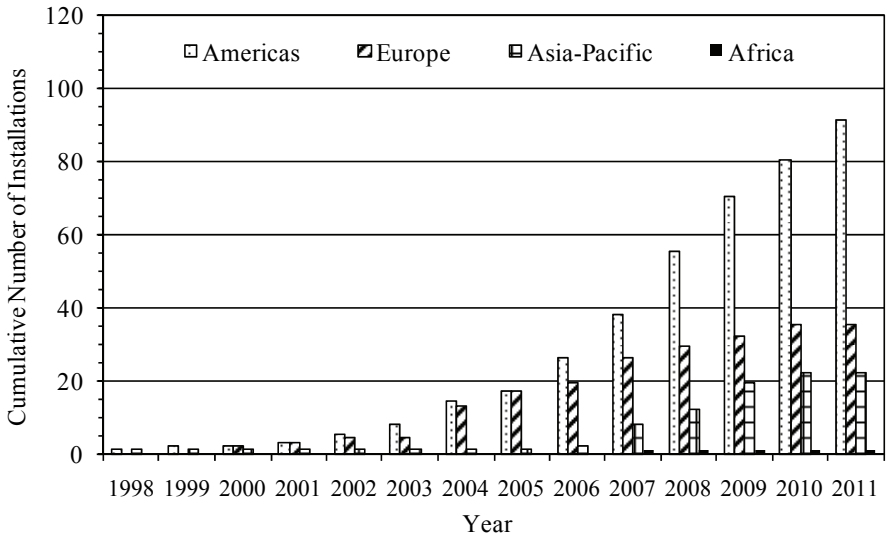


Figure 3.5. Growth in number of MBR installations by region.

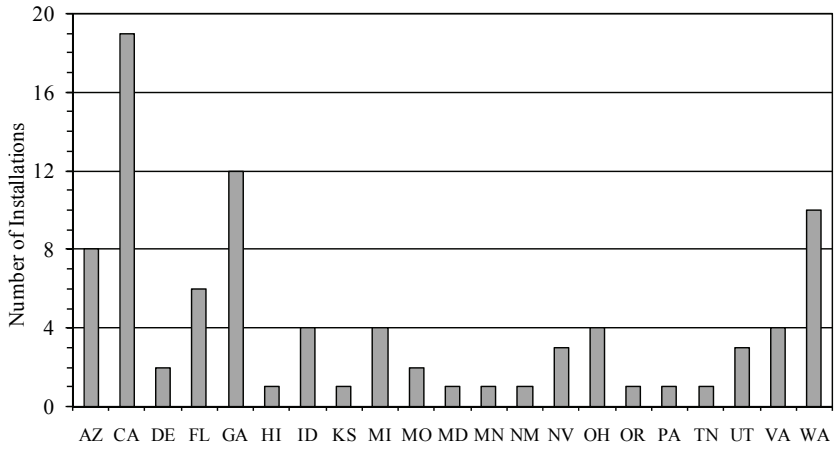


Figure 3.6. Number of MBR installations in various states in the U.S.

3.1.1.3 Market Share by Vendors

Among the eight vendors surveyed, GE/Zenon, Kubota, and Siemens were found to have the major market share for MBR plant installations worldwide with GE/Zenon at 61%, followed by Kubota at 23%, and Siemens at 6%. Figure 3.7 further demonstrates that GE/Zenon dominates the MBR market in every capacity range but does so most prominently for the larger capacity installations greater than 5 MGD (18,927 m3/d). Kubota/Enviroquip also dominates the MBR market for installations up to 5 MGD, but their dominance decreases for

the larger capacity installations. GE/Zenon and Kubota were the first MBR vendors to commercialize their systems for municipal wastewater applications and the first vendors to introduce their MBR products to the U.S. market, which probably accounts for their greater market share relative to the other vendors.

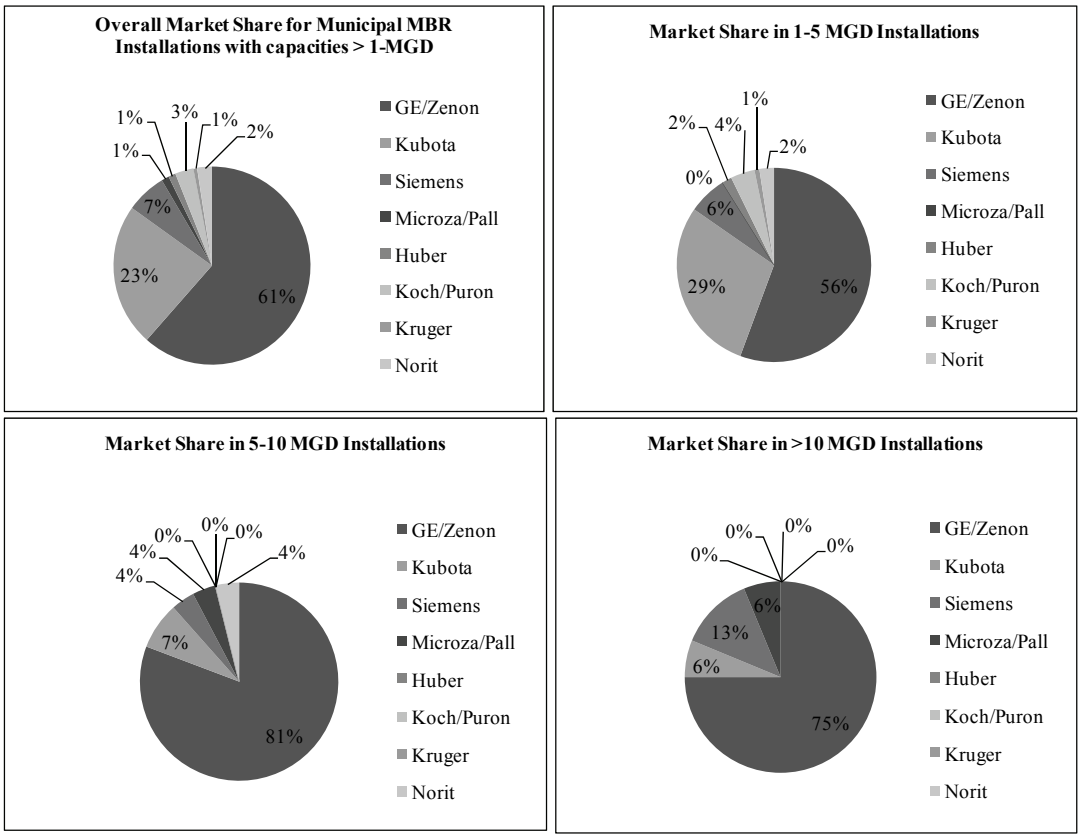


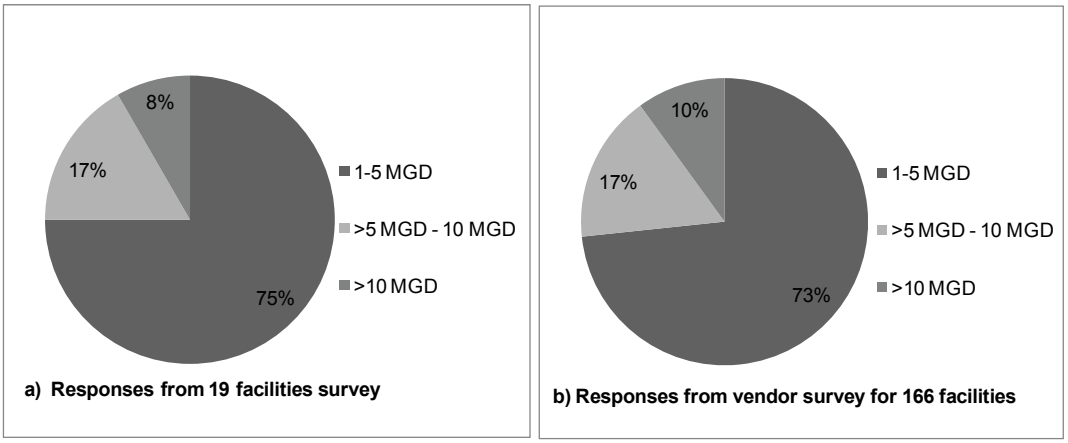
Figure 3.7. Market share of municipal MBR installations by vendors.

3.1.2 Results of Full-Scale Facility Survey

Forty-three facilities were invited to participate in the survey of full-scale installations. The objective was to obtain a response rate of 40–50% in order to characterize approximately 20 facilities that were then evaluated for representativeness of the larger list of worldwide municipal MBR installations reported in the vendor survey. In order to assess whether the group of facilities that responded to the facility survey were representative of the broader group of reported worldwide installations obtained from the vendor survey, the distribution of responses from both surveys were compared directly with regard to the following:

- Capacity
- Region
- Vendor

Figure 3.8 compares the distribution of MBR design capacities obtained from the facility and vendor surveys for the full-scale MBR plants. The greatest distribution with regard to plant capacity for both the facility and vendor survey was in the range of 1 to 5 MGD (3,785–18,927 m3/d). The vendor survey did not include plants with design capacities less than 1 MGD; therefore, this capacity range, which represents 37% of plants that completed the facility survey, was excluded from the comparison.



Note: The distribution shown for the facility survey (a) excludes facilities with design capacities of less than 1 MGD.

Figure 3.8. Distribution of MBR design capacity from (a) facilities survey and (b) vendor survey.

From a location standpoint, as shown in Figure 3.9, both the facility and vendor surveys had distributions largest to smallest in the United States, EU, and Asia Pacific. From a membrane supplier standpoint, as shown in Figure 3.10, both surveys captured information from plants using seven different membrane suppliers with the most number of plants for both surveys listed in decreasing order as Zenon, Kubota, and Siemens.

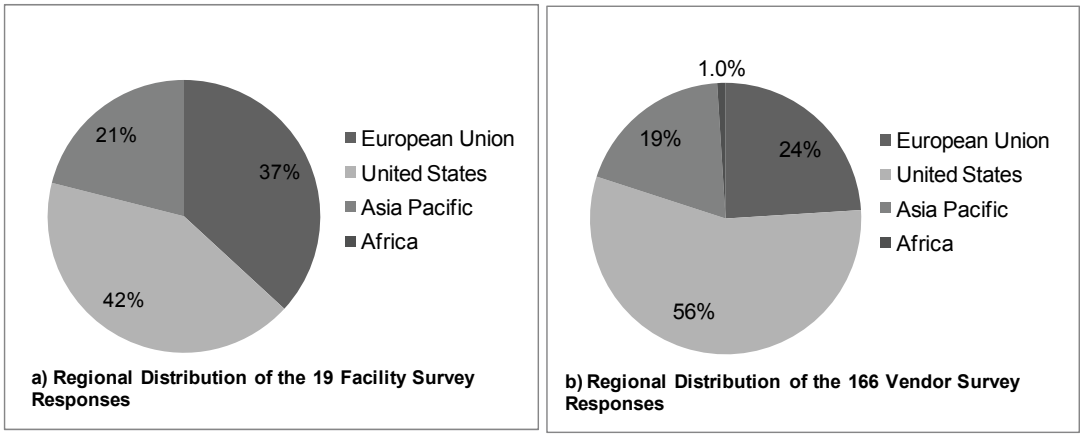


Figure 3.9. Distribution of MBR plant location by region from (a) facility survey responses and (b) vendor survey responses.

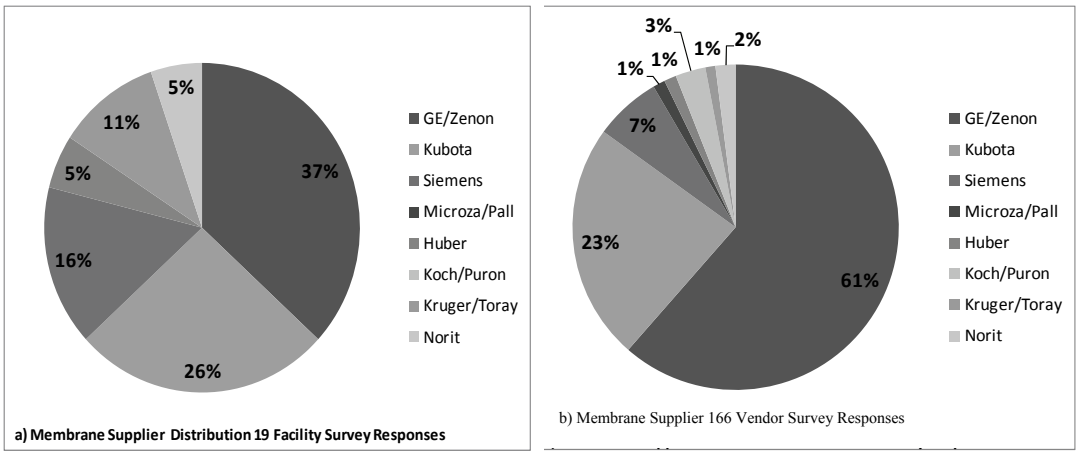


Figure 3.10. Distribution of membrane suppliers from (a) facility survey responses and (b) vendor survey responses.

3.2 Drivers Behind Selection of the MBR Process Over the CAS Process

Some of the process benefits of MBR technology over CAS technology include a smaller footprint, production of more consistent higher quality effluent, high microbial contaminant removal, better solids separation, and effluent quality suitable as feed to RO (low silt density index). In recent years, the automation potential of MBR technology as well as its ability to achieve low nutrient concentrations in the effluent have also factored into its selection. In order to assess the key market criteria for MBR process selection, MBR vendors were asked to provide their assessment of the major drivers behind MBR process selection for their installations. Figure 3.11 summarizes the distribution of various process selection criteria for MBR installations provided by the vendors. Improved water quality and reliability (52%) and footprint limitation (30%) were found to be the key drivers behind MBR process selection. Use of a membrane for solids separation in the MBR process allows operation at high MLSS, because sludge settling is not required as it is with clarifiers. Operation at high MLSS allows smaller bioreactor volume, and replacing secondary clarifiers and media filters with membrane filtration significantly reduces the plant's footprint. Use of a membrane also helps in producing more consistent high quality effluent free of any particulate matter. Cost-effectiveness (9%), low nutrient requirement (5%), and disinfection credit (2%) were also stated as some of the drivers behind MBR process selection. Because only a few wastewater treatment plants use RO to produce very high quality effluent because of its associated cost, use of MBR to produce RO feed was not found to be a key driver behind MBR process selection at this time.

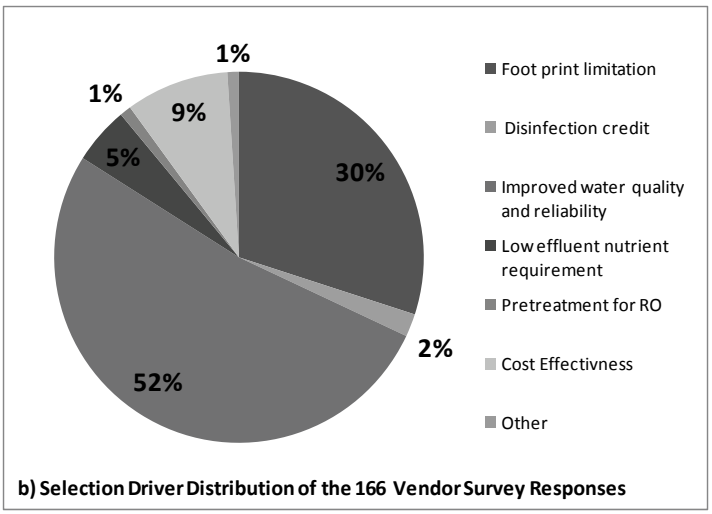


Figure 3.11. Drivers behind selection of the MBR process.

3.3 Membrane Configurations and Materials

MBR systems can be classified into the two major categories of submerged or external membrane placement relative to the bioreactor. Submerged MBR systems use a vacuum to draw the filtrate from the outside to the inside of the membrane. They are available in hollow-fiber or flat-sheet configurations. External MBR systems, which use pressure to draw the filtrate from inside to the outside of the membrane tubes, are operated in a cross-flow configuration and are available only in tubular configurations. Table 3.3 provides the membrane configuration for each of the vendors that participated in the vendor survey component of the study.

Table 3.3. MBR Configurations From Vendor Survey Participants

Vendor Survey Participant	MBR Configuration
GE/Zenon	Submerged Hollow Fiber
Siemens	Submerged Hollow Fiber
Koch/Puron	Submerged Hollow Fiber
Asahi Kasei/Pall	Submerged Hollow Fiber
Kubota/Enviroquip	Submerged Flat Sheet
Huber	Submerged Flat Sheet
Kruger/Toray	Submerged Flat Sheet
Norit/Parkson	External Tubular

Figure 3.12 shows the distribution of different MBR system configurations and membrane materials being used in MBR installations worldwide. The hollow-fiber configuration constitutes the major market share (79%), followed by the flat-sheet configuration (18%), and then the tubular configuration (3%). The hollow-fiber configuration usually offers more membrane surface area per unit volume (relatively lower footprint) compared to the flat-sheet membranes, but recently flat-sheet MBR vendors have introduced modules that can be stacked on top of each other to increase membrane surface area available per unit volume and to reduce the air scour required for minimizing membrane fouling and maintaining the membrane flux. External tubular MBR systems used to have higher O&M costs arising from the higher sludge recirculation required for membrane scouring, which limited their use in municipal wastewater treatment. However, recent advances in external MBR systems have significantly lowered this cost. Norit, for example, uses a blend of scouring air and sludge recirculation for membrane scouring to minimize the sludge recirculation requirement.

MBR installations surveyed as shown in Figure 3.12 use membranes made of Polyvinylidenedifluoride (PVDF), Polyethylene (PE), and Polyethersulfone (PES). PVDF is the most common membrane material, used in 79% of the MBR installations, followed by PE (16%), and PES (5%). Five of the eight MBR vendors surveyed use PVDF membranes, two of them use PES membrane, and one uses PE membranes.

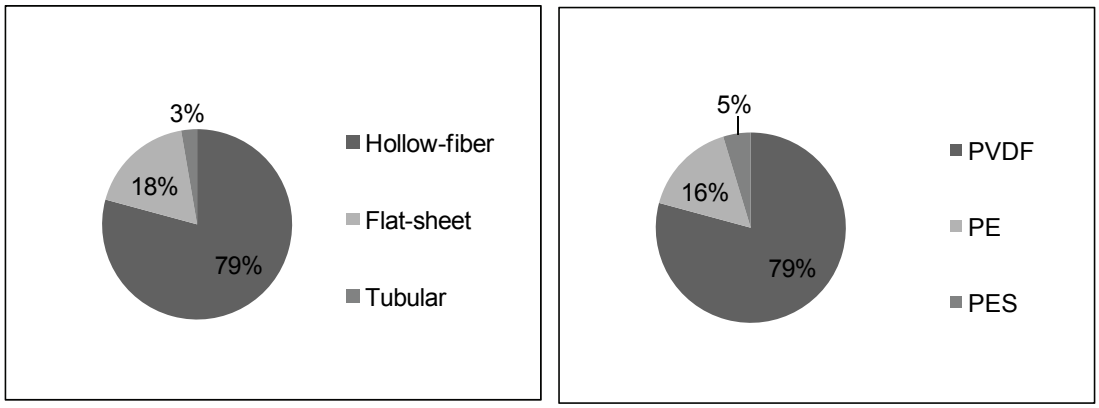


Figure 3.12. Membrane configurations and materials used in surveyed MBR installations.

3.4 Bioreactor and Membrane Design Parameters

The MBR is an advanced treatment process consisting of an activated sludge biological reactor coupled with membrane solids separation. Several key design and operational parameters affect the effluent water quality that can be achieved by MBRs.

- Solids retention time (SRT)
- Hydraulic retention time (HRT)
- Mixed liquor suspended solids (MLSS) concentration
- Membrane flux and transmembrane pressure (TMP)
- Membrane fouling control strategies

This section describes the importance of each key design/operation parameter and the range of values employed for that particular parameter as derived from the literature and facility survey.

3.4.1 Solids Retention Time (SRT)

SRT is a key design/operations parameter for any activated sludge process because it dictates the biomass concentration in the reactor at a given HRT. A higher SRT is a prerequisite to establishing the slower growing microorganisms such as autotrophic nitrifiers that are needed for nitrification. Higher SRT is also believed to aid in reducing trace organic compounds because it results in a greater variety of microorganisms capable of participating in co-metabolism or secondary utilization of these compounds. In treatment plants where biological phosphorus removal is required, a lower SRT allows a reduction in the effluent phosphorus concentration.

MBR installations are usually designed to nitrify, and many studies have shown that severe membrane fouling tends to occur in MBR systems when the nitrification rate is reduced or ceases completely (Adham & Trussell, 2001). Nitrification requires MBR designs that achieve a minimum SRT of 7 to 10 days depending mostly on temperature. Based on the results obtained from the facility survey, design values of SRT ranged from 11 to 30 days.

3.4.2 Hydraulic Retention Time (HRT)

HRT, along with SRT, dictates the organic loading rate for the reactor, the reactor volume (i.e., footprint), and the MLSS concentration. In conventional activated sludge systems, the HRT is restricted by the maximum MLSS concentration that can be accommodated by the settling capacity of the secondary clarifiers. Use of membrane separation, instead of clarifiers, allows the MBR process to operate at higher MLSS concentrations and allows for smaller bioreactor volumes and reduced HRTs without loss of effluent quality that is due to solids carryover. Based on the results obtained from the facility survey, HRT values ranged from 3 to 20 hours. These values were calculated from facility respondents' reported values of average plant design flow and total biological reactor volume. The high HRT of 20 hours is for a facility that may have been designed for its peak dry weather flow or perhaps had higher strength wastewater, which could not be confirmed because of a lack of data for COD/BOD ratios.

3.4.3 Mixed Liquor Suspended Solids (MLSS)

MBR installations are usually designed to operate at higher MLSS levels compared to installations using a conventional activated sludge process in order to reduce the footprint of the installation. MLSS concentrations in MBR installations usually range from 6,000 to 12,000 mg/L for municipal wastewater applications. Operation of MBR systems at MLSS concentrations in excess of 15,000 mg/L can result in "high solids fouling." High MLSS concentration (15,000 mg/L) also can reduce the oxygen transfer efficiency of the system correlated to increased viscosity of the sludge. This can result in a low DO concentration in the reactor, which can adversely affect the nitrification process. The range of MLSS values observed in the full-scale survey was 4,200 to 18,000 mg/L. As shown in Figure 3.13, 80% of the plants surveyed operated at MLSS concentration of less than 12,000 mg/L.

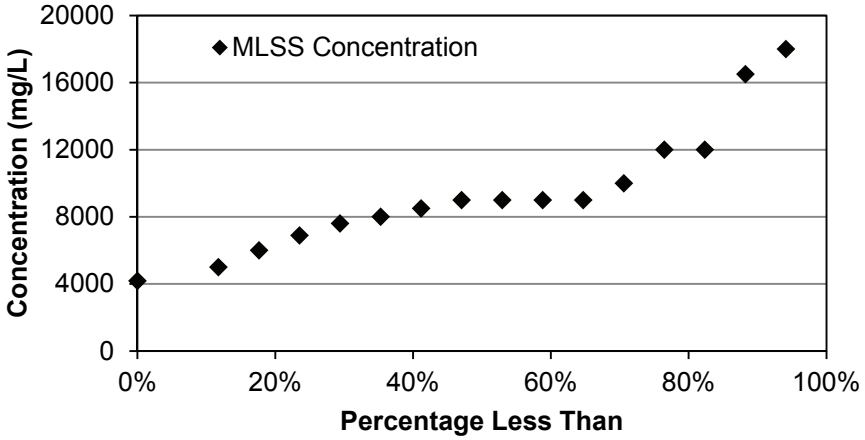


Figure 3.13. MLSS concentrations reported for full-scale installations.

3.4.4 Membrane Flux and Transmembrane Pressure

Membrane flux is defined as the unit volume of water filtered through unit membrane area in a given period of time and is usually presented as gallons per sq. ft per day (gfd) or liters per sq. meter per hour (lmh). Membrane flux does not have a direct impact on effluent organic matter, but it relates to the HRT of the system and, hence, dictates the organic loading rate of the reactor for a given reactor volume. Membrane flux also affects the membrane fouling rate and operating pressure of the system. Figure 3.14 shows the probability plot for the membrane flux values reported in the facility survey. As shown, average flux values for MBR installations were reported to be less than 15.5 gfd (26.3 lmh) for 80% of the installations surveyed. The reported values of operating flux ranged from 6.9 to 18 gfd (11.7–30.6 lmh). The ratio of operating flux to design flux based on reported values ranged from 0.67 to 2.6.

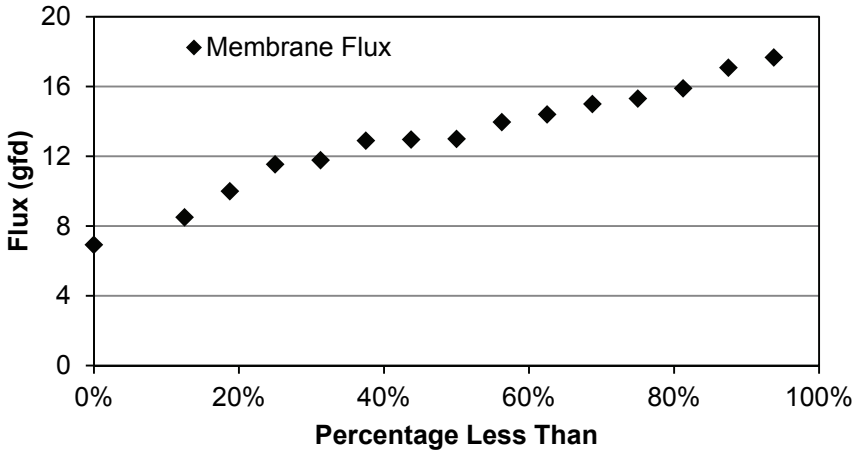


Figure 3.14. Membrane flux values reported for full-scale installations.

The range of operating TMP for these facilities was reported to be between 0.2 and 7 psi (1.4–48.3 kPa) with an overall average TMP of 2.2 psi (15.2 kPa). The range of reported membrane age from the participating facilities ranged from 10 months to 6 years. The range of reported membrane warranties ranged from 5 to 11 years; it should be noted the type of warranty (i.e., proration, coverage, reporting/monitoring requirements, etc.) was not reported and most likely varies from one facility to another as well as from one manufacturer to another.

3.4.5 Membrane Fouling Control Strategies

In order to mitigate membrane fouling, various strategies are employed at full-scale MBR installations that include application of scouring air across the membrane surface, high rate recirculation of MLSS across the membrane modules, frequent relaxation or backwashing of the membranes, and implementation of frequent maintenance cleaning. Results obtained from the facility survey showed the normalized air scour rates per unit membrane area varied from 0.05 to 0.35 $m^3/hr/m^2$. The air scour rate is calculated from the reported membrane air scour flow and the membrane area in use. The 0.05 $m^3/hr/m^2$ rate seems unusually low and could have been due to the reporting of installed membrane area rather than the actual membrane area in use. This seems likely because the reported area is too high for the design flow, but this could not be verified. Approximately two-thirds of survey respondents reported that their MBR plant operated with frequent relaxation (as opposed to backwashing) of the membranes. Of those that reported backwashing, the backwash flush rates ranged from 21 to 207 gfd (35.7–351.4 lmh). Reported filtration cycles and backwashing/relaxation durations ranged from 4 to 30 min. and 10 to 120 s, respectively.

The majority of survey respondents reported implementing maintenance cleans on a routine basis to mitigate membrane fouling. Typical frequencies for maintenance cleans were reported as 1 per week, and they varied from 4 per week to 4 per year. Sodium hypochlorite

solution with concentrations ranging from 100 ppm to 5,000 ppm was being used for these cleans. In some instances, recirculation with citric acid was also employed (following NaOCl recirculation and rinsing) to achieve a target pH between 2 and 3. Although the maintenance cleans are considered preventive measures for membrane fouling, MBR systems must also undergo recovery-cleaning events to recover the permeability of membranes. The facility survey results showed most plants implement soak cleanings; however, the reported frequencies varied from once every 3 months to once every 2 years. Soak times using NaOCl or NaOCl and citric acid were reported to be 3 hours to 1 day. Reported concentrations of NaOCl ranged from 500 to 5000 mg/L.

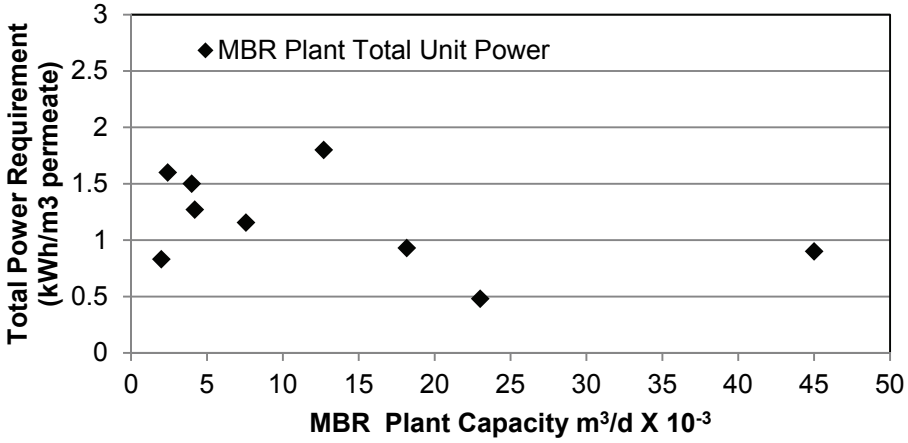
The operational and influent water quality data reported from the facilities' surveys was also used to assess boundary values for key input parameters used in the MBR model. The purpose of this was to use input values for the model scenarios representative of actual operating plants. Model scenarios performed at the low and high end of each parameter while keeping all other parameters constant helps to better define the impact of MBR operating parameters on effluent water quality.

3.5 MBR Energy Requirements

One of the challenges facing MBR technology today is the relatively high energy consumption as compared to CAS processes. As part of the facility survey, participants were asked to report the overall unit energy consumption of their facility. Nine facilities reported total power requirements (kWh/m^3 of permeate produced) as provided in Figure 3.15. However, it should be noted that MBR plant capacity shown on the x-axis of the figure does not necessarily represent average daily flow for each plant. As shown, the reported values range from 0.48 to 1.8 kWh/m^3 (1.7–6.5 MJ/m^3).

Another important aspect of the plant power requirement is the operational versus design capacity. The factors that impact specific energy demand of the plant include optimization and operating temperature. It was also reported by one facility that membrane air scour, process aeration, and permeate pumping accounted for 35%, 15%, and 14% of the total plant power consumption, respectively. In comparison, the reported value of electricity used by CAS sludge processes that include nitrification and filtration (Metcalf and Eddy, 2003) for a wastewater flow rate of 4,000 m^3/day is approximately 0.7 kWh/m^3 (2.5 MJ/m^3). The reported power requirements of the four MBR facilities surveyed with similar capacities were 0.8 to 1.6 kWh/m^3 (2.9–5.8 MJ/m^3).

Factors identified in the literature and facility survey that can affect the unit power consumption of the MBR plants include: membrane aeration strategy, operational flow vs. design capacity, and ability to turn down process equipment such as pumps and blowers during periods of low flow. Figure 3.16 presents values of membrane air scour per unit membrane area, based on the reported values of total membrane area in use and the total membrane air scour rate from the facility survey. As shown, the average values reported ranged from 0.05 to 0.35 $m^3/hr\text{-}m^2$. Two facilities reported maximum values of 0.4 and 0.67 $m^3/hr\text{-}m^2$, respectively.



*MBR plant capacity shown on x-axis of the figure does not necessarily represent average daily flow for each plant.

Figure 3.15. Total MBR power requirements (kWh/m^3 permeate produced*) reported from facility survey.

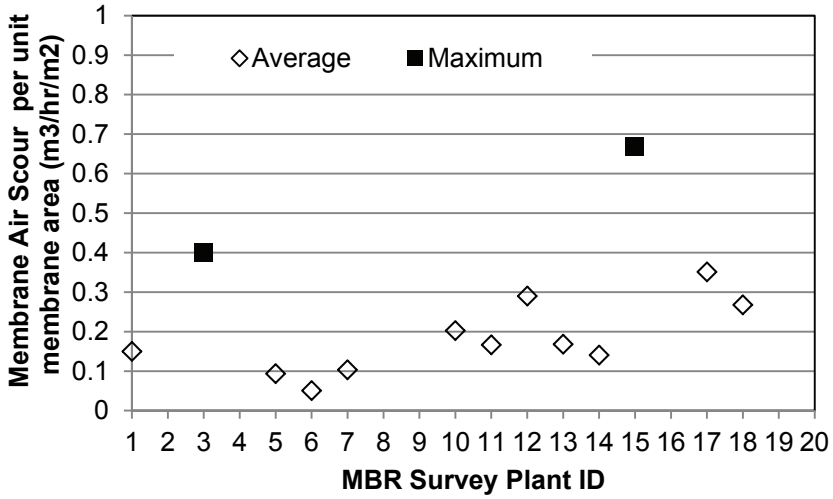


Figure 3.16. Membrane air scour rates per unit membrane area (m^3/h-m^2) reported from facility survey.

Chapter 4

MBR Effluent Water Quality

Removal of five categories of wastewater contaminants by MBRs was assessed based on literature findings and facility survey information. Model scenarios were also incorporated for aggregate organics and trace organic compounds. The general contaminant categories examined are

- aggregate organics (i.e., COD, BOD)
- microbial contaminants/particulate matter
- nutrients (i.e., nitrogen and phosphorus)
- trace metals
- trace organic compounds (including EDCs/PPCPs)

4.1 Aggregate Organics

The MBR eliminates conventional design and operational constraints needed to ensure effective clarification, which allows higher MLSS and, in turn, higher volumetric loading rates, shorter hydraulic retention times, and a smaller reactor footprint than a conventional activated sludge system.

Aggregate organic content fed to an activated sludge system consists of particulate and dissolved organic matter that is contributed by domestic and municipal discharges, inflows, infiltration, and in-plant return flows. In some communities, contributions can also arise from storm water when a combined collection system is utilized and from industrial sources when there is an institutional or industrial component in the service area.

4.1.1 Removal Mechanisms

The removal mechanisms for biodegradable aggregate organics are described in Section 2.4.1. Upon entering the reactor, the original substrate takes one of the following four paths:

- Synthesis of active biomass
- UAP production, which once produced is released to the aqueous solution surrounding the cell
- Production of EPS, which is part of the solid (biomass) phase
- Substrate respiration, in which remaining electrons are sent to an electron acceptor to generate energy

For wastewater treatment plants, the effluent organic matter is usually measured as COD or BOD, with no attempt to further partition this material into more defined sub-categories. The key activated sludge operational parameters of an MBR that control removal of aggregate organic matter are SRT, influent COD concentration, HRT, and DO. The filtration efficiency of the small organic colloids is also an important removal process for the membrane.

4.1.2 MBR Model Predictions for Aggregate Organics Removal

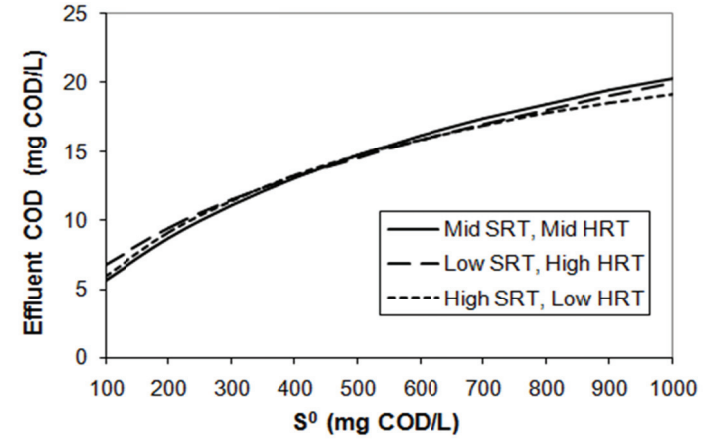
The base MBR model for predicting removal of aggregate organics considers SRT, reactor volume, influent COD, BAP small fraction (fraction of BAP that passes through the membrane), and DO as input parameters to predict MLSS/MLVSS, active biomass concentration, and EPS concentration in the reactor as well as effluent COD concentration.

Table 4.1 presents the predictions for modeling scenarios for aggregate organics; details of which are presented as Appendix B. As shown in Scenarios 6, 7, and 8, when the SRT of the system is increased from 2 to 50 days while keeping HRT constant at 0.13 days (3.12 hours) and influent COD constant at 170 mg/L, the MLSS concentration in the reactor increases from 1770 to 10700 mg/L, because higher SRT values are achieved by greater total system mass. The corresponding active biomass concentration increases from 440 to 2230 mg/L. The EPS concentration increases with SRT as it is related to substrate metabolism and biomass decay. The VSS/TSS ratio reduces from 86 to 73% as more inert substances are retained in the reactor at higher SRT. Higher SRT slightly increases total biodegradation of organic matter as the effluent COD drops from about 16 mg/L to about 14 mg/L, and SRT is increased from 2 to 15 days. No further biodegradation is observed when the SRT increases from 15 to 50 days.

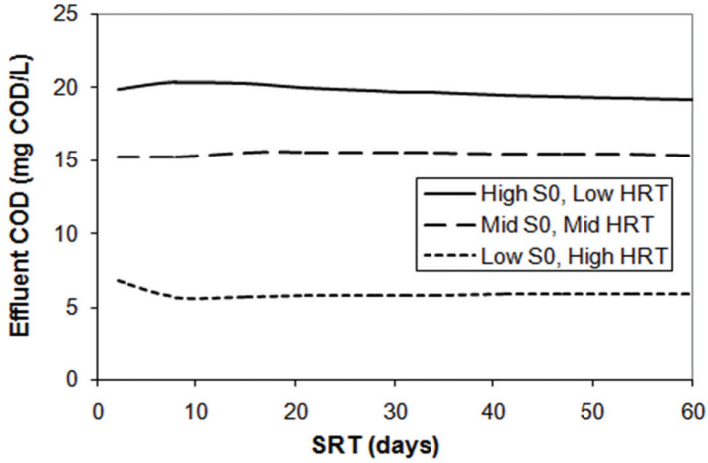
Scenarios 10 and 18 show the impact of the influent COD and DO. An increase in the influent COD from 170 to 370 mg/L and DO from 1 to 3 mg/L (for a constant SRT of 15 days and HRT of 0.33 day) causes the MLSS to increase proportionally from 2970 to 4830 mg COD/L, whereas the effluent COD increases from about 14 to 27 mg/L.

Scenarios 2 and 5 demonstrate the effect of increased HRT on bioreactor conditions and effluent COD concentration. When increasing the HRT from 0.33 day (8 hours) to 1 day (24 hours) while keeping the SRT and influent COD constant, the MLSS concentration in the reactor decreases from 4830 to 1810 mg/L, because solids concentration per unit reactor volume decreases as larger reactor volume is provided for higher HRT while maintaining constant total biomass wasting rate. As the SRT on the system is unchanged, the VSS/TSS ratio as a percentage remains unchanged at increased HRT. The effluent COD decreases slightly from 27 to 25 mg/L while increasing HRT from 0.33 day (8 hours) to 1 day.

These snapshot scenarios indicate little change in effluent COD concentrations as the MBR parameters of SRT or HRT are varied. The overall percentage removal of COD appears fairly constant at approximately 92 to 93% for municipal wastewater regardless of operating conditions. Only a change in the influent COD concentration appears to influence the effluent COD concentration. This is supported by model-generated data presented in Figure 4.1, which presents effluent COD as a function of soluble biodegradable influent COD (S^o), SRT, and HRT for the following range of parameter values (S^o= 100 mg COD/L for low, 550 mg COD/L for mid, and 1000 mg COD/L for high; SRT = 2 days for low, 12.5 days for mid, and 60 days for high; and HRT = 1 hour for low, 5.5 hours for mid, and 10 hours for high).



(a)



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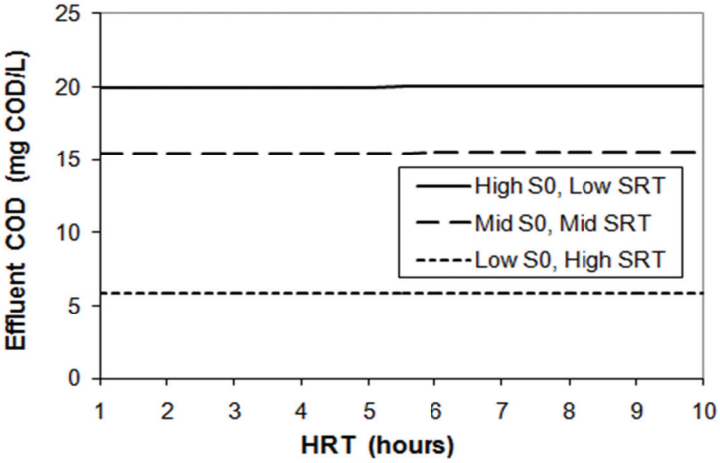

(c)

Figure 4.1. Effect of (a) S^o, (b) SRT, and (c) HRT on effluent COD.
***Note*: From Kiser et al., 2010**

Table 4.1. Predicted Modeling Results for Aggregate Organics by MBR

	Scenario 6	Scenario 7	Scenario 8	Scenario 10	Scenario 18	Scenario 2	Scenario 5
Model Input Parameters							
SRT (days)	2	15	50	15	15	15	15
HRT (days)	0.13	0.13	0.13	0.33	0.33	0.33	1
Influent COD (mg/L)	170	170	170	370	170	370	370
DO (mg O_2/L)	1	1	1	3	1	3	6
BAP small fraction (passes through membrane)	0.5	0.5	0.5	0.7	0.5	0.7	0.7
Process Output							
MLSS (mg COD/L)	1770	7340	10700	4830	2970	4830	1810
MLVSS (mg COD/L)	1520	6070	7870	4140	2470	4140	1560
% MLVSS/MLSS	86%	83%	73%	86%	83%	86%	86%
Active Biomass (mg COD/L)	440	1720	2230	1850	740	1850	720
EPS (mg COD/L)	270	730	880	720	280	720	240
Effluent COD (mg COD/L)	15.7	14.3	14.5	26.6	13.8	27	25.1
Predicted Percentage Removal for COD	91%	92%	92%	93%	92%	93%	93%

4.1.3 Observed Water Quality Performance

4.1.3.1 Chemical Oxygen Demand (COD)

The total organic content is regulated in the wastewater field as COD or BOD. COD measures all chemicals that can be oxidized by a dichromate reflux and, therefore, can overestimate the organic carbon fraction by including non-organic oxidizable species such as hydrogen sulfide. COD values of MBR effluent were observed from the literature to range from 8 to 30 mg/L for municipal sources without industrial input. Data for full-scale and pilot-scale facilities demonstrate a COD-removal percentage that is usually at or above 95% (Lesjean et al., 2002; Ahn et al., 2003; Hasar and Kinaci, 2004; Chae et al,, 2006; Lv et al., 2006; Ottoson et al., 2006; Chae and Shin, 2007; Holakoo et al., 2007; Kang, Cho et al., 2007; Choi et al., 2008; Mohammed et al., 2008; Reif et al., 2008; Sartor et al., 2008) and the impact of operational changes in SRT, MLSS, or use of sequencing versus continuous aeration mode have little apparent impact on performance (Innocenti et al., 2002; Fatone et al., 2005; Janga et al., 2007; Lobos et al., 2007). Bench-scale studies suggest no difference in COD removal as a function of use of different carbon sources that can impact the microbial community structure (Ahmed et al., 2008), or different permeate recirculation configurations (Ersu et al., 2008). Because the COD test lacks low level mg/L sensitivity, it is unlikely to detect any impacts, if any, from these types of operational differences because recalcitrant organic compounds represent a minor percentage of the effluent total organic content. Studies

that contain a large percentage of industrial wastewater do demonstrate lower COD removals as would also occur with a conventional activated sludge system. One MBR study with a 60% industrial wastewater component showed a COD-reduction range of only 68% to 89% (Qin et al., 2007).

An activated sludge computer model of filtration performance of a submerged hollow fiber MBR calibrated with operating data of a full-scale treatment facility consisting of activated sludge and microfiltration units simulated the long-term decreasing permeability of the membrane that was due to cake layer formation and fouling and accurately predicted the final effluent quality COD with a measured value of 23.0 mg/L and a model-simulated COD value of 23.4 mg/L (Wintgens et al., 2003).

Merlo et al. (2007) compared the performance of MBR and CAS processes at SRT of 10 days and found that the effluent soluble COD concentration for the submerged MBR process (19–28 mg/L) was lower than that of a CAS process (34–59 mg/L). The authors attributed this to retention of some soluble and colloidal materials by the membrane used in the MBR process. The clarifiers used in the CAS process do not retain colloidal material as efficiently as the membrane (and cake layer on the membrane surface) does in the MBR process. The authors also observed that the MBR sludge had colloidal material concentration one order of magnitude higher than that in the CAS system.

Figure 4.2 provides average influent and effluent COD (mg/L) values from responses to the facility survey. Influent values ranged from 110 to 600 mg/L with effluent values ranging from 6 to 29 mg/L, which represented removal rates of 92 to 98%. This range of reported effluent COD values agrees well with the values reported in the literature and observed during modeling.

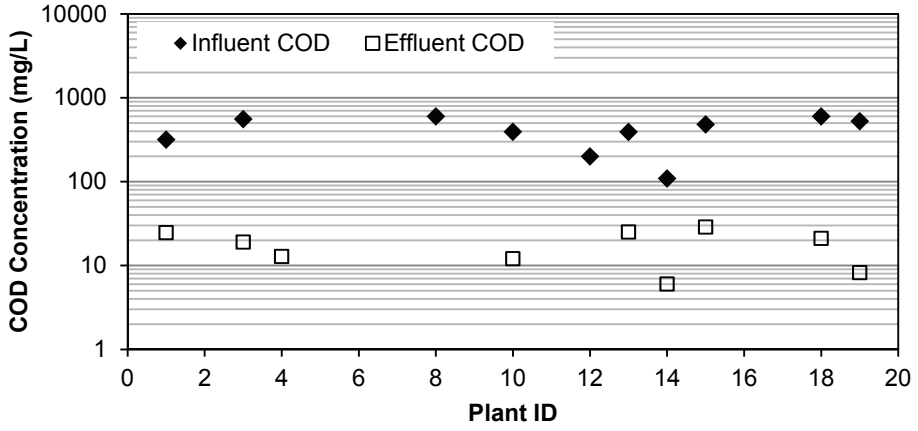

Figure 4.2. Average influent and effluent COD values reported from facility survey.

4.1.3.2 Biochemical Oxygen Demand (BOD)

The BOD of a wastewater is determined by running a standardized laboratory test targeted to assess the oxygen demand that is due to aerobic microbial oxidation processes. Interferences can occur if reduced inorganic material is present (i.e., sulfide and ferrous ions). An inhibitory chemical can be used during BOD testing to eliminate interference from oxidation of reduced forms of nitrogen such as ammonia (i.e., nitrogenous BOD). Discharge permit requirements may require isolation of the carbonaceous BOD and a testing incubation period of 5 days, which is referred to as $CBOD_5$. The majority of the literature reviews containing $CBOD_5$ performance data were primarily focused on removal of other constituents. Removal percentages of $CBOD_5$ for MBR systems were usually at or above 99% for municipal wastewater (Yoon et al., 2004; Ottoson et al., 2006; Zhang and Farahbakhsh, 2007; Liu et al., 2008; Mohammed et al., 2008).

Figure 4.3 provides average influent and effluent BOD_5 (mg/L) values from responses to the facility survey. Influent values ranged from 132 to 600 mg/L with effluent values ranging from <5 to 0.5 mg/L, which represented removal rates of 97 to 100%.

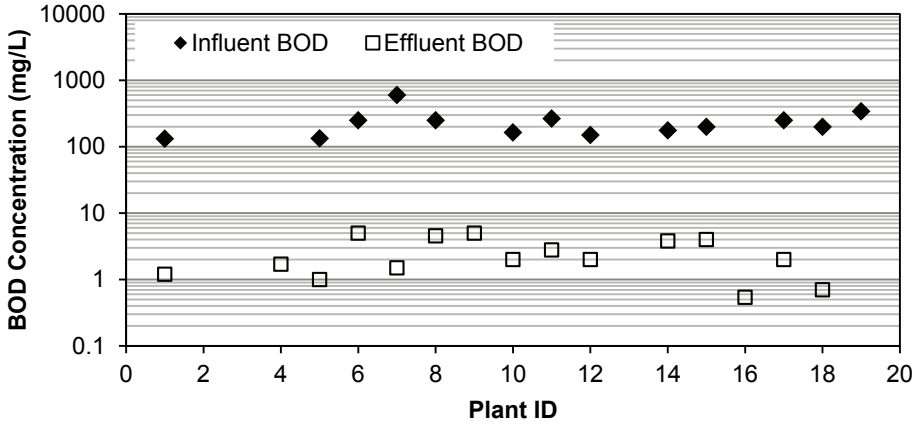

Figure 4.3. Average influent and effluent BOD_5 values reported from facility survey.

4.1.3.3 Total Organic Carbon (TOC)

The total organic carbon was shown to be consistently lower in the effluent of a pilot-scale MBR (4.9–5.1 mg/L) than from the pilot-scale MF permeate of the equivalent full-scale activated sludge process (6.8–6.9 mg/L), which was attributed to better performance of the MBR for reduction of biodegradable components (Qin et al., 2006). Another comparison of pilot-scale MBR effluent to tertiary filter effluent from a biological nitrification activated sludge process showed equivalent percentage removals of 95% but more variability of removal with the MBR process (Ottoson et al., 2006). Effluent TOC concentrations always remained below 5 mg/L, regardless of changes in influent TOC values varying from 156 to 72 mg/L, and molecular weight distribution profiles demonstrated that a biofouled

MBR can retain both high molecular weight (greater than 30 kDa) and low molecular weight (<1 kDa) fractions (Kang, Lee et al., 2007).

4.1.3.4 Biologically Degradable Organic Fraction

The biologically degradable fraction of the organic matter that contributes to BOD can be measured directly as BDOC or AOC. These tests are typically used in the water industry to assess distribution system regrowth potential, whereas wastewater treatment facilities are regulated to achieve a BOD effluent target goal. AOC and BDOC are standardized bioassays that are based on the growth of bacterial organisms in response to organic contaminants. AOC utilizes specific bacterial species and converts cell densities to AOC concentrations using yield coefficients. BDOC uses indigenous microorganisms and utilizes the difference in DOC measurements to measure the biodegradable organic fraction. Understanding the AOC and BDOC content of treated effluent and its relationship to BOD is becoming more important because of increasing implementation of water recycling infrastructure projects. Maintaining sufficiently low concentrations of AOC and BDOC in treated effluent is critical to preventing the water quality problems associated with microbial regrowth within recycled water distribution systems. The BOD values attained in an MBR effluent are typically below 5 mg/L (Yoon et al., 2004; Liu et al., 2008; Mohammed et al., 2008; Winward et al., 2008), and ongoing studies indicate that MBR processes also have the lowest values of AOC and BDOC, most likely because of the longer SRT and absolute particle separation achieved with this technology.

Figure 4.4 shows the effluent AOC and BDOC concentrations reported in different wastewater treatment processes.

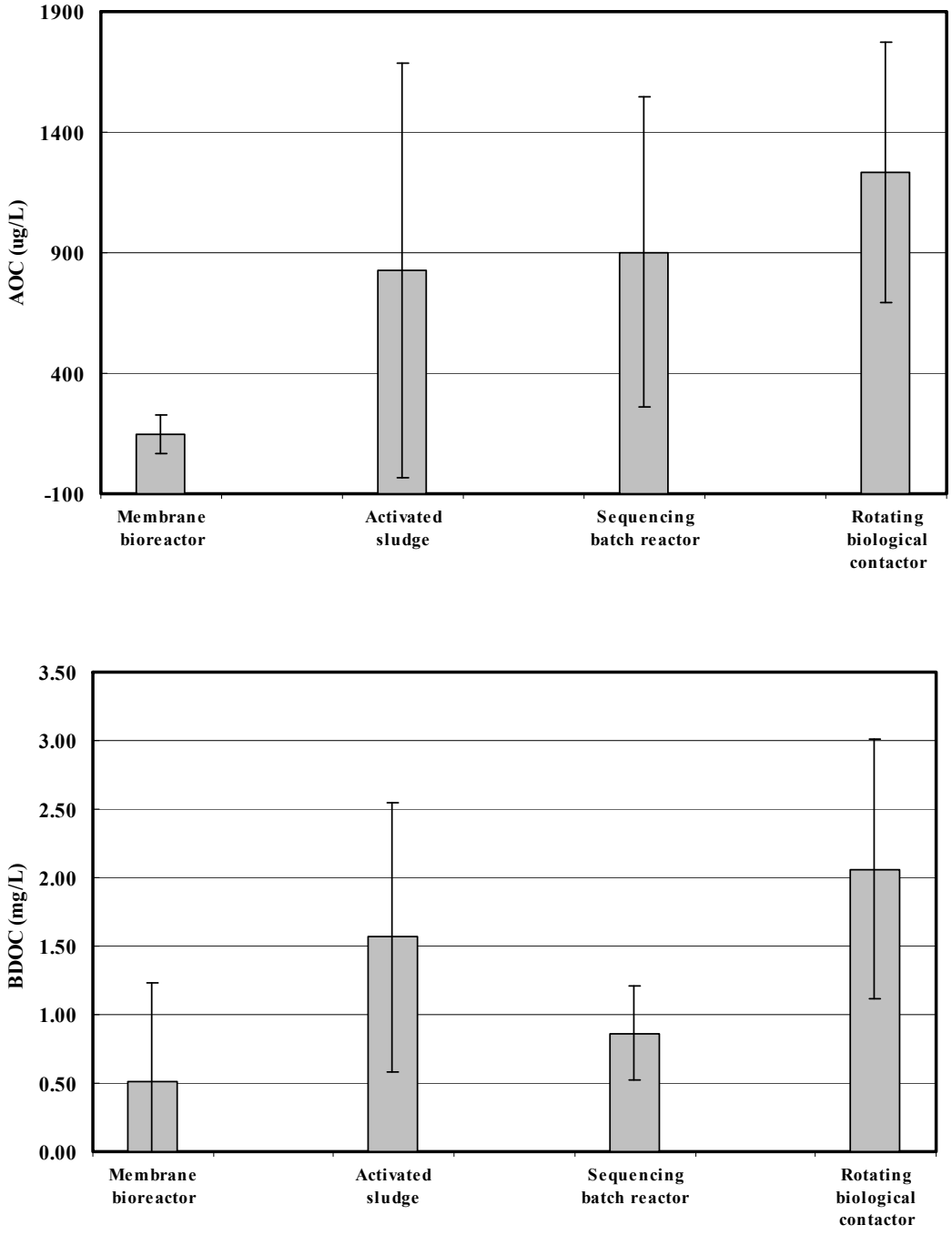

Figure 4.4. Effluent concentrations of AOC and BDOC reported in various wastewater treatment processes.

***Note*. Graphic reproduced from *Guidance Document on the Microbiological Quality and Biostability of Reclaimed Water Following Storage and Distribution* by Jjemba et al., 2009, with permission from the WateReuse Research Foundation.**

4.2 Microbial Contaminants/Particulate Matter

The MBR process produces superior water quality, compared to conventional wastewater treatment processes because the membrane provides an absolute barrier to many pathogenic organisms and particulate matter that increases the efficacy of disinfection processes by removing suspended solids that can shield pathogens during disinfection.

Many types of pathogenic organisms excreted by infected human beings and animals are found in wastewater. Microbial contaminants of concern in wastewater treatment consist of bacteria, protozoa, and viruses. The total coliform bacteria concentration in raw wastewater usually ranges from 10^7 to 10^9 CFU/100 mL, whereas that of fecal coliform bacteria ranges from 10^6 to 10^8 CFU/100 mL. The coliphage concentration in raw wastewater usually ranges from 10^3 to 10^4 PFU/100 mL.

4.2.1 Removal Mechanisms

4.2.1.1 Coliforms

Because the typical size of coliform bacteria (0.6–1.2 μm in diameter and 2–3 μm in length) is larger than the absolute pore size of the membranes used for MBRs, size exclusion by the membrane is the dominant removal mechanism for coliforms in MBRs with intact membranes.

4.2.1.2 Coliphages

Because coliphages range from 0.022 to 0.026 μm in size, smaller than the absolute pore sizes of most of the membranes used in MBR systems, they would be expected to partially pass through the membrane. However, several studies have reported removal of indigenous coliphages through MBR process. The removal of coliphages can be attributed to the following mechanisms:

Adsorption to the membrane surface or membrane pores

- Adsorption to the membrane plays a critical role in the removal of compounds smaller than membrane pore sizes for a clean membrane surface. Farahbakhsh and Smith (2004) showed inertial impaction to be the dominant removal mechanism for indigenous coliphages for a clean membrane while filtering secondary effluent. At the inception of secondary filtration with a clean membrane, indigenous coliphages are adsorbed to the membrane surface and pores depending on the availability of adsorption sites and water chemistry (pH and conductivity). The study showed 1.2 log removal of indigenous coliphage by a clean membrane. Shang et al. (2005) showed 0.4 log removal of seeded MS-2 phage solely by a membrane with a nominal pore size of 0.4 μm in a MBR.

Removal by Membrane-Attached Biofilm

- During the initial stages of the filtration process, deposition of particles and bacterial cells occurs on the membrane surface. After several days of filtration, this slimy gel layer becomes more rigid such that shear force produced on the membrane surface by scouring air cannot remove it. This layer of biofilm reduces the effective pore size of the membrane and increases the filtration resistance. Several studies have demonstrated the role of membrane biofilm as well as high molecular weight organic matter as a secondary barrier to the passage of microbial contaminants (Madaeni et al., 1995; Ueda and Horan, 2000;

Farahbakhsh and Smith, 2004; Shang et al., 2005; Jacangelo et al., 2006; Kang, Lee, et al., 2007). Once a biofilm is formed on the membrane surface, the dominant removal mechanism for coliphages is interception by this layer. Shang et al. (2005) showed that the membrane biofilm formed after 21 days of filtration contributed up to 2.1 log removal of seeded phage.

Adsorption to the Sludge

- Association of coliphages with biomass and resulting removal in the secondary process in conventional treatment and MBR has been documented in a few studies (Rose et al., 1996; Ueda and Horan, 2000; Shang et al., 2005). Rose et al. (1996) showed 0.75 log removal of indigenous coliphage during secondary biological treatment process. While conducting seeding studies, Ueda and Horan (2000) showed 1.5 to 2.2 log removal of T-even–like phage by activated sludge. Shang et al. (2005) showed 0.8 log removal of seeded MS-2 phage by biomass. Predation of coliphages by higher level microorganisms can also be assumed to occur in the bioreactor, but the exact contribution of this mechanism in MBRs is not documented.

The following factors have been shown to impact coliphage removal by MBRs:

Permeate Flux and Filtration Resistance

- Permeate flux has been shown to impact the log-removal values (LRV) of indigenous coliphages by membranes. Three reasons can be cited (Farahbakhsh and Smith, 2004; Jacangelo et al., 2006):
  - Higher permeate flux reduces the residence time of coliphages in membrane pores, thereby reducing the likelihood of adsorption of coliphages on a clean membrane.
  - Higher permeate flux causes an increase in TMP that results in reduction of cake layer porosity, consequently increasing the LRV for coliphages.
  - Higher permeate flux results in higher shear forces in the membrane pores resulting in the dislodging of captured coliphages and releasing them in the permeate.
- During bench-scale studies performed on an MBR (with a 0.4 μm membrane), Ueda and Horan (2000) reported a strong correlation between membrane flux and T-even–like phage removal, and phage removal declined exponentially as the flux increased. The authors also reported an increase in LRV of phage with increasing filtration resistance. As the filtration resistance of the membrane increases because of the biofilm formation on the membrane surface, the biofilm also reduces the effective pore size of the membrane, thereby increasing the virus removal ability of the membrane.

Feed Phage Concentration

- While conducting experiments on an MBR with seeded phage, Ueda and Horan (2000) showed an increase in LRV of T-even–like phage (200 nm in size) with increase in feed concentration above 106 CFU/100 mL in a bench-scale MBR using a 0.4 μm flat-sheet membrane. They also showed no impact of feed concentration on LRV of seeded phage by the 0.4 μm membrane itself in the absence of activated sludge. In another study, a higher concentration of indigenous coliphages in the feed (secondary effluent) was shown to increase the likelihood of passage of coliphages through the membrane pores of a clean membrane, but once cake layer fouling occured, it nullified the impact of feed concentration (Farahbakhsh and Smith, 2004).

SRT, MLSS, and F/M

- SRT, MLSS and F/M are interrelated operating parameters in a MBR system. Even though these parameters have been shown to have negligible direct impact on virus removal (Shang et al., 2005), they do affect the EPS concentration in the reactor. Because EPS is at least partly responsible for pore blocking and biofilm fouling on the membrane, virus removal is presumed to be affected by EPS concentration in the bioreactor. None of the research studies so far have shown a direct impact of EPS (membrane fouling by EPS) on virus removal. Shang et al. (2005) showed no significant difference in the LRVs of seeded MS-2 phage for MLSS concentrations ranging from 6,000 to 10,000 mg/L at a constant SRT of 200 days. The researchers also operated MBR system at two different F/M ratios (0.06/day and 0.03/day) at a constant HRT of 9 hours and did not notice any statistically significant difference in LRVs of seeded MS-2 phage.

4.2.2 Observed Microbial Removal Performance

4.2.2.1 Coliforms

Figure 4.5 shows the log removal of coliforms by MBRs reported in various studies (Adham et al., 2004; Hirani et al., 2007; Ottoson et al., 2006; Ueda and Horan, 2000; Zhang and Farahbakhsh, 2007). As shown in the figure, MBR systems achieved 5–6 log removal of total coliforms and 5–7 log removal of fecal coliforms. The difference in LRV between total and fecal coliforms by MBR systems reported in Hirani et al. (2007) can be explained by lower influent concentrations of fecal coliforms (5.4E+06 CFU/100 mL) compared to total coliforms (6.6E+07 CFU/100 mL). Because both total and fecal coliforms are similar in size and are expected to be removed completely by membranes, lower influent concentration of fecal coliforms would result in lower LRV compared to total coliforms.

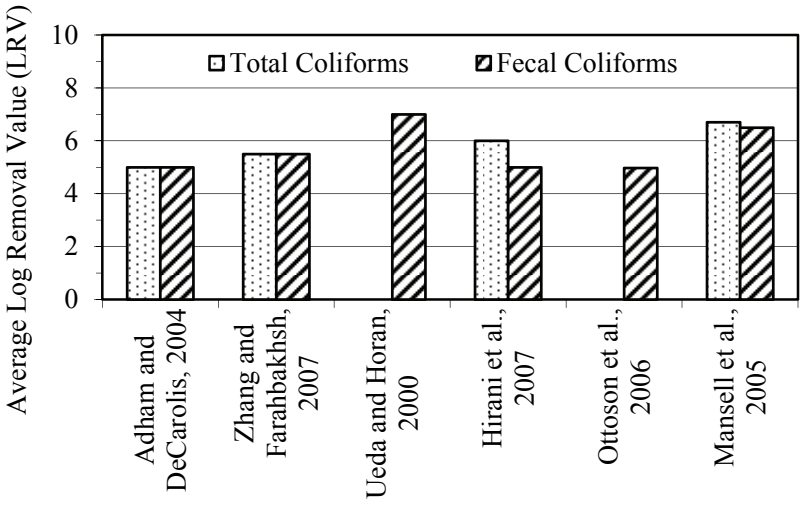

Figure 4.5. Coliform removal reported in various studies.

Adham et al. (2004) reported the presence of both total and fecal coliforms in MBR permeate for one of the four systems tested. The authors observed better coliform removal after 1700 hours of operation and attributed this enhanced removal to plugging of a portion of the larger pores within the pore size distribution. After conducting a series of experiments and sampling, the authors concluded that contamination of permeate piping could have been one of the reasons for the presence of coliforms in the permeate. Second, cleaning of the membranes during backwashing removed the dynamic layer formed on the membrane surface, thereby reducing the sieving ability of the membranes. The authors also observed total coliform concentration of up to 5000 MPN/100 mL in the effluent of another MBR system and attributed it to contamination on the permeate side of the membrane because the concentration of fecal coliforms and coliphages was below the detection limit.

Zhang and Farahbakhsh (2007) reported the presence of total coliforms (up to 250 CFU/100 mL) in MBR permeate, but the concentration of total coliforms in permeate did not correlate with influent concentrations, confirming the integrity of the membrane system. If the membrane was breached, the total coliform concentration in the permeate would vary with the influent concentration. In addition, no fecal coliforms were present in the permeate indicating that the presence of total coliforms could be attributed to the contamination inside the permeate piping. Usually, when a membrane breach occurs, presence of both total and fecal coliforms would be expected in the permeate because they are similar in size. The authors attributed the presence of total coliforms in the MBR effluent to the biofilm formed inside the permeate line.

Figure 4.6 provides average effluent total coliform concentrations based on responses to the facility survey. Influent concentrations for municipal wastewater were not reported, whereas reported average effluent concentrations ranged from greater than 1 to 53 PFU/100 mL. As discussed earlier, presence of coliforms in MBR filtrate may be attributed to either contamination of the backwash basin/piping or to the removal of dynamic cake layer on the membrane surface.

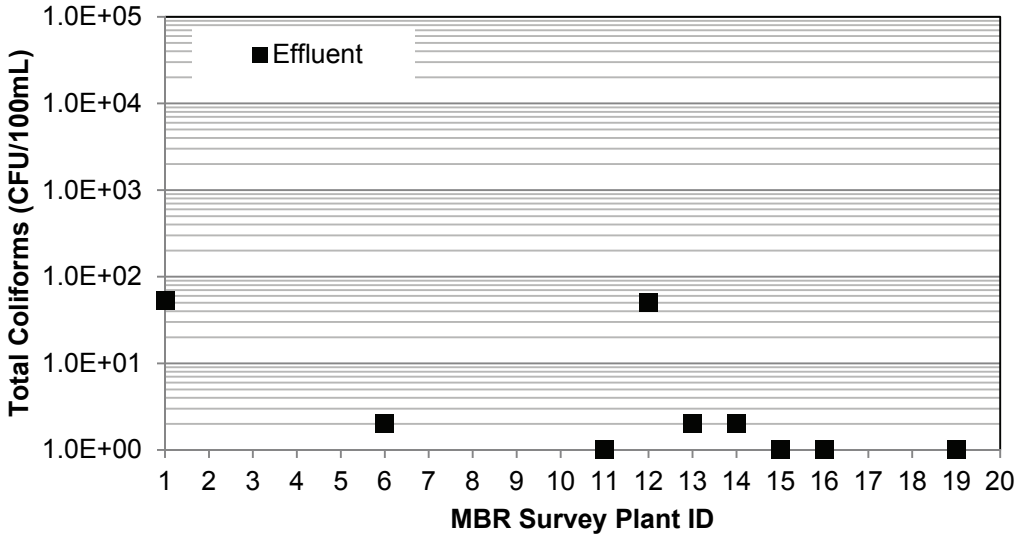

Figure 4.6. Average effluent total coliform values reported from facility survey.

4.2.2.2 Coliphages

Several studies have reported complete removal of indigenous coliphages from wastewater by MBR systems (Adham et al., 2004; Hirani et al., 2007; Zhang and Farahbakhsh, 2007; Hirani et al., 2010). Because indigenous phage is particle-associated, complete removal of indigenous phage is expected by MBR because the membrane retains all particulate matter in the reactor. Variations in operating conditions have been shown to have little or no impact on indigenous coliphages removal capability of MBR systems (Zhang and Farahbakhsh, 2007; Hirani et al., 2007). Figure 4.7 shows the results reported for phage removal by various MBR studies. As shown, these studies reported 2.3 to 4.5 log removal of indigenous coliphages.

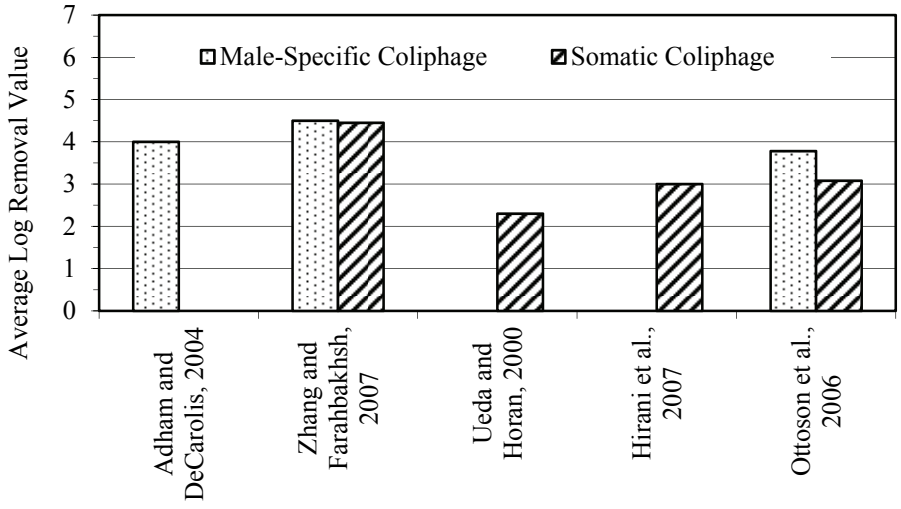

Figure 4.7. Indigenous coliphage removal reported in various studies.

Even though several studies have reported complete removal of indigenous coliphages by MBR systems, removal of seeded phage has varied for different membranes and different operating conditions in several virus-seeding studies (Hirani et al., 2007; Madaeni et al., 1995; Ueda and Horan, 2000). This difference in virus removal between indigenous and seeded coliphages by MBR systems can be explained by particle association of indigenous coliphages. Figure 4.8 shows the difference in virus removal (1.0–5.9 log) by various membranes during virus-seeding studies. It should be kept in mind that each of these virus-seeding studies was conducted at different operating conditions (flux, membrane fouling condition, and bioreactor conditions).

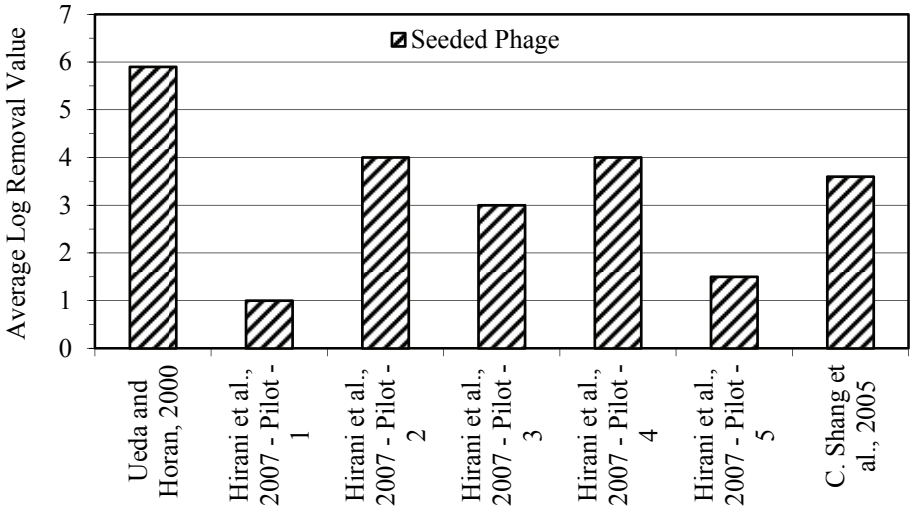

Figure 4.8. Seeded coliphage removal reported in various studies.

4.2.3 Observed Particulate Removal Performance

Figure 4.9 provides average effluent turbidity values based on responses to the facility survey. The range was from 0.02 to less than 1 NTU.

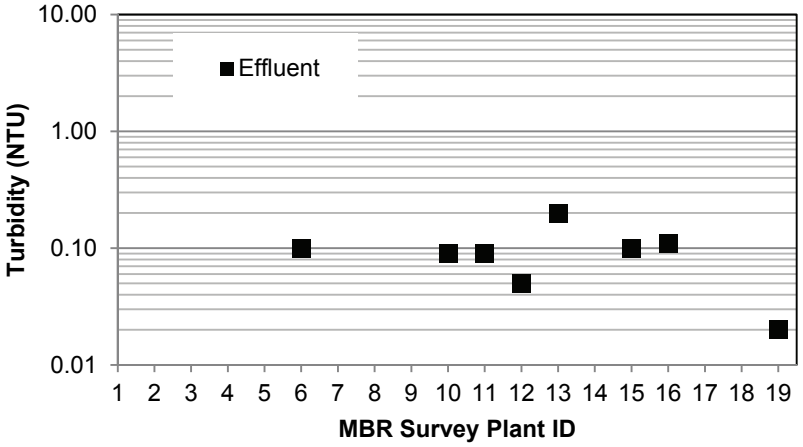

Figure 4.9. Average MBR effluent turbidity reported from facility survey.

Figure 4.10 provides average influent and effluent TSS (mg/L) values based on responses to the facility survey. Influent values ranged from 112 to 400 mg/L with effluent values ranging from 0.2 to 15.3 mg/L. TSS concentration in membrane-filtered effluent is typically less than the detection limit of 2 mg/L, which was observed in the data reported from most of the full-scale installations.

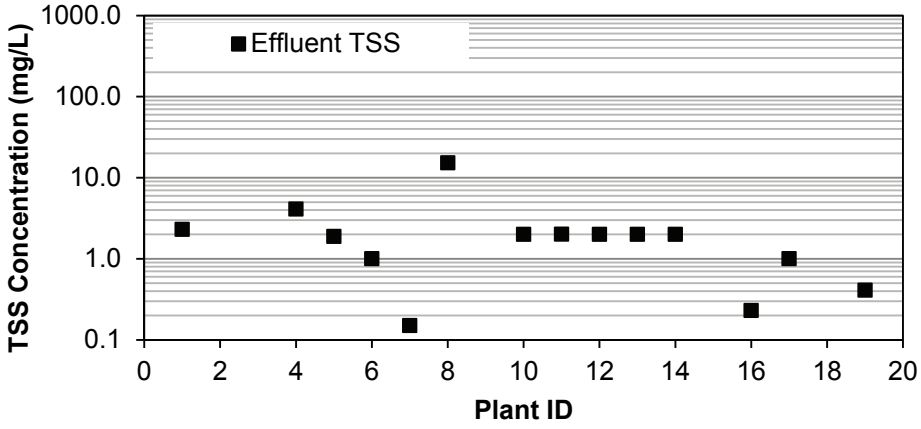

Figure 4.10. Average influent and effluent TSS reported from facility survey.

4.3 Nutrients

Nutrient removal in wastewater treatment is concerned with nitrogen and phosphorus. The main drivers for nutrient removal in wastewater treatment include

- Prevention of adverse impacts that occur from the discharge of nitrogen compounds such as ammonia to receiving waters that can cause aquatic toxicity
- Control of eutrophication in downstream receiving waters
- Meeting the requirements of specific water reuse applications such as groundwater recharge for water quality

Nitrogen and phosphorus can be removed by activated sludge processes by providing anoxic basins for denitrification and anaerobic selectors that promote the growth of phosphorus accumulating organisms. Phosphorus can also be removed through chemical precipitation.

4.3.1 Removal Mechanisms

The basic biological and chemical principles associated with nutrient removal in conventional and MBR processes are the same. Some studies have shown that the specific nitrification rates can vary in MBR systems compared to CAS systems. Some report higher rates, whereas others report lower rates. The differences may lie in the fact that different microbial communities exist at different SRTs (Kraume et al., 2005).

4.3.1.1 Biological Nitrification

Nitrification is a two-step process that includes the oxidation of ammonia to nitrite (Step 1) and the oxidation of nitrite to nitrate (Step 2). Nitrification processes normally involve two groups of aerobic autotrophic bacteria. The first type is the ammonia-oxidizing bacteria (AOB) that are responsible for the first step. *Nitrosomonas* is a well-known and important AOB. The second type is the nitrite-oxidizing bacteria (NOB) that are responsible for the second step. Although the genus *Nitrobacter* often is mentioned as an NOB, the main genus in activated sludge systems usually is in the genus *Nitrospira*.

The energy-generating reactions of nitrification (Tchobanoglous et al., 2003) are

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4\,H^+ + 2\,H_2O \text{ (Step 1)} \quad (16)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \text{ (Step 2)} \quad (17)$$

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \text{ (Overall Reaction)} \quad (18)$$

Complete oxidation of ammonia theoretically requires 4.57 g O_2/g N oxidized. Approximately 75% of the oxygen is associated with nitrite production, whereas the remaining 25% is used for the oxidation of nitrite. Each gram of ammonia nitrogen converted theoretically requires 7.14 g of alkalinity (as $CaCO_3$)/g N oxidized.

The growth rate of nitrifying organisms is much lower than heterotrophic organisms; therefore, operation at higher SRT is required for stable nitrification. The reported specific growth rates for nitrifiers range from 0.25 to 0.77 per day. With a safety factor of 5, the SRT needed for stable nitrification will be 6.5 to 20 days. Slower growth can occur because of the presence of inhibitory materials, low temperature, extreme pH, and low DO. When the DO

concentration in the aerobic basins is less than approximately 0.5 mg/L, nitrification is greatly slowed and can result first in increased nitrite concentrations and ultimately total loss of nitrification.

4.3.1.2 Biological Denitrification

Denitrification is the stepwise reduction of nitrate to nitrite, nitric oxide, nitrous oxide, and nitrogen gas. The biological denitrification process readily occurs in activated sludge processes because of the wide range of heterotrophic bacteria that can respire nitrate and nitrite, as well as DO. During biological denitrification these organisms use nitrate or nitrite as electron acceptors to oxidize organic donors when the DO is low.

Denitrification processes can be designed with either pre-anoxic or post-anoxic basins. A pre-anoxic denitrification process involves use of influent wastewater BOD to provide for organic electrons for denitrifiers to reduce nitrate produced that is recirculated from the aerobic basins. A post-anoxic denitrification process (also called tertiary denitrification) uses electron donors from endogenous respiration of biomass or, more commonly, through the addition of an external organic donor. When post-anoxic denitrification is designed without external donor source addition, the denitrification rate is slower than that for pre-anoxic denitrification or when an external donor is added.

Common equations for biological denitrification (Metcalf and Eddy, 2003) are

$$C_{10}H_{19}O_3N + 10NO_3^- \rightarrow 5N_2 + 10\,CO_2 + 3H_20 + NH_3 + 10OH^- \text{ (wastewater)} \quad (19)$$

$$5CH_3OH + 6NO_3^- \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^- \text{ (methanol)} \quad (20)$$

During the denitrification process, one equivalent of alkalinity is produced per equivalent of NO_3-N reduced. This equates to 3.57 g of alkalinity ($CaCO_3$) produced per g of NO3-N reduced; hence, approximately 50% of the alkalinity that was lost in the nitrification process can be recovered through denitrification.

4.3.1.3 Biological Phosphorus Removal

Biological phosphorus removal in activated sludge processes results from the uptake of phosphorus (P) present in the raw wastewater and incorporated into the cell mass. The phosphorus is eventually removed from the system through wasting of the biomass. Biological phosphorus removal depends on the mass of sludge wasted, which is ultimately governed by the SRT of the system and the P content of the wasted biomass.

Some microorganisms contain an unusually large amount of P in their biomass; they are referred to as phosphorus accumulating organisms (PAOs). Typically, PAOs contain upward of 20% P by dry weight in the form of polyphosphates. In comparison, typical activated sludge biomass comprises approximately 2.5% P. A biological wastewater treatment system designed for biological P removal typically contains an anaerobic zone followed by anoxic/aerobic zones. The presence of the anaerobic zone (typical HRT = 0.5–1.5 hr) allows the PAOs to flourish. Under the anaerobic conditions, PAOs dominate other heterotrophic bacteria because they use stored polyphosphate as energy to assimilate acetate.

Several factors in wastewater treatment systems can affect biological phosphorus removal performance. In order to achieve good biological P performance, the influent should contain a significant concentration of readily biodegradable soluble COD (e.g., volatile fatty acids), and certain cations including Mg^{+2}, K^+, and Ca^{+2} must be available in sufficient concentrations to

allow polyphosphate storage (Metcalf and Eddy, 2003). Of high importance is avoiding the addition of electron acceptors (DO, nitrate, or nitrite) to the anaerobic zone.

4.3.1.4 Chemical Phosphorus Removal

Phosphorus can be removed from wastewater using chemical precipitation through the use of lime, alum, or ferric chloride. The general equations for phosphate precipitation and other considerations are presented elsewhere (Metcalf and Eddy 2003). Precipitation using alum or ferric can also be used in combination with bio P removal in the biological reactors.

4.3.2 Factors that Impact Nutrient Removal Performance in the MBR Process

The following factors can impact nutrient removal performance of MBR processes:

4.3.2.1 SRT

Nitrification—MBR installations designed to achieve nitrification are usually designed to operate at an SRT of 7 days or greater in order to retain slow-growing nitrifiers. In regions with low temperature, a higher SRT may be required to achieve sufficient nitrification. Figure 4.11 shows the effect of SRT on nitrification processes as reported in several different MBR studies. With an SRT of greater than 10 days, nitrification efficiency of greater than 95% was reported in several studies (Chae and Shin, 2007; Fatone et al., 2005; Geng and Hall, 2007; Hasar and Kinaci, 2004; Holakoo et al., 2007; Innocenti et al., 2002; Kang, Lee, et al., 2007; Lesjean et al., 2002; Liu et al., 2008; Mohammad et al., 2008; Pulefou et al., 2008; Qin et al., 2006; De Wever et al., 2007; Wintgens et al., 2002).

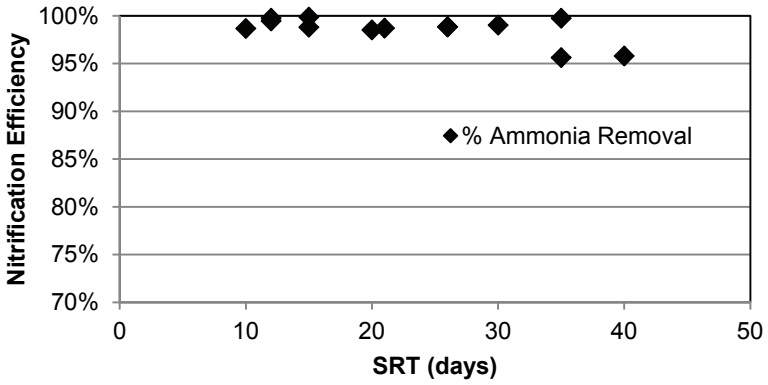

Figure 4.11. Impact of SRT on nitrification efficiency as reported in MBR studies.

Phosphorus Removal—Even though operation at low SRT is desirable to achieve higher biological phosphorus removal, Lesjean et al. (2002) showed greater than 90% removal of total phosphorus at an SRT of 26 days. The authors also showed that MBR systems achieved slightly higher phosphorus removal than the CAS systems under similar operating conditions of sludge age and mass organic load. This was attributed to the rejection of particles and colloids through the microfiltration membrane used in an MBR process.

4.3.2.2 Carbon-to-Nitrogen Ratio

Denitrification—Because the COD concentration in the wastewater to achieve effective denitrification is critical, estimates of COD/TKN ratios to achieve effective denitrification have been reported at 7 to 10 g COD/g N (Choi et al., 2008).

Figure 4.12 shows the effect of COD/TKN ratio on the denitrification process in MBR as reported in various MBR studies (Chae and Shin, 2007; Fatone et al., 2005; Geng and Hall, 2007; Hasar and Kinaci, 2004; Holakoo et al., 2007; Innocenti et al., 2002; Janga et al., 2007; Lesjean et al., 2002; Qin et al., 2006, 2007). As shown, the denitrification efficiency of the system increases as the COD/TKN ratio increases, and denitrification efficiency of greater than 50% was achieved in every study where the COD/TKN ratio was calculated to be at least 7. The practical ratio must be considerably greater than the theoretical minimum ratio because some COD is oxidized through oxygen respiration.

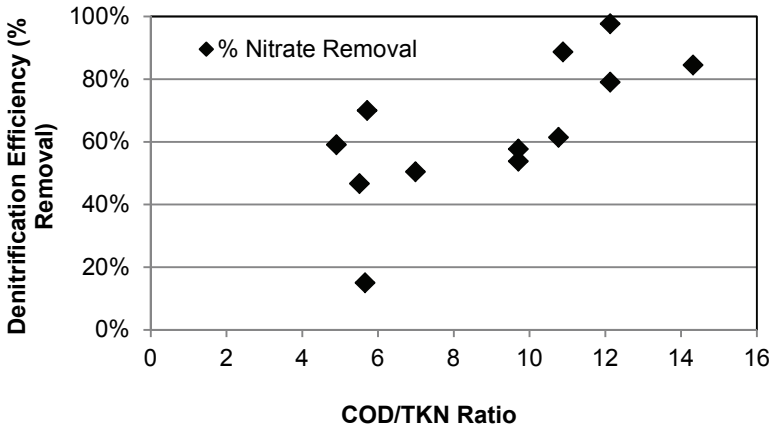

Figure 4.12. Effect of COD/TKN ratio on denitrification in MBR.

4.3.2.3 Process Configurations

Scouring air, used to mitigate membrane fouling in MBR installations, results in high DO concentration (3–5 mg/L) in the membrane basins. Presence of such high DO concentration in the membrane basin makes it difficult to transfer the sludge directly from the membrane basin to anoxic/anaerobic basins without DO carryover to the anoxic/anaerobic basin. To lessen DO carryover, many MBR installations are designed with a dual recycle configuration as shown in Figure 4.13.

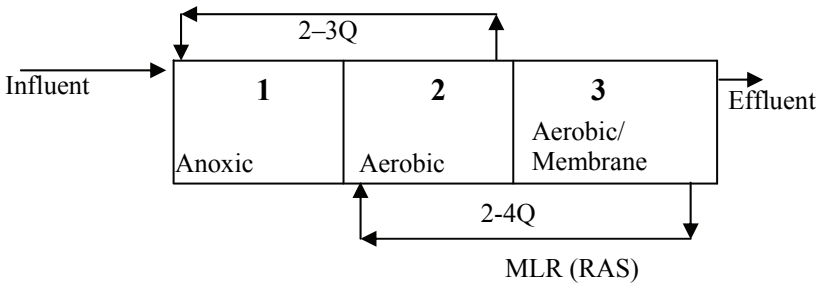

Figure 4.13. Dual recycle configuration for nitrification–denitrification.

Some installations use single recycle configuration (Figure 4.14) by directing membrane recycle flow directly to the anoxic basins and providing larger anoxic volumes to quench the DO in the recycled flow. The anoxic volume will consist of 15 to 20% of the total reactor volume in CAS process, whereas the anoxic volume in a single recycle MBR process will consist of 20 to 40% of the total volume to minimize the impact of DO carryover (WEF, 2006).

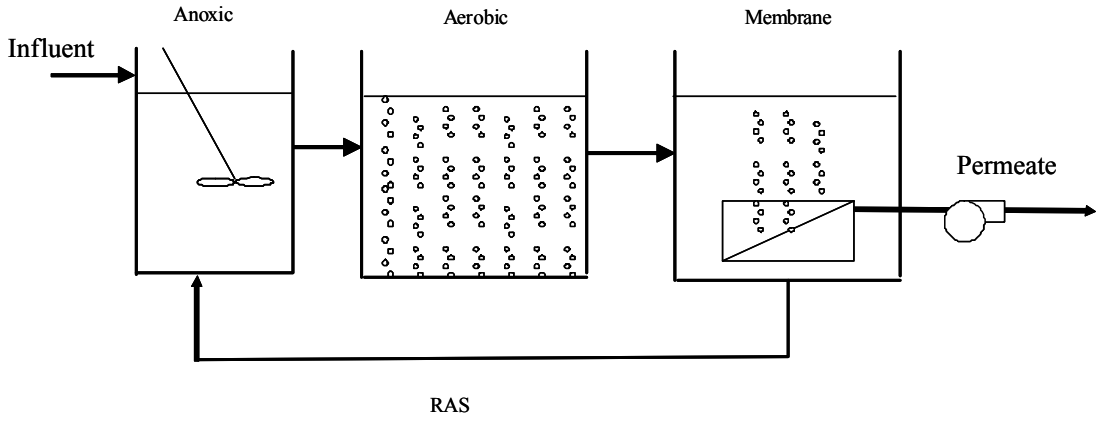

Figure 4.14. Single recycle configuration for nitrification–denitrification.

As with CAS systems, MBR systems can be designed to achieve simultaneous nitrification-denitrification in a single basin by monitoring DO/ORP concentration in the anoxic/aerobic basin and controlling the process air accordingly (Fatone et al., 2005; Rittmann and Langeland, 1985). Monitoring Nicotinamide Adenine Dinucleotide (NAD^+) has also been used to achieve simultaneous nitrification/denitrification in a single basin (Farabegoli et al., 2003; Trivedi and Heinen, 2000).

In order to maximize use of BOD in influent wastewater by denitrifiers, MBR installations can be designed with a step-feed configuration as shown in Figure 4.15. As with CAS systems, this configuration allows addition of influent wastewater in different anoxic basins in the process; each of which receives nitrified wastewater from an aerobic basin. Such a configuration may reduce use of an external carbon source to achieve low nitrogen concentration in the effluent (Crawford et al., 2006).

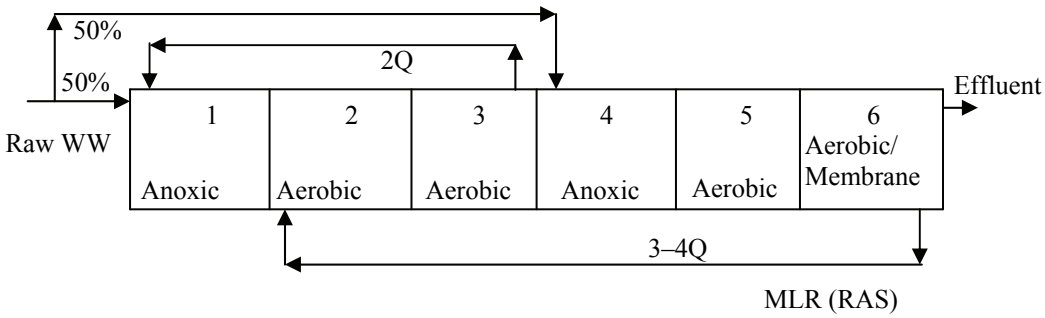

Figure 4.15. Step-feed configuration for nitrification-denitrification.

Biological phosphorus removal can be achieved in MBR systems by providing an anaerobic zone in front of the anoxic/aerobic zone. A schematic for such a configuration is shown in Figure 4.16. As shown, this configuration allows PAOs to preferentially utilize readily biodegradable carbon in the influent wastewater. To minimize DO and nitrate in the anaerobic zone, the recycle stream from the aerobic/membrane tank will be diverted to the anoxic zone with a second recycle to the anaerobic zone. This configuration allows reduction of nitrate from wastewater in the anoxic zone before passing it to the anaerobic zone.

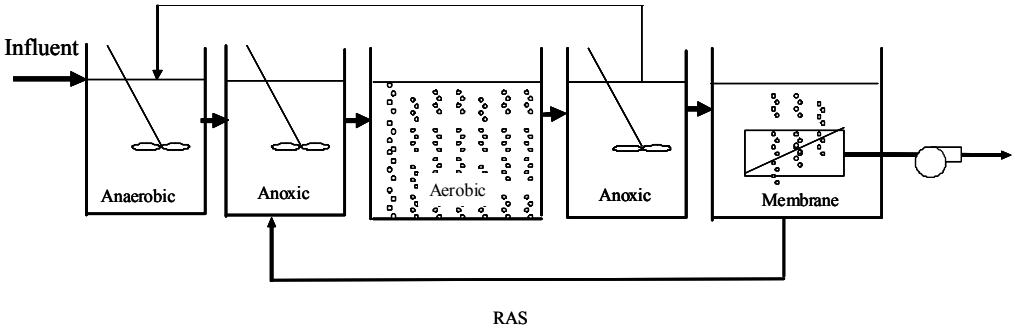

Figure 4.16. MBR configuration for biological nitrogen and phosphorus removal.

Because biological phosphorus removal requires removal of phosphate by larger sludge wasting volumes, which is achieved through operation at lower SRTs, it becomes difficult for plants operating at higher SRTs to produce low effluent phosphorus. These plants require addition of coagulant to achieve the target effluent phosphorus requirements (Kraume et al., 2005).

In general, the required coagulant for MBR systems may be lower than that required for CAS systems because of the complete particulate phosphorus removed by MBR. Figure 4.17 shows the schematic of a plant utilizing enhanced biological and chemical phosphorus removal to achieve a very low effluent phosphorus concentration (Crawford et al., 2006).

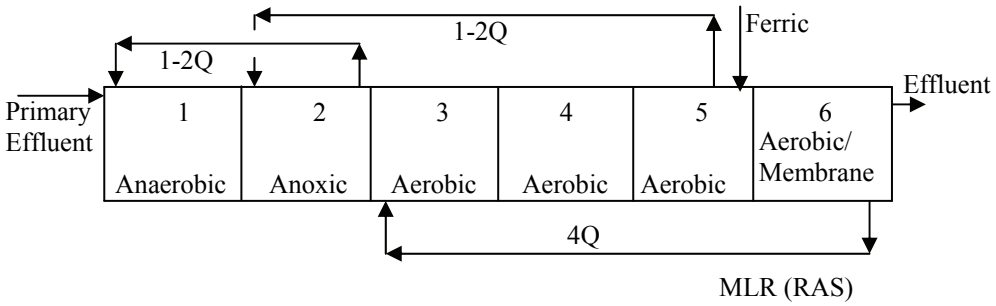

Figure 4.17. MBR configuration for enhanced biological and chemical phosphorus removal.

4.3.3 Observed Nutrient Removal Performance

4.3.3.1 Ammonia

Because MBR systems usually operate at higher SRTs (7 days or higher), effluent ammonia concentration of <0.5 mg/L-N and greater than 97% removal are common (Adham et al., 2004; Hirani et al., 2007; Innocenti et al., 2002; Lesjean et al., 2002; Qin et al., 2006; Wintgens et al., 2002). Figure 4.18 shows the influent and effluent ammonia concentration reported in various MBR studies at different SRT values (Fatone et al., 2005; Geng and Hall, 2007; Hasar and Kinaci, 2004; Holakoo et al., 2007; Innocenti et al., 2002; Kang et al., 2007; Lesjean et al., 2002; Mohammad et al., 2008; Wintgens et al., 2002). With influent ammonia concentrations ranging from 10.5 to 54 mg/L-N, effluent ammonia concentrations varied from <0.5 to 7.1 mg/L-N at SRT values of 4 to 68 days. Influent ammonia in municipal wastewater is approximately two-thirds of the influent nitrogen because part of influent nitrogen is in the form of organic nitrogen. Because 95% of the influent TKN is converted to either ammonia or cell mass, influent ammonia is a relative indicator of the total nitrogen that is oxidized during the treatment process.

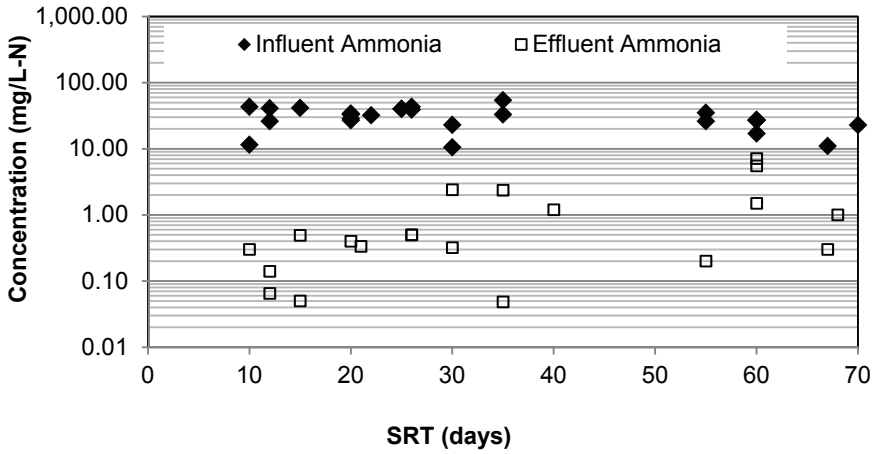

Figure 4.18. Ammonia removal reported in various MBR studies.

Figure 4.19 shows the influent and effluent ammonia concentrations reported in full-scale installations. As shown, most of the installations achieved effluent ammonia concentrations of < 1 mg/L-N with influent concentrations varying from 12 to 55 mg/L-N.

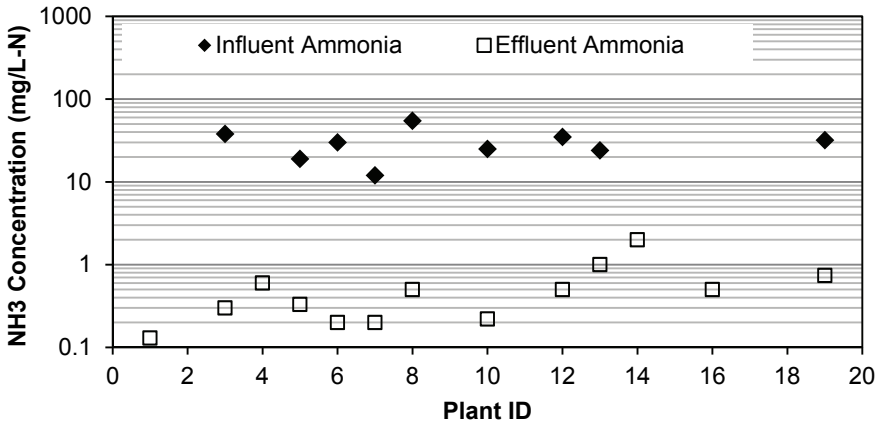

Figure 4.19. Effluent ammonia reported in facility survey.

4.3.3.2 Nitrate

Figure 4.20 shows the influent ammonia and effluent nitrate concentrations as reported in several MBR studies (Chae and Shin, 2007; Fatone et al., 2005; Geng and Hall, 2007; Hasar and Kinaci, 2004; Holakoo et al., 2007; Innocenti et al., 2002; Janga et al., 2007; Lesjean et al., 2002; Pulefou et al., 2008; Qin et al., 2006, 2007). The influent ammonia concentration ranged from 10.5 to 54 mg/L-N, whereas the effluent nitrate concentration ranged from 1.0 to 39.1 mg/L-N at SRT values of 4 to 68 days. Nitrate concentrations in the MBR effluent depend on several factors including process configuration, DO concentrations, aerobic-to-anoxic recycle flow-rate, and carbon-to-nitrogen ratio in the feed wastewater. Nitrate removal cannot be predicted simply on the basis of process SRT.

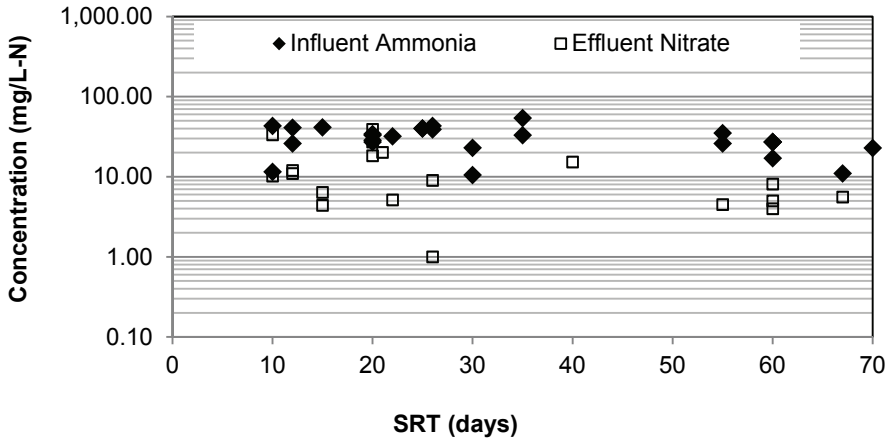

Figure 4.20. Effluent nitrate reported in various MBR studies.

Figure 4.21 shows the influent ammonia and effluent nitrate concentrations reported in full-scale installations. Effluent concentrations were reported at <10 mg/L-N for four out of five facilities that reported nitrate concentrations. Effluent nitrate concentrations were determined by subtracting reported values of ammonia from TIN (total inorganic nitrogen), based on information received from the facility survey. As shown, average effluent nitrate concentrations (mg-N/L) ranged from 1.5 to 7.5. Each of the four facilities reported having been designed for total nitrogen removal. The difference in effluent nitrate concentrations could be due to differences in anoxic volume, RAS recycling design, or influent COD/TKN ratio; however, this could not be confirmed from the information provided in the survey.

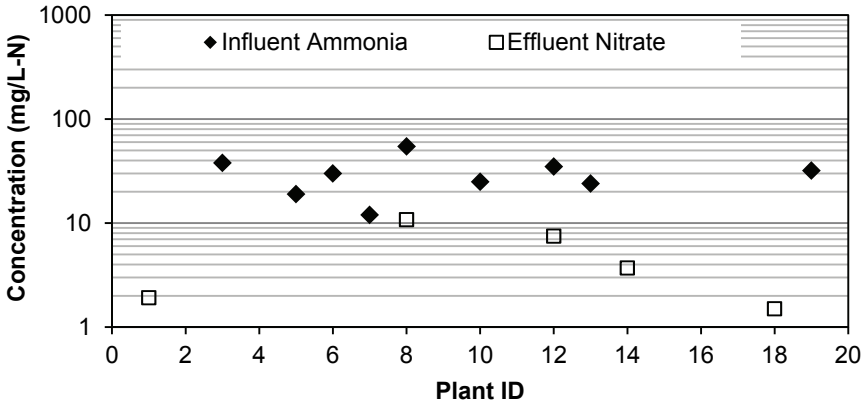

Figure 4.21. Effluent nitrate removal reported in facility survey.

4.3.3.3 Total Nitrogen

Figure 4.22 provides average influent and effluent total nitrogen (mg/L-N) values based on responses to the facility survey. Influent values ranged from 40 to 58.7 mg/L-N, with effluent values ranging from 3 to 4.7 mg/L-N (with the exception of one facility that reported the average effluent total nitrogen of 8.3 mg-N/L), which represented removal rates of 70.2 to 93.3%. Each of the seven facilities reported having been designed for total nitrogen removal. The data suggests the plant with the low nitrogen removal may be due to insufficient COD/TKN ratio; however, confounding factors may exist.

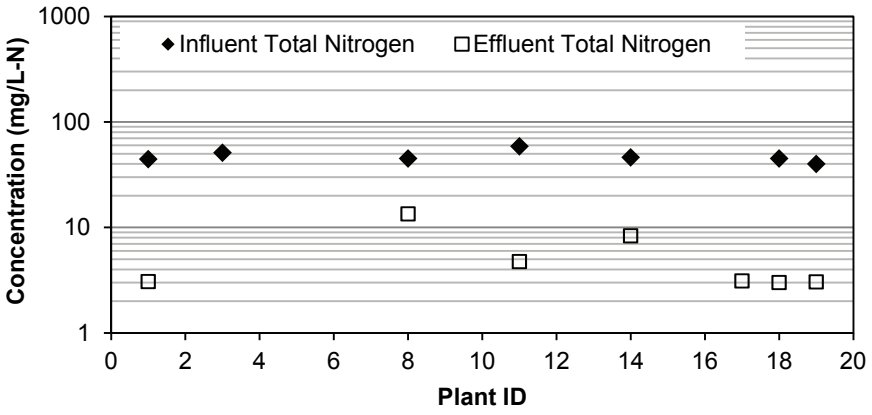

Figure 4.22. Total nitrogen removal reported in facility survey.

4.3.3.4 Phosphorus

Figure 4.23 shows the influent and effluent phosphorus concentration reported in various MBR studies (Ahn et al., 2003; Chae and Shin, 2007; Fatone et al., 2005; Geng and Hall, 2007; Hasar and Kinaci, 2004; Holakoo et al., 2007; Innocenti et al., 2002; Kang et al., 2007; Lesjean et al., 2002; Liu et al., 2008; De Wever et al., 2007; Yoon et al., 2004). Reported influent phosphorus concentration ranged from 2.1 to 15 mg/L-P, and effluent phosphorus ranged from 0.07 to 3.2 mg/L-P at SRT values of 4 to 70 days.

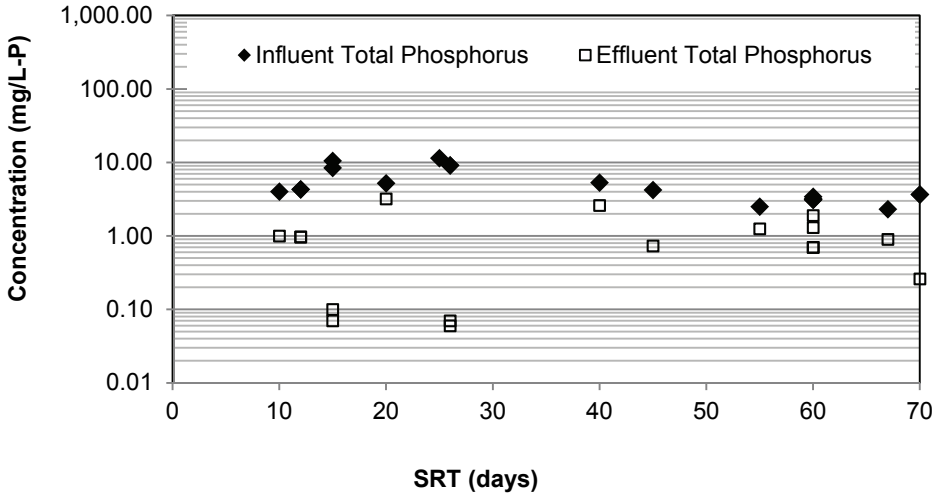

Figure 4.23. Phosphorus removal reported in various MBR studies.

Figure 4.24 provides average influent and effluent total phosphorus (mg/L P) values based on responses to the facility survey. Influent values ranged from 4.7 to 15 mg/L-P with effluent values ranging from 0.04 to 5.0 mg/L-P. The plants that participated in the survey were either designed for total nitrogen only, chemical or biological phosphorus removal, chemical phosphorus removal only, or biological phosphorus removal only. A breakdown of reactor type for various reported levels of phosphorus removal is provided in Figure 4.25.

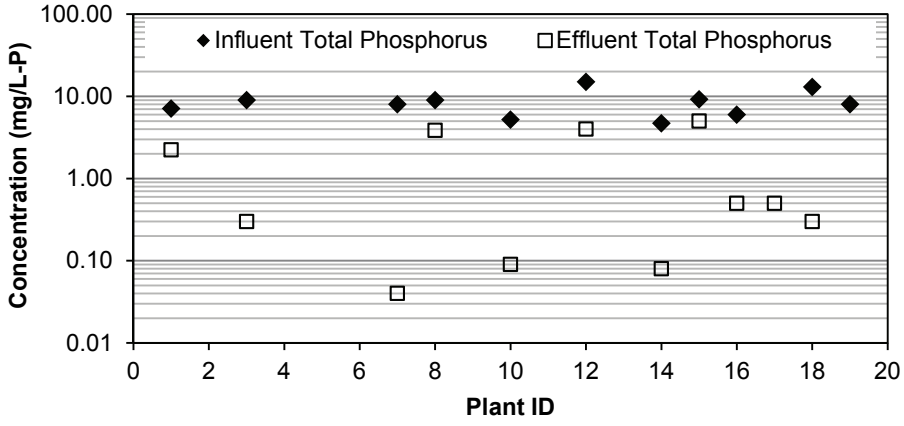

Figure 4.24. Average influent and effluent total phosphorus reported from facility survey.

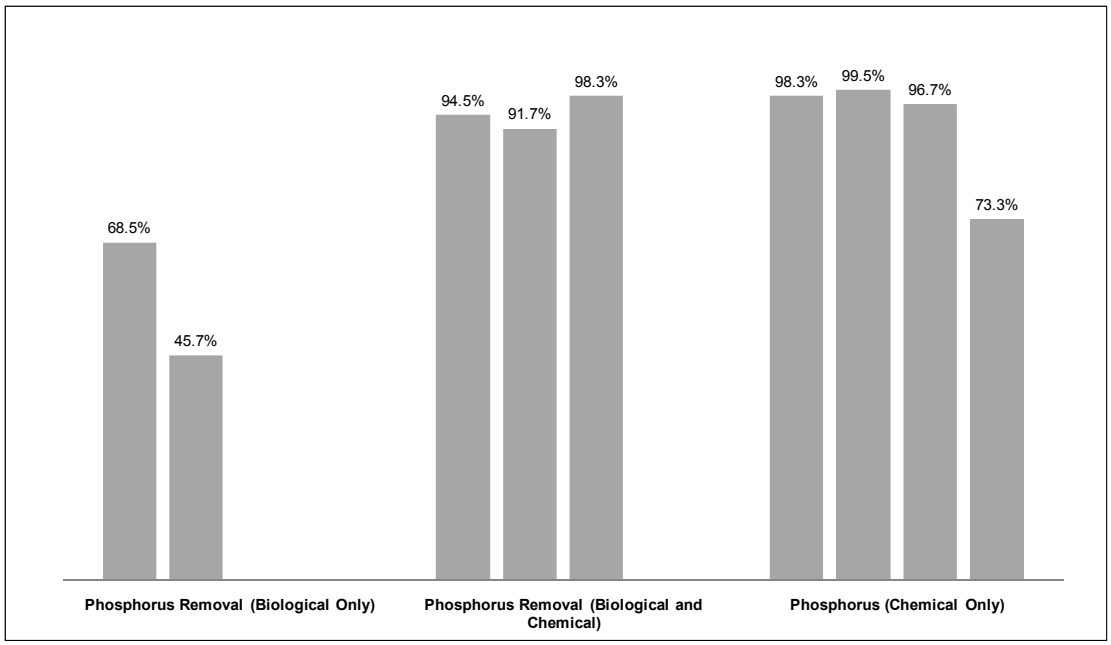

Figure 4.25. Average percentage total phosphorus removal for different reactor designs reported from facility survey.

4.4 Trace Metals

The trace metals of greatest concern, because of aquatic organism sensitivity, are the priority pollutant trace metals. Toxicity and removal behavior during secondary treatment are dependent on the metal species that are present. Particle-associated metals and dissolved inorganic metal species are easiest to remove through solids separation or sorption followed by solids separation. Dissolved metals complexed by organic ligands are the most difficult species to remove but frequently less toxic than their dissolved inorganic counterparts. These organic ligands include synthetic chelating agents such as ethylenediaminetetraacetate (EDTA) and the biopolymers produced by activated sludge.

Speciation calculations, performed using the computer program MINTEQA2 (U.S. EPA, 1991), for major anion, cation, and metal concentrations typically measured in the San Jose/Santa Clara Wastewater Treatment Plant in California and relevant publication values utilized for other constituents impacting metal speciation (i.e., thiol-containing amino acids, biopolymers, Fe(III), and EDTA), predicted that most metals typically exist as organic ligand complexes. Metals with high affinity for EDTA exist predominantly as EDTA complexes, provided that the EDTA is not complexed with iron. Metal affinity for EDTA is strongly dependent on pH levels typically above pH 7 (Sedlak et al., 2000).

4.4.1 Removal Mechanisms

The activated sludge process removes particle-associated and dissolved metals. Floc incorporation of particle-associated metals occurs through attachment, flocculation, and coagulation, whereas dissolved metal incorporation occurs through uptake or adsorption. Dissolved metal uptake may be related to the activated sludge growth rate with dissolved copper removal observed for activated sludge with a 2 to 3 day SRT and for biological nutrient removal for activated sludge with an SRT of 7 to 8 days but not for activated sludge

with an SRT ≥ 15 days. Perhaps this is due to the decrease in active biomass, which is responsible for the uptake. Data from several San Francisco Bay wastewater treatment plants and from pure culture studies suggest that dissolved, strongly complexed metals are not removed by activated sludge, but the exact nature and physical state of these complexes in wastewater is not sufficiently characterized (Sedlak et al., 2000).

The MBR is expected to provide better removal of particle-associated metals and dissolved metals than conventional activated sludge because of the more effective capture of the solids where these metals reside. It is less clear how removal of metals strongly complexed with organic ligands will differ in an MBR, because this is related to the specific nature of the complexing ligand and the charge condition of the complex.

Data on trace metal removal through MBRs rarely contain sufficiently rigorous analytical data to be able to discern the speciation of each metal and the percentage removal of each species as a function of reactor pH, oxidation reduction potential (ORP), and aeration conditions. Publications demonstrate high percentage removal of metals at long SRT values of 55 days to more than 200 days, which implies that removal occurs predominantly through floc sorption or complexation to polymeric type organics such as humic acids. Even when high removal percentages in the range of 50 to 95% are demonstrated, residual metal is left in the effluent, and it is assumed that this is probably nonlabile complexes that are not adsorbed by particulates, taken up by biomass, or retained by the membrane. Protonated metal species such as arsenic and selenium tend to show the worst removal rates, and this is thought to be due to charge repulsion from organically fouled membrane surfaces.

Table 4.2 summarizes the MBR variables thought to impact metal removal.

Table 4.2. Variables in the MBR Process that May Impact Removal of Metals

Variable	Anticipated Impact
Specific Metal	Similar to CAS process, poorer removal is observed for anionic species (e.g., As, Se, B) that is probably due to electronic repulsion that limits adsorption to solids.
Metal Speciation	Particulate metals should be well removed because of membrane size exclusion.
	Inorganic dissolved metals should be well removed because of membrane separation of uptake organisms, but high SRT may impede uptake because of a larger percentage of inert solids.
	Organically bound dissolved metals should be less well removed depending on metal-complex lability and water quality impacts on complex stability.
Water pH, ORP	May influence sorption and organic complex stability.
Membrane Fouling	Should increase negative charge on membrane surface, possibly impeding retention of anionic metallic species.
% Inert MLSS	Higher inert volatile and nonvolatile MLSS resulting from higher SRT might decrease removal of dissolved constituents.

4.4.2 MBR Observed Trace Metals Removal

Three of the 19 plants that completed the facility survey reported water quality goals with respect to metals. One of the plants reported a permitted discharge requirement for copper of 9.6 to 16 µg/L with average influent values ranging from 50 to 150 micrograms per liter and average effluent value of 6.8 micrograms per liter. The average effluent copper concentration of the second plant was reported to be less than 8 micrograms per liter; however, no information was provided with respect to influent concentrations. The third plant for which MBR effluent is used for groundwater recharge reports meeting permit requirements with respect to groundwater monitoring for cadmium (5 micrograms/L), arsenic (10 micrograms/L), chromium (100 micrograms/L), mercury (2 micrograms/L), nickel (100 micrograms/L), iron (0.3 mg/L), silver (100 micrograms/L), and zinc (5000 micrograms/L). It should be noted the metals are measured in the groundwater basin only; therefore, no information was available regarding the actual MBR performance.

Data across a number of studies indicate that the only consistent trend in metals removal is that it is most effectively achieved through efficient solids separation, and that this represents the primary advantage offered by the MBR. As such, MBRs achieved averaged metals removals that are consistently but not dramatically higher than the ranges reported by the activated sludge process (ASP): 64 to 92% versus 46 to 87% (Table 4.3), with no more than a 55% decrease on average for the MBR effluent concentration compared with the ASP effluent (Figure 4.26). The slightly greater removal attained is attributable to the additional suspended solids retention attained by the membrane process. In either case, further removal of metals would demand a tertiary process for removal of the dissolved material.

Table 4.3. Comparison of Activated Sludge and MBR Processes Mean Metal Feed Concentrations (ug/L) and Mean Percentage Removal Efficiencies

Process Type	Cd	Cr	Cu	Pb	Hg	Ni	Zn
ASP							
Mean Concentration	8.5	81.3	117.5	139.0	5.0	154.3	886.6
% SD	91	107	71	113	59	163	78
Mean % Removal	**62**	**69**	**68**	**74**	**87**	**46**	**68**
% SD	52	13	25	30	16	60	25
MBR							
Mean Concentration	1.3	124.0	178.2	39.1	3.4	32.8	533.9
% SD	50	203	230	63	81	71	75
Mean % Removal	**74**	**83**	**83**	**73**	**92**	**64**	**75**
% SD	34	16	15	22	11	32	23
Difference in % removal, MBR *vs*. ASP	**12**	**14**	**15**	**-1**	**5**	**18**	**7**
Mean % reduction in residual, MBR *vs.* ASP	**32%**	**45%**	**47%**	**-4%**	**38%**	**27%**	**22%**

Note. From Santos, A. and Judd, S. The Fate of Metals in Wastewater Treated by the Activated Sludge Process and Membrane Bioreactors: A Brief Review. *J. Enviorn.Monit.* **2010**, 12, 110–118. Reproduced by permission of The Royal Society of Chemistry. Original article available at http://dx.doi.org/10.1039/B918161J

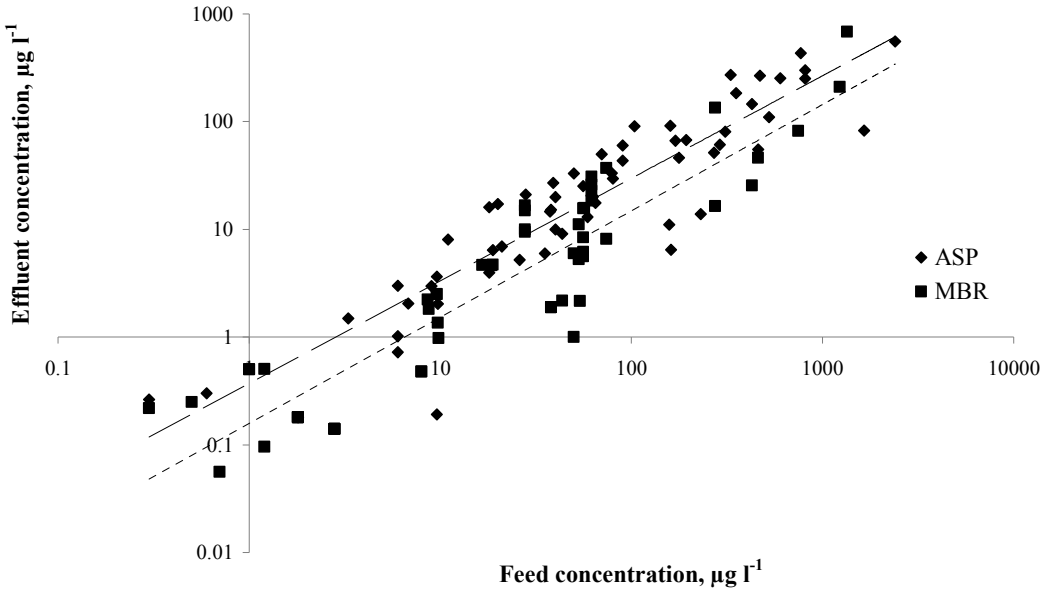

Figure 4.26. Effluent versus feed metal concentrations reported in the literature for activated sludge and MBR processes.

Note. From Santos, A. and Judd, S. The Fate of Metals in Wastewater Treated by the Activated Sludge Process and Membrane Bioreactors: A Brief Review. *J. Enviorn.Monit.* **2010**, 12, 110–118. Reproduced by permission of The Royal Society of Chemistry. Original article available at http://dx.doi.org/10.1039/B918161J

4.5 Trace Organic Compounds

Trace organic compounds occur in untreated wastewater below milligram per liter levels. A major source of these compounds in raw wastewater are household wastes with additional background loading possibly arising from the potable water used to convey these wastes to municipal treatment facilities.

The trace organic compounds garnering the greatest degree of concern are those that might behave as hormonally active agents (also referred to as endocrine disrupting compounds) and the large number of pharmaceuticals and personal care products released to treatment facilities from consumers rather than from industries with waste discharge permits. Promulgated analytical methods are not yet available for these compounds, but there are several peer-reviewed methods with standardized target lists of compounds actively in use. Table 4.4 provides citations for the methods being evaluated for the Water Research Foundation sponsored project entitled, “Evaluation of Analytical Methods for EDCs and PPCPs via Inter-Laboratory Comparison #4167.”

Table 4.4. Water Research Foundation Study Method Citations for "Evaluation of Analytical Methods for EDCs and PPCPs via Inter-Laboratory Comparison #4167"

Vanderford, B. J.; Pearson, R. A.; Rexing, D. J.; Snyder, S. A. *Anaytical Chemistry* **2003**, *75*, 6265–-6274.

Bradley, P. M.; Barber, L. B.; Chapelle, F. H.; Gray, J. L.; Kolpin, D. W.; McMahon, P. B. *Environmental Science & Technology* **2009**, *43*, 1902-1910.

Yu, C.-P.; Roh, H.; Chu, K.-H. *Environmental Science & Technology* **2007**, *41*, 486–-492.

Miao, X.-S.; Bishay, F.; Chen, M.; Metcalfe, C. D. *Environmental Science & Technology* **2004**, *38*, 3533–-3541.

Hao, C.; Lissemore, L.; Nguyen, B.; Kleywegt, S.; Yang, P.; Solomon, K. *Analytical & Bioanalytical Chemistry* **2006**, *384*, 505–-513.

U.S. EPA, Method 1694. Washington, DC, 2007

Vanderford, B. J.; Snyder, S. A. *Environmental Science & Technology* **2006**, *40*, 7312–-7320.

Trenholm, R. A.; Vanderford, B.; Holady, J. C.; Rexing, D. J.; Snyder, S. A. *Chemosphere* **2006**, *65,* 1990–-1998.

Reddersen, K.; Heberer, T. *Journal of Separation Science* **2003**, *26*, 1443–-1450.

Tan, B. L. L.; Hawker, D. W.; Mueller, J. F.; Leusch, F. D. L.; Tremblay, L. A.; Chapman, H. F. *Environment International* **2007,** *33*, 654–-669.

Gros, M.; Petrovic, M.; Barcelo, D. *Talanta* **2006***, 70*, 678–-690.

Shareef, A.; Angove, M. J.; Wells, J. D. *Journal of Chromatography A* **2006**, *1108*, 121–-128.

Mol, H. G. J.; Sunarto, S.; Steijger, O. M. *Journal of Chromatography A* **2000**, *879*, 97–-112.

Kojima, M.; Tsunoi, S.; Tanaka, M. *Journal of Chromatography A* **2003**, *984*, 237–-243.

4.5.1 Removal Mechanisms

Activated sludge processes in MBR and CAS promote volatilization, sludge adsorption, biotransformation, and photodegradation fate processes. Volatilization is minimal for most pharmaceutical and personal care products because the majority of these target compounds have low Henry's constants. Photodegradation reactions are minimal for all trace organic compounds because of the opacity of the activated sludge. MBRs are expected to perform better than CAS systems in reducing the aqueous phase passage of trace organic compounds that adsorb to solids because the membrane is a better solids separator than a conventional clarifier. MBR systems also operate at higher MLSS concentrations with smaller reactor volumes and different aeration conditions that might also impact biotransformation and volatilization as well as sludge sorption performance.

4.5.1.1 Adsorption

Many trace organic compounds exhibit significantly different adsorption coefficient (K_d) values for primary and secondary sludge. A higher secondary sludge K_d value is believed to occur because of better adsorption of compounds with positive functional groups to the negatively charged surfaces of secondary sludge microorganisms (e.g., ciprofloxacin; Joss et al., 2006). A higher primary sludge K_d is thought to occur when hydrophobic absorption is dominant and the hydrophobic component of the raw sludge is degraded during secondary

biological treatment (e.g., galaxolide; Joss et al., 2006). Some researchers have found that MBR sludge exhibits a higher sorption coefficient than CAS and hypothesize this might be due to higher hydrophobicity and/or smaller floc size of the MBR sludge. Although semiquantitative estimates of organic trace contaminant partitioning between solid and aqueous phases can be made from published partition coefficients, quantitative models that incorporate more detailed reactor solids characteristics and more refined partitioning coefficients are needed for more accurate performance predictions.

4.5.1.2 Biotransformation

The susceptibility of a trace organic compound to biotransformation is expressed per sludge dry weight concentration and assumed to result from co-metabolism because of the compounds trace concentration. Therefore, the following sludge characteristics are expected to influence biotransformation rates:

- Biodiversity of the active biomass
- Fraction of the active biomass within the total suspended solids
- Floc size of the sludge

All of these factors will be influenced by the SRT at which the MBR is operated. The higher SRT utilized for nutrient removal systems should increase the biodiversity of the active biomass. Because the exact biological transformation mechanisms have not been fully elucidated, it is unclear whether the key processes are associated with autotrophic nitrifiers or in combination with other organisms, and the redox potential in the reactor might also influence the transformation rate. Higher SRT will decrease the fraction of active biomass, but because of the trace levels of these constituents, this might not be a key consideration. Floc size might be important for compounds affected by mass transfer limitations. In this case, the MBR should show better transformation because of the smaller floc size where there are fewer inner floc layers contributing to the biological activity.

Other factors expected to influence biotransformation rates are temperature effects and the electron acceptor(s) present. A detailed discussion of the theoretical removal mechanisms for trace organic compounds during MBR treatment was previously provided in Chapter 2.4.1.

4.5.2 MBR Model-Predicted Removal of Trace Organic Compounds

The predictive model developed in this study was used to explore the interplay of different trace organic compound removal coefficients (i.e., solids partitioning, biodegradation, and volatilization) and the impact of key MBR operational parameters on the removal of these compounds. The model scenarios all used an input influent trace organic compound concentration of 0.5 mg/L in order to magnify trends. Although this concentration is higher than the part-per-billion and the part-per-trillion levels typically observed for these compounds in wastewater influent, the starting concentration should have little impact on removal because the model assumes that the removal mechanisms are first order in the trace organic compound concentration. Thus, the key outcome for this modeling effort is the proportional fate of a trace organic compound among the different fate mechanisms.

Figure 4.27 summarizes the interplay of activated sludge removal mechanisms (i.e., volatilization, sorption, and biodegradation) as a function of the key design characteristics of an MBR, namely, the SRT and the MLSS concentration. Compounds receptive to volatilization because of high Henry's constants (K_H) will show more removal at higher SRT and higher MLSS. This occurs because this condition requires higher aeration, which lowers

the gaseous equilibrium pressure and drives more of the constituent into the gas phase. Compounds receptive to removal because of their solids partitioning constants (K_D) will best be removed at a lower SRT and lower MLSS because these conditions require higher wasting of the activated sludge, which reduces the likelihood that the solids loading concentration will exceed the equilibrium coefficient and begin to re-suspend within the aqueous phase. Compounds receptive to removal because of their biodegradation constants (K_B) will best be removed at a higher SRT and lower MLSS because these conditions promote the highest concentration and variety of active biomass and associated enzyme processes. It is not possible to increase the SRT and simultaneously decrease the MLSS operationally because the decreased sludge-wasting rate needed to raise the SRT will also result in a higher MLSS. The only way to also decrease the MLSS as the SRT increases is by decreasing the reactor volume in addition to reducing the wasting rate. It is therefore important to understand how influential the MLSS is compared with the SRT in affecting the biodegradation mechanism because the MLSS is a design element rather than an operational parameter.

Because the three fate mechanisms each maximize within a different SRT/MLSS region, model scenarios were executed for trace organic compounds selected on the basis of differences in their removal constants (i.e., K_H,K_D,K_B) in order to demonstrate the range of removal capabilities of an MBR.

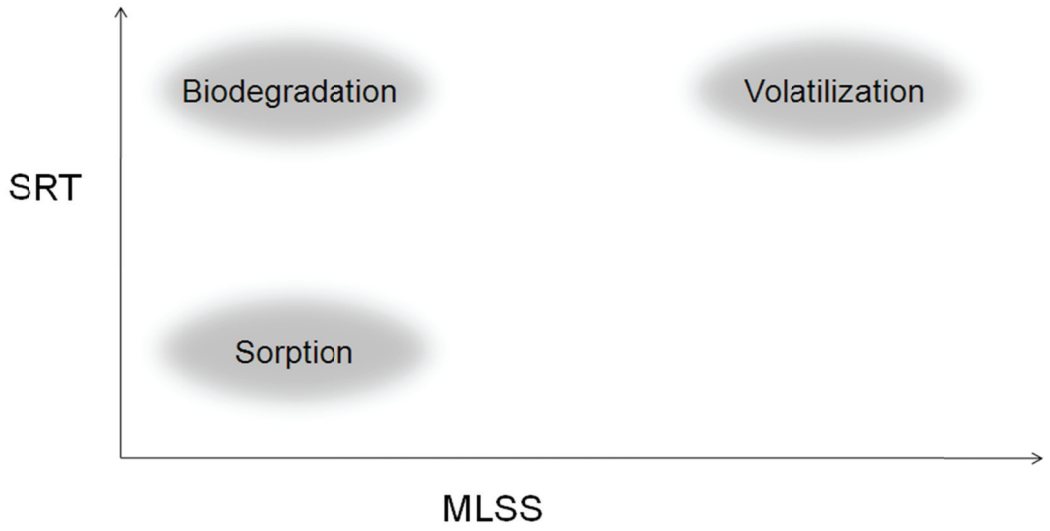

Figure 4.27. Generalized removal mechanisms for EDCs and PPCPs by MBR operating conditions of SRT and MLSS.

Although there are many trace organic compounds that may be present in wastewater, the major concern is with pharmaceuticals and personal care products (PPCPs). Many pharmaceutical compounds are nonvolatile and have little affinity for solids; yet, there are numerous exceptions. Many antibiotics have high absorption constants (Joss et al., 2006; Adams, 2009), and some personal care products (e.g., galaxolide) are poorly biodegradable but have significant absorption and volatilization constants. During initial model scenario analyses, PPCP compounds with a range of fate coefficients were selected in order to assess

the removal performance range for these compounds under one set of MBR operating conditions. Once this was understood, more targeted scenarios were run in order to assess the impact of changes in MBR design and operational parameters on removal efficiencies.

The selected compounds, their fate coefficients, and the removal percentages derived for the initial modeling scenarios performed at assumed typical MBR conditions consisting of a 15-day SRT, 20,000 mg/L MLSS, 600mg/L influent COD, and 3mg/L DO are presented in

Table **4.5**. These data indicate that MBR treatment might provide a wide range of removal efficiencies at a standard set of operating conditions even for pharmaceuticals with similar analgesic properties (e.g., diclofenac, naproxen, and ibuprofen). Although such information might prove useful in future licensing and distribution of medicines, it also demonstrates an inability of the MBR process to remove compounds with little volatility, sorption capacity, or biodegradability (e.g., diclofenac).

Table 4.5. Initial Model Scenario Analysis: Five Target Organic Compounds, Fate Mechanism Removal Percentages Predicted for Typical MBR Input Parameters

Scenario 1: Diclofenac (Non-steroidal anti-inflamatory)	**Scenario 2: Clofibric Acid** (Hyperlipidemia drug)	**Scenario 3: Naproxen** (Non-steroidal anti-inflamatory)	**Scenario 4: Ibuprofen** (Non-steroidal anti-inflamatory)	**Scenario 5: Galaxolide** (Synthetic polycyclic musk fragrance)
K_H=4.73x10^{-12} atm-m^3/mol[1]	K_H=2.19x10^{-8} atm-m^3/mol[1]	K_H=3.4x10^{-10} atm-m^3/mol[1]	K_H=1.5x10^{-7} atm-m^3/mol[1]	K_H=1.3x10^{-4} atm-m^3/mol[1]
K_D=0.016 L/g SS	K_D=0.005 L/g SS	K_D=0.013 L/g SS	K_D=0.007 L/g SS	K_D=2.4 L/g SS
K_B=0.1 2 L/g SS-d	K_B=0.2 2 L/g SS-d	K_B=0.6 2 L/g SS-d	K_B=16 .2 L/g SS-d	K_B=0.03 L/g SS-d
7% total	13% total	33% total	93% total	50% total
6% biodegradation	12% biodegradation	33% biodegradation	93% biodegradation	1% biodegradation
0.2% sorption	0% sorption	0% sorption	0% sorption	12% sorption
0.3% surface volatilization	0.2% surface volatilization	0.2% surface volatilization	0% surface volatilization	0% surface volatilization
0% bubble aeration	0% bubble aeration	0% bubble aeration	0% bubble aeration	35% bubble aeration

Note. 15-day SRT, 20,000 mg/L MLSS, 600 mg/L influent COD, 3 mg/L DO, and 50% membrane passage of biologically active particles.

Table 4.6 compares these model-predicted removal rates with the range of removals found in the literature. Insufficient information was available to correlate each specific literature removal rate with a specific MBR operating SRT; instead, the overall range of reported removals is provided with the overall range of reported SRT conditions.

A more detailed summary of compound-specific observations and treatment trends for trace organic compound removal by MBRs compiled from the literature is provided in

Appendix C. This comparison indicates that the model-predicted compound removal trends match those observed in the field but may underpredict removal efficiencies for compounds that are poorly or moderately removed. There could be a number of reasons for this. First, with respect to biodegradation, the model must rely on limited published rate constants that might not be fully representative of the conditions being modeled. The model is also a heterotrophic model that does not consider the potential degradation from autotrophic organisms, whereas some of the field studies were performed in facilities with nutrient removal capabilities. The impact of this discrepancy is uncertain because the published rate constants employed in the model may have been derived utilizing seed stock containing autotrophic organisms. With respect to partitioning, the model assumes all solids are retained by the membrane and should not underestimate this mechanistic removal process. Finally, regarding volatilization, the model may provide lower results because it does not incorporate air scour.

Table 4.6. Comparison of Model-Predicted Removal Rates with Range of Removals Found in Literature for Five Target Organic Compounds

	Model Predicted Removal (%)*	Literature Removal (%)	Reported Range of SRT Values (days)
Diclofenac	7	0–58 (n=12)	8–115; higher removals do not correlate with higher SRT
Clofibric Acid	13	54–88 (n=3)	Largely unspecified
Naproxen	33	69–99 (n=11)	4–72; some unspecified
Ibuprofen	93	63–100 (n=15)	3->400
Galaxolide	50	49– 92 (n=4)	10–70

*(Model parameters = 15-day SRT, 20,000 mg/L MLSS, 600 mg/L influent COD, 3 mg/L dissolved oxygen, 50% membrane passes of BAPs)

In order to gain additional insights, the MBR SRT and MLSS values were varied to model the impact of operating conditions on the range of removals observed for the compounds presented in Table 4.6. These results, provided in Table 4.7 demonstrate limited sensitivity in removal rates because of changes in SRT or MLSS operating conditions within the ranges typically used for MBRs.

As shown in Figure 4.28, the major benefit of the MBR comes from operating at an MLSS of at least 10,000 mg/L but results in diminishing returns as MLSS values continue to increase (at correspondingly higher SRT) as the removal curves begin to flatten out in this region (e.g., diclofenac and erythromycin) because of a reduction in active biomass. For compounds removed only through a combination of volatilization and solids partitioning (e.g., galaxolide), the overall removal remains relatively constant as MLSS and SRT are increased because of their opposing effects on volatilization and partitioning (as previously depicted in Figure 4.27).

Table 4.7. Model-Predicted Change in Organic Compound Removal Due to SRT Increase from 15 to 50 Days at Constant MLSS of 20,000 mg/L

Scenario 1: **Diclofenac** (Non-steroidal anti-inflammatory drug)	Scenario 2: **Clofibric Acid** (Hyperlipidemia drug)	Scenario 3: **Naproxen** (Non-steroidal anti-inflammatory drug)	Scenario 4: **Ibuprofen** (Non-steroidal anti-inflammatory drug)	Scenario 5: **Galaxolide** (Synthetic polycyclic musk fragrance)
Biodegradation removal increased from 6% to 7% and adsorption removal decreased from 0.2% to 0.1% when the SRT was increased from 15 to 50 days and MLSS remained at 20,000 mg/L.	Biodegradation removal increased from 12% to 14% and no change in 0% adsorption removal when the SRT was increased from 15 to 50 days and MLSS remained at 20,000 mg/L.	Biodegradation removal increased from 33% to 37% and no change in 0% adsorption removal when the SRT was increased from 15 to 50 days and MLSS remained at 20,000 mg/L.	Biodegradation removal increased from 93% to 94% and no change in 0% adsorption when SRT was increased from 15 to 50 days and MLSS remained at 20,000 mg/L.	Adsorption decreased from 12% to 4% and aeration bubble volatilization increased from 35% to 41% when the SRT was increased from 15 to 50 days and MLSS remained at 20,000 mg/L.

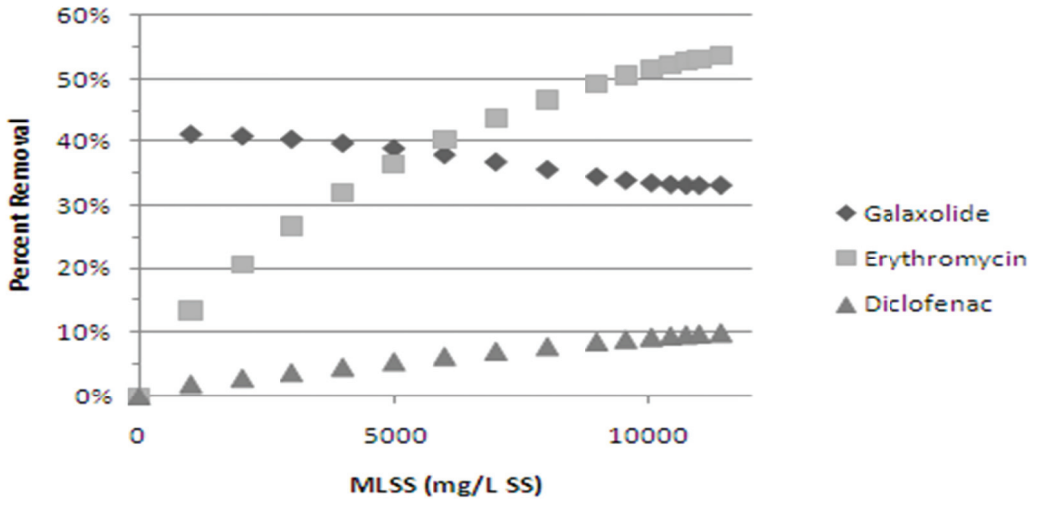

Figure 4.28. Model-predicted results for removal of three PPCP compounds under different MBR operating conditions of SRT and MLSS.

Because of all of the variables involved, modeling is the best means by which to predict the relative removals that can be achieved in an MBR, provided that mechanistic fate constants are available. Table 4.8 provides model-predicted trace organic compound percentage removals obtained by considering each mechanistic fate constant individually over a range of MBR operating conditions for SRT and MLSS. These data are also shown graphically in Figure 4.29. The predictions demonstrate the dominance of the mechanistic fate constant in

driving the removals that will occur and how changes in the MBR operational conditions have a relatively minimal impact on these removal percentages. For biodegradation, most of the percentage removal occurs when the SRT is increased from 5 to 10 days and begins to level off as the SRT approaches 15 days. Volatilization impacts are similar to biodegradation, whereas for partitioning, the removal actually decreases as the SRT increases.

Table 4.9 and Figure 4.30 illustrate the overall removals achieved for different combinations of values for the mechanistic fate constants. By considering these different combinations, it is possible to demonstrate the overall range of compound removals that might be achieved with an MBR under different operating conditions. The data clearly show that for all cases where partitioning is a key contributing removal mechanism, a lower SRT is beneficial. When partitioning is not one of the significant removal mechanisms, removal increases by increasing the reactor SRT, but the rate of increase continually declines, and this flattening in the percentage removal is more pronounced when biodegradation is more dominant than volatilization as the removal mechanism.

Table 4.8. Model-Predicted Percentage Removals of Trace Organic Compounds as a Function of Individual Mechanistic Fate Constant Parameter Values (binned as low, moderate, and high values) and MBR Operating Conditions of MLSS in mg/L and SRT in Days Are Varied

			PERCENT REMOVAL						
						MLSS			
			5463	7739	8882	9585	10451	11008	11430
						SRT			
PARAMETER	BIN	VALUE	5	10	15	20	30	40	50
K_B (L/g_{SS}-d)	LOW	0.5	21%	27%	30%	32%	33%	34%	34%
	MODERATE	1	35%	43%	46%	48%	50%	50%	51%
	MODERATE	1.75	48%	57%	60%	62%	63%	64%	65%
	MODERATE	2.5	57%	65%	68%	70%	71%	72%	72%
	HIGH	5	73%	79%	81%	82%	83%	84%	84%
K_D (L/g_{SS})	LOW	4	44%	35%	30%	25%	20%	16%	14%
	MODERATE	15	74%	67%	61%	56%	47%	41%	36%
	HIGH	40	89%	84%	81%	77%	70%	65%	60%
	HIGH	50	91%	87%	84%	81%	75%	70%	65%
	HIGH	100	95%	93%	91%	89%	86%	82%	79%
	HIGH	1000	99%	99%	99%	99%	98%	98%	97%
K_H (atm-m^3/mol)	LOW	2.25E-04	20%	27%	31%	33%	36%	38%	39%
	MODERATE	7.50E-04	45%	55%	59%	62%	65%	67%	68%
	HIGH	2.25E-03	71%	78%	81%	83%	85%	86%	86%

Table 4.9. Model-Predicted Percentage Removals of Trace Organic Compounds as a Function of Different Combinations of Mechanistic Fate Constant Parameter Values and MBR Operating Conditions of MLSS in mg/L and SRT in Days Are Varied

	PERCENT REMOVAL						
				MLSS			
	5463	7739	8882	9585	10451	11008	11430
				SRT			
PARAMETER COMBINATIONS	5	10	15	20	30	40	50
Moderate K_B + Moderate K_D	79%	77%	75%	74%	72%	71%	70%
Moderate K_B + Moderate K_H	64%	71%	75%	76%	78%	79%	80%
Moderate K_D + Moderate K_H	79%	76%	75%	74%	73%	73%	73%
Moderate (K_B + K_D + K_H)	82%	82%	82%	82%	82%	82%	82%

Moderate KB = 1.75 L/gSS-d; Moderate KD=15 L/gss; Moderate KH =7.50E-04 atm-m3/mol

	PERCENT REMOVAL						
				MLSS			
	5463	7739	8882	9585	10451	11008	11430
				SRT			
PARAMETER COMBINATIONS	5	10	15	20	30	40	50
HIGH Kb + MOD KD	85%	85%	85%	85%	85%	85%	85%
MOD Kb + HIGH KD	90%	87%	85%	83%	80%	78%	77%
HIGH Kb + MOD Hc	78%	83%	85%	86%	87%	88%	88%
MOD Kb + HIGH Hc	77%	83%	85%	87%	88%	89%	89%
HIGH KD + MOD Hc	91%	90%	89%	89%	89%	89%	89%
MOD KD + HIGH Hc	84%	85%	85%	86%	87%	87%	87%

Note: High K_B = 5 L/g_{SS}-d; High K_D=40 L/g_{ss}; High K_H =2.25E-03 atm-m^3/mol

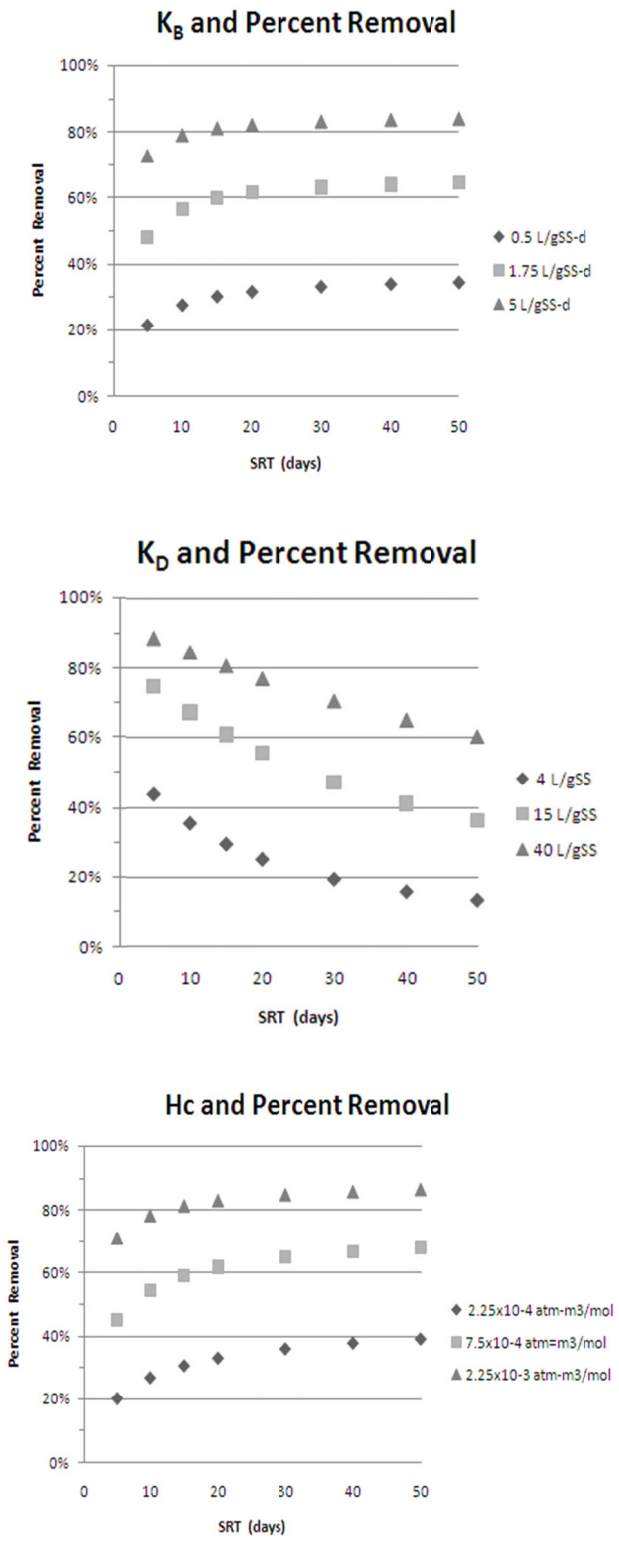

Figure 4.29. Model-predicted impact of MBR SRT conditions for individual organic micropollutant mechanistic fate constants.

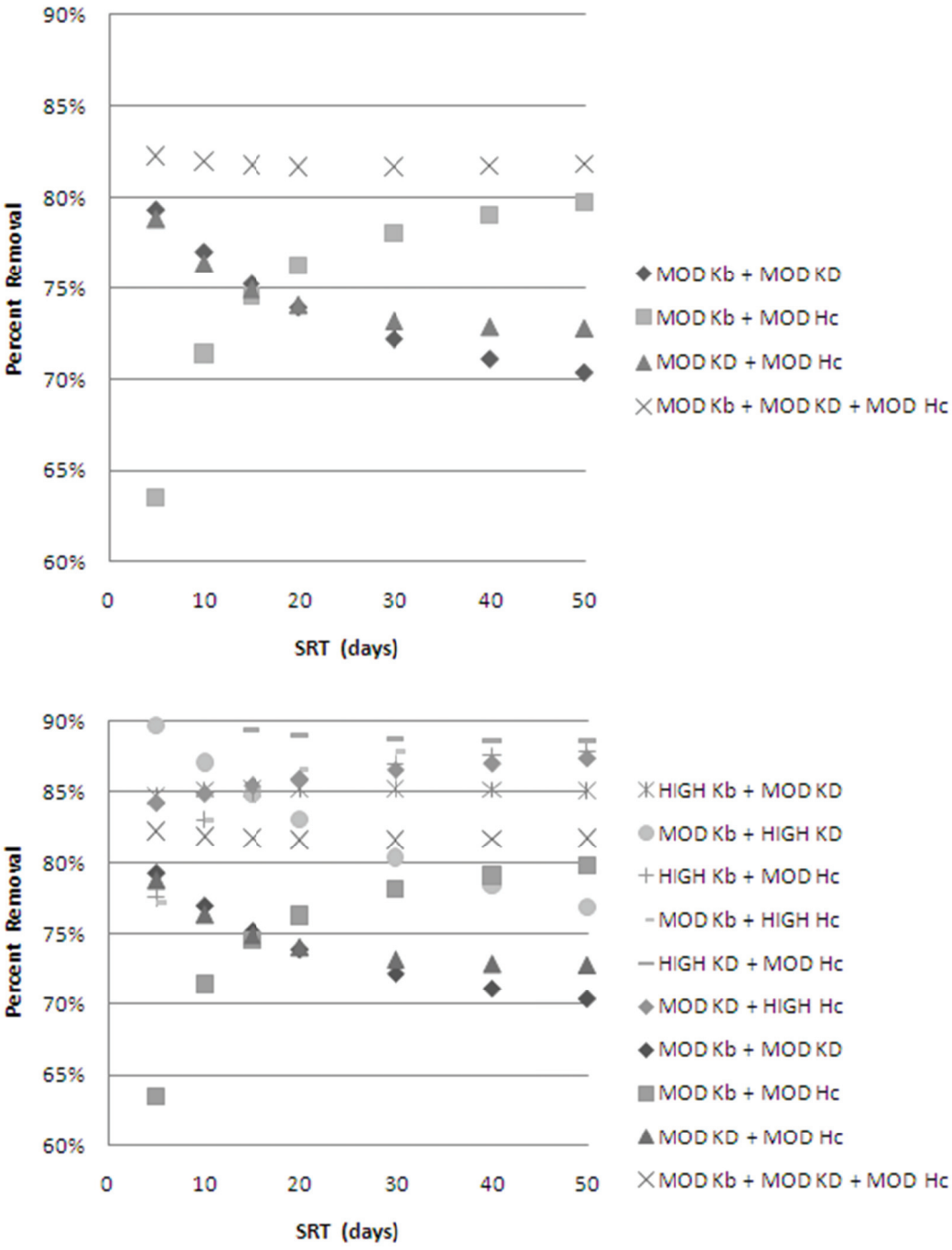

Figure 4.30. Model-predicted impact of MBR SRT conditions for combinations of micropollutant mechanistic fate constants.

For organic compounds, the following major trends can be summarized on the basis of the literature review findings and the performance of the modeling scenarios:

- Provided that a compound's fate constants are known for volatilization, biodegradation, and solids partitioning, then the removal through each fate pathway can be predicted for a given set of MBR design and operating conditions. The removal predictions presented in this report were conservative estimates of the removals observed in the literature.
- When removal is occurring through more than one fate mechanism, the operating conditions will not affect all mechanisms in the same manner. Biodegradation and volatilization both increase at higher SRT conditions, whereas solids partitioning will decrease as the SRT is raised. Furthermore, the declining rate of removal with increasing SRT is more severe for biodegradation than it is for volatilization. Figure 4.30 provides an approximation of how much removal can be expected for different combinations of fate constants over a range of MBR SRT conditions.
- The predominant removal mechanism for PPCP compounds in MBRs, based on literature-reported compound fate constants, appears to be biodegradation. Although an MBR should provide good removal through volatilization, very few PPCP compounds exhibit high enough Henry's constants for significant volatilization to occur. Furthermore, although the membrane will provide an absolute barrier to compounds that partition to the biosolids, the higher SRT at which an MBR is operated will result in less solids sorption because of the lower sludge wasting rate.
- Biodegradation will increase with increasing SRT because of the increase in MLSS for a given basin volume, flow rate, yield, and amount of substrate utilization. The percentage removal will start to decline, however, as endogenous decay increases and less of the biomass is active. This is the same trend that is evident for aggregate organics such as COD. It is still unclear to what extent the inclusion of autotrophic organisms and anoxic conditions needed for nitrogen reduction contributes toward the greater biodegradation observed at a longer SRT.
- Compounds that are only poorly to moderately removed under a lower SRT MBR operating condition cannot achieve high removal by modifying the SRT or MLSS conditions of the reactor.

4.6 Key Differences Between the MBR and the CAS Processes That Impact Effluent Water Quality

Based on the findings from this study, key differences have been identified between the MBR and the CAS processes that may impact the effluent water quality.

4.6.1 Membrane Separation

Membranes in the MBR process replace clarifiers used in the CAS process for solids separation. This allows the MBR process to operate over a wide range of SRT and MLSS concentrations for a certain reactor volume. Membrane separation in an MBR process affects the effluent water quality in the following ways:

- Microfiltration or ultrafiltration membranes used in the MBR process provide higher removal of microbial contaminants including coliforms and coliphages than what is achieved with clarifiers and media filters.

- Membranes provide higher retention of particulate matter and biomass compared to clarifiers and media filters; hence, nutrients, trace organic compounds, and trace metals associated with particulate matter or biomass should be removed at a higher level compared to a CAS process.
- Poorer removal of anionic species, such as As, Se, and B, has been observed in MBR as well as CAS processes and is probably due to electrostatic repulsion that limits adsorption to biomass.

4.6.2 Operation at Higher SRT Coupled with Lower HRT

Membrane separation allows operation of the MBR process at a higher MLSS concentration because sludge settling characteristics do not control the effluent water quality in the MBR process. MBR installations can therefore be designed to operate at higher SRTs compared to the CAS process while maintaining a smaller footprint or lower HRT. Operation at higher SRT affects the effluent water quality in following ways:

- Higher SRT allows growth and retention of slow-growing microorganisms that are responsible for nitrogen reduction and may contribute toward biodegradation of trace contaminants.
- When operated at a longer SRT than a conventional system, the higher percentage of inert solids should result in lower biodegradation of organic contaminants per unit MLSS concentration.
- The greater diversity of microorganisms at a higher SRT might enhance co-metabolism of more recalcitrant compounds. This is particularly true when different terminal electron acceptors are present for nutrient reduction processes.

4.6.3 Aeration Intensity

In order to mitigate membrane fouling, MBR installations use scouring air in addition to the process air used for biodegradation. Because of the additional aeration provided in the membrane tank, volatile trace organic compounds may be removed to a higher extent by the MBR process compared to the CAS process.

4.6.4 Floc Size in the Reactor

The smaller floc formed at equivalent SRTs and the more complete solids separation provided by the membrane could benefit removal of compounds that partition onto solids because of hydrophobicity or charge attraction. It should also reduce biodegradation mass transfer limitations; but mass transfer rates are usually insignificant compared to the biodegradation rates of most compounds.

Chapter 5

Summary of Project Findings and Identified Knowledge Gaps

MBR technology has seen a significant growth in the past few years primarily driven by stricter water quality regulations and smaller footprint requirements. Use of membranes for solids separation provides some advantages to the MBR process over the CAS process with respect to effluent water quality and operational flexibility. However, it also increases the capital and O&M cost for the treatment. The primary objective of this project was to investigate the current status of MBR technology and assess the impact of MBR design and operating parameters on effluent water quality. The secondary objective of the project was to determine the factors that can result in differences in effluent water quality between the CAS and the MBR processes and identify knowledge gaps that warrant further investigation.

5.1 Current State of MBR Technology

Based on survey results obtained from eight MBR vendors, 166 municipal MBR installations with a capacity of 1 MGD (3,785 m3/d) or greater are known to be in operation or under contract as of February 2009. Over the last 5 years, there has been a 250% increase in the number of installations worldwide.

- During the last 5 years, a 300% increase was observed in the cumulative capacity of municipal MBR installations with a capacity of 1 MGD (3,785 m3/d) or greater, and the cumulative capacity of such installations is expected to grow to 700 MGD (2,649,788 m3/d) by end of 2011.
- Improved water quality reliability and footprint limitation were found to be the key drivers behind MBR process selection.
- Hollow-fiber configuration with PVDF membrane material was used in the majority of the MBR installations (79%).
- SRT of surveyed facilities ranged from 11 to 30 days, whereas the MLSS concentration ranged from 4,200 to 18,000 mg/L, with 80% of the facilities operating at MLSS values of less than 12,000 mg/L.
- Filtration flux values for facilities surveyed ranged from 6.9 to 18 gfd (11.7–30.6 lmh) with 80% of the facilities operating at a flux of less than 15.5 gfd (26.3 lmh). TMP values ranged from 0.2 to 7 psi (1.4–48.3 kPa) with an overall average of 2.2 psi (15.2 kPa).
- Reported total unit energy requirements from the surveyed MBR plants ranged from 0.48 to 1.8 kWh/m^3 (1.73–6.48 MJ/m^3) of permeate. Factors identified in the literature and survey results that can impact the unit power consumption of the MBR plant include: membrane aeration strategy, percentage usage of design capacity, and the ability to turn down process equipment during periods of low flow. The literature and facility survey results indicated that energy for membrane air scour accounts for more than 30% of the total energy required for the MBR process. One facility survey respondent indicated that the energy

utilized for membrane air scour was more than twice the energy needs for process aeration.

- Several factors were reported to impact the operational performance of the surveyed MBR facilities. Specific factors reported included:
  - Insufficient prescreening
  - Changes in feed water temperature
  - Low DO resulting in poor sludge filterability, necessitating membrane cleaning
  - Inconsistent chlorine dosing
  - Failure of compressor controlling valves
  - Failure of membrane aeration controllers
  - Influent discharges from food manufacturing processes led to an observed decrease in membrane permeability that probably occurred because of high solids or organic fouling of the membrane

5.2 MBR Water Quality Performance and Identified Knowledge Gaps

Several removal mechanisms occur within an MBR, and removal effectiveness is a function of contaminant properties within the water quality matrix and the impact of key system design and operating parameters. Removal mechanisms that are associated with the MBR process are biotransformation, sorption to solids/size exclusion, adsorption to the membrane, and volatilization. Descriptions of the key removal mechanisms and observed findings for the five constituent categories are presented in the following.

5.2.1 Microbial Contaminants/Particulate Matter

Particulate matter removal by MBRs occurs primarily because of size exclusion of particles larger than the membrane pore size (i.e., suspended solids, bacteria, protozoa, and helminths). Secondary removal mechanisms for coliphages include adsorption to the membrane surface/pores, removal by membrane-attached biofilm, and adsorption to the sludge. Very few studies have looked into the individual contribution of these different mechanisms in removal of viruses. The impact of membrane cleaning on the virus rejection capability of the membrane system and the impact of routine operations on membrane integrity also needs to be assessed in order to predict worst-case removal of these contaminants by an MBR process. Such assessments will allow regulators to reconsider disinfection requirements for MBR effluents by assigning some log removal credit to the MBR process. Membrane operating conditions such as chemical cleaning frequencies, backwashing, filtration flux, and air scour intensity could impact pore blocking and biofilm formation.

Several studies have reported greater than 5 log removal of total and fecal coliforms by MBR systems. Results from the facility survey showed average effluent total coliform concentrations of greater than 1 to 53 CFU/100 mL corresponding to a 4.9 to 6.6 LRV. A few studies have shown that systems employing membrane backwash as a fouling control strategy can cause the presence of low levels of coliforms in the effluent. Based on the existing literature, hypotheses for occurrence of these contaminants in the membrane-filtered effluent have been: (1) removal of membrane-attached cake layer during backwash and (2) regrowth of microbes/contamination in the backwash tank. It would be helpful to assess the implication of employing backwash as a fouling control strategy on the presence of microbial contaminants in the MBR effluents. Indigenous coliphage removal by MBR systems, as

reported in the literature, ranged from 2.3 to 4.5 LRV, and that for seeded coliphage ranged from 1.0 to 5.9 LRV. This difference in virus removal between indigenous and seeded coliphages by MBR systems can be explained by the particle association of indigenous coliphages.

MBR performance, as obtained from the facility survey, with respect to particulate matter was consistent among different MBR installations with average effluent turbidity concentrations ranging from 0.02 to 0.2 NTU and average effluent TSS below 0.5 mg/L.

5.2.2 Aggregate Organics

The removal of organic constituents by MBR systems is largely a result of biotransformation. MBR performance with respect to aggregate parameters (i.e., COD, BOD) commonly regulated to assess organics removal has been well established. However, these parameters alone do not provide enough detailed information about organic content from which to further optimize MBR process performance. Laspidou and Rittmann (2002a) developed a uniform theory for extracellular polyermeric substance (EPS), soluble microbial product (SMP), and active and inert biomass to further characterize various fractions of COD. The theory assumes that bound EPS and utilization-associated products (UAP) are produced as active biomass utilizes substrate to reproduce. The bound EPS is further hydrolyzed to biomass-associated products (BAP). Modeling scenarios performed as part of this study showed that the retention of BAP is directly related to effluent COD. Although it is certain the membrane component of the MBR will retain a portion of the BAP that would pass through a CAS, the exact amount needs to be characterized.

Initial studies also show MBR to be superior to CAS with regard to BDOC and AOC removal, but it has not been systematically demonstrated to what extent this performance is due to the membrane barrier and not to higher SRT and MLSS operational parameters. Further understanding of the factors that can impact effluent values of these parameters is important as they are an indicator of regrowth potential in distribution systems.

Based on the findings from the literature review, MBR systems can produce effluents with COD concentrations ranging from 8 to 30 mg/L while treating municipal wastewater. Several full-scale and pilot-scale facilities have reported COD removal of greater than 95%. Effluent BOD concentrations have been reported to be below the detection limit in several MBR studies. Removal percentages of $CBOD_5$ for MBR systems were reported to usually be at or above 99%. Results obtained from the facility survey showed similar trends with COD removal ranging from 92 to 98%, whereas BOD removal ranged from 97 to 100%.

5.2.3 Nutrients

Nutrient removal by an MBR process, as with CAS processes, is largely impacted by the biological reactor design and the influent wastewater characteristics. Parameters that can impact nitrogen removal common to both processes include influent wastewater characteristics (i.e., COD/TKN ratio, alkalinity, and feedwater temperature) along with biological reactor conditions such as SRT, HRT, and redox conditions. However, the utilization of membranes for solids separation in the MBR process warrants additional considerations in how to optimize operation and design of the biological reactor.

One of the key differences between CAS and MBR process design/operation is that the return activated sludge (RAS) stream flow rate in an MBR process is governed by membrane

performance/high solids fouling instead of simply returning concentrated/settled biomass to the bioreactors, as is the case with the CAS process. In order to minimize high solids fouling, membrane manufacturers require that the RAS stream in an MBR process to typically be 3 to 5 times the filtrate flow rate in submerged MBR systems and 12 to 20 times the filtrate flow rate in external MBR systems. The RAS stream in an MBR process also carries high levels of DO because of the use of scour air in the membrane tank. Routing RAS to the anoxic/anaerobic basins in MBR installations can lead to the inhibition of both denitrification and enhanced biological phosphorous removal (EBPR) processes that are due to the carryover of DO to the anoxic and anaerobic selectors, respectively. However, these issues can be addressed by using a dual recycle configuration where membrane recycle streams are diverted to aerobic basins instead of anoxic basins. Additional research would be beneficial in assessing how to further optimize the membrane and biological design and operation in order to enhance nutrient removal.

Review of existing literature shows that MBR systems can achieve nitrification efficiencies greater than 95% when operated at an SRT greater than 10 days. This higher SRT allows retention of slower growing autotrophs in the bioreactor basin. Operation at even higher SRT is required in regions with low temperature where the nitrification rate could be lower. Results from the facility survey show that most of the installations achieved effluent ammonia concentration of less than 1 mg/L-N for facilities with SRT values ranging from 11 to 30 days.

The effluent nitrate concentration in MBR systems will vary depending on the bioreactor configuration and influent wastewater characteristics. Based on existing literature, the denitrification efficiency increases as the COD/TKN ratio in the influent wastewater increases, and the MBR systems were shown to achieve greater than 50% nitrate removal when the COD/TKN ratio was greater than 7. Results from the facility survey show that effluent nitrate concentrations for four out of five installations were below 10 mg-N/L. Effluent total nitrogen concentration ranged from 3 to 13 4 mg-N/L corresponding to average removal rates of 70 to 93%.

Effluent phosphorus concentrations from MBR systems have been reported to range from 0.07 to 3.2 mg-P/L at SRT values ranging from 4 to 70 days in various MBR studies. Reported MBR performance from the facility survey with respect to total phosphorus showed a range of effluent concentrations from 0.04 to 5.0 mg-P/L, corresponding to average removal rates of 46 to 99.5%. Better removals were demonstrated when chemical addition was used either alone or in combination with biological phosphorus removal.

Specific factors that were reported to impact effluent nutrient concentrations at the surveyed facilities included:

- Insufficient BOD/COD in the influent wastewater to achieve complete denitrification
- Presence of excess DO in the anoxic zone inhibiting denitrification
- Insufficient DO in the aerobic tank (because of high MLSS) inhibiting nitrification
- Insufficient BOD/COD in the influent wastewater and excess DO in the anaerobic zone disrupting the biological phosphorus removal (BPR) process.
- Insufficient alkalinity concentration in the influent wastewater to achieve complete nitrification
- Seasonal changes in temperature of the influent wastewater

- Changes in the influent wastewater organic concentration because of factors such as storm flows resulting in excess DO in the anoxic basins and low alkalinity, which impacts nitrification process

5.2.4 Trace Metals

Removal of trace metals by MBR and CAS processes is highly dependent on the speciation of the metals that are present. Metals in particulate or ionic dissolved form are well removed by MBR via size exclusion and/or sorption followed by size exclusion. However, dissolved metals that are bound to organic matter rather than adsorbed onto particulates have the potential to pass through the membrane depending on the molecular size, charge, and spatial characteristics of the complex. More research is needed to better understand whether there is any potential advantage of MBRs in removing such soluble metal complexes. Studies to date are not consistent as to whether MBR processes offer any advantage over CAS with regard to metals removal. There is conflicting data where some studies infer that the smaller floc size associated with the higher SRT/MLSS of the MBRs enhances removal, whereas others suggest no removal benefit. Data across a number of studies indicate that the only consistent trend in metals removal is that it is most effectively achieved through efficient solids separation, and that this represents the primary advantage offered by the MBR. MBRs have been shown to be effective in reducing some metals, such as copper and chromium, below regulatory levels. Overall, it is generally accepted that reduction of dissolved metals below a certain threshold usually requires chemical precipitation and/or posttreatment with processes such as membrane nanofiltration or granular activated carbon (GAC).

Review of the literature demonstrates a high percentage removal of metals by MBRs at long SRT values of 55 to more than 200 days. Despite high removal percentages of 50 to 95% reported in MBR studies, residual metal was still reported in the effluents. Of the 19 facilities surveyed, only three facilities reported having water quality goals with respect to metals. Two of these facilities were required to meet copper discharge limits and were able to do so with effluent copper concentration reported at 6.8 µg/L and less than 8 µg/L.

5.2.5 Trace Organic Compounds

There are several mechanisms associated with the removal of trace organic compounds. These include volatilization (surface and aeration bubble), sorption, and biodegradation. All of these mechanisms occur in both MBRs and conventional CAS systems, but MBRs are more readily operated at higher SRT and MLSS conditions. No empirical data was found, however, demonstrating superior biodegradation for an MBR system over a CAS system when both are operated at the same SRT. Model scenarios conducted as part of this study showed biodegradation to be dominant as the removal mechanism for the majority of trace organic compounds because of their low sorption and volatilization rate constants. For such compounds, more effective removal is achieved at the higher SRT conditions needed for nitrogen removal. For a given SRT, the model also predicts more biodegradation will occur at lower MLSS levels, although the enhancement is small and not worth the cost to construct a larger reactor volume in order to achieve a lower MLSS at a particular SRT.

For a given tank volume, a longer SRT or higher MLSS will also increase the removal of volatile organics because of the higher aeration requirements. Although both MBR and CAS systems should exhibit this effect, it should be greater in an MBR because of the use of scour air for maintaining membrane flux. The developed model did not include scour air and,

therefore, could not be used to discern volatilization differences between an MBR and a CAS process. Because the majority of PPCP compounds have extremely low volatilization constants, this omission should be of little consequence in the assessment of overall compound removal, but might explain why higher removals of galaxolide were observed in the literature than the model scenario predictions reported herein.

Compounds that adsorb (e.g., antibiotics and galaxolide) show better solids partitioning for model scenarios with lower SRT and MLSS conditions. This is the same trend that would be observed with a CAS system; however, the membrane offers the following advantages: (1) a barrier that eliminates effluent carryover of particles containing adsorbed compounds and (2) smaller biosolids particle distribution that could add in mass transfer efficiency. Because of the trace concentrations of these compounds, the second factor is less likely to be important.

The model results of this study reveal how the fate of various fractions of the active biomass in an MBR system impact effluent water quality. By integrating a membrane size exclusion factor and a fate and transport model with an activated sludge model, predictive removal scenarios can be run for any trace organic compound with known volatilization, adsorption, and biodegradation constants. The model scenarios presented in this report demonstrate that compounds removed through biodegradation and/or volatilization processes exhibit greater removal percentages as SRT increases; however, this increase is logarithmic, and the biggest gain is achieved at SRTs of 15 to 20 days. This leveling-off effect may be more pronounced for biodegradation than it is for volatilization. The model may also underpredict MBR volatilization because it does not include scour air. Partitioning of compounds actually decreases with increasing SRT because of the reduced wasting rate. For this reason, compounds that show the best removal are susceptible to biodegradation and/or volatilization removal. Volatilization is minimal for most PPCP compounds, so biodegradation should be the dominant removal mechanism at the typical SRT operating levels of an MBR. Therefore, an MBR process should offer little benefit over a CAS process other than that it might be operated at a higher SRT because of footprint constraints for a CAS system.

5.2.6 Knowledge Gaps

Knowledge gaps with respect to MBR effluent water quality performance for municipal wastewater reuse have been identified. The knowledge gaps, organized under the five target constituent categories (i.e., particulate matter, aggregate organics, nutrients, trace metals, and trace organic compounds) address what is not fully understood mechanistically, what is not fully explored in the literature, and what has not been adequately demonstrated from the full-scale survey responses.

Table 5.1 provides a summary of key design and operational factors that can impact effluent water quality for both CAS and MBR processes, along with possible MBR design and operational issues that should be considered for future research in order to further enhance effluent water quality performance.

Table 5.1. Summary of MBR Performance Characteristics and Research Needs

Contaminant Category	MBR Removal Mechanisms	Benefits of MBR over CAS with Media Filtration	Key MBR Factors Impacting Removal Performance	MBR Research Needs
Particulates Microbes	Adsorption Size Exclusion Charge Exclusion	Membrane filtration for solids separation allows operation at a higher MLSS resulting in a smaller process footprint.	Membrane integrity Membrane cleaning	monitoring device
Aggregate Organics	Biodegradation	Complete retention of biomas and extracellular polymeric substances in the reactor due to the membrane barrier; better retention of biomass-associated products; production of effluent with lower AOC and BDOC content that reduces re-growth potential in the distribution piping.	Membrane integrity Membrane cleaning	Better understanding of the role that the membrane and associated cake layer formation plays in removal of soluble organics; how to maximize cake layer role as a barrier while minimizing air scour and cleaning
Nutrients: Nitrogen	Nitrification Denitrification	Higher SRT needed for nitrification is achievable with a smaller footprint	Internal recycle flow is required in addition to membrane recirculation (RAS) in order to optimize denitrification.	Optimize design of air scour in order to reduce process air requirements.
Nutrients: Phosphorus	Biological uptake Chemical precipitati	Better solids separation of either chemical precipitate or biomass helps to achieve very low phosphorus limits.	Internal recycle flow between anoxic and aerobic zones should be optimized such that complete nitrate removal is achieved in the anoxic zone.	Impact of chemical coagulation on membrane fouling.
Trace Metals	Adsorption Biological uptake	Better solids separation of biomass containing metals due to surface sorption or uptake.	Membrane integrity Membrane cleaning	Use of non-toxic chelating additives that prevent passage through the membrane due to size or charge exclusion.
Trace Organics	Biodegradation Adsorption Volatilization	Higher SRT for better biodegradation is achievable with smaller footprint; better volatilization due to air scour.	Same factors that enhance CAS biodegradation will improve the MBR, which is to run at the higher SRT needed for reduction of nutrients.	Obtain database of compound specific fate and transport properties or ability to to utilize a tool such as quantitative structure activity relationships to estimate them.

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Appendix A

Questionnaire Used For Facility Survey

WateReuse Foundation Project No. WRF-06-007

Investigation of Membrane Bioreactor Effluent Water Quality and Technology

MEMBRANE BIOREACTOR PLANT QUESTIONNAIRE

Plant name: _____

IV. MEMBRANE DESIGN AND OPERATIONAL CHARACTERISTICS

1. Manufacturer / Model ID: _____

2. Membrane module type _____ flat sheet _____ hollow fiber _____ tubular

3. Membrane configuration: _____ submerged _____ external

4. Nominal pore size of membrane _____ µm

5. Membrane area _____ ft2 _____ m2

6. Filtration cycle duration _____ minutes

7. Backwash (Y/N) _____ Relaxation (Y/N)_____

8. Backwash / Relaxation duration _____ seconds

9. Backwash flux _____ gfd _____ lmh

10. Scouring air per unit membrane area

Average	_____	scfm	_____	m3/h
Minimum	_____	scfm	_____	m3/h
Maximum	_____	scfm	_____	m3/h

11. What is the total unit power consumption of your MBR plant? Please specify units (kWh/1000 gallons of permeate). If possible, please provide break down of total power requirement i.e. % of total power consumption related to membrane air scour, activated sludge and treatment of waste activated sludge (if applicable).

_____

12. Design flux _____ gfd _____ lmh

13. Operational flux _____ gfd _____ lmh

14. Transmembrane Pressure (TMP) range _____ psi _____ kPa

15. Maintenance cleans
    - Frequency (for eg. 1/week) _____
    - Chemical and dose (for eg. 2000 mg/L NaOCl) _____

16. Recovery cleans (Soak cleans)
    - Frequency (for eg. 1/year) _____
    - Chemical and dose (for eg. 500 mg/L NaOCl), soak time, temperature _____

17. Membrane age: _____ years (warrantied) _____ years (actual)

II. PRELIMNARY AND PRIMARY TREATMENT

1.	Bar screening:	_____ yes	_____ no	
2.	Grit removal	_____ yes	_____ no	
3.	Primary Clarification	_____ yes	_____ no	
4.	Equalization	_____ yes	_____ no	
5.	Fine screening	_____ yes	_____ no	
	If yes, please provide the location (i.e. influent, return sludge, etc.) type screen type, perforation/slot size (mm):	_____	_____ mm	
6.	Does plant have any bypass capabilities?	_____ yes	_____ no	
7.	Are any chemicals added to the plant?	_____ yes	_____ no	
	If yes, then please specify the purpose (i.e. phosphorus removal, sludge dewatering, etc.) chemical, location and target dose.	_____	_____ mg/L	

III. BIOREACTOR DESIGN AND OPERATIONAL CHARACTERISTICS

1. **Type of biological system design employed in plant (please check one):**

   Nitrification only _____

   Total nitrogen removal

   Pre-denitrification _____

   Tertiary denitrification _____

   Phosphorus removal

   Biological _____

   Chemical _____

   Both _____

   If other, please specify _____

   Other parameters

2. MLSS (aerobic tank) _____ mg/L
3. MLVSS (aerobic tank) _____ mg/L
4. MLSS (membrane tank) _____ mg/L
5. Waste Activated Sludge

   Design waste flow _____ MGD m3/d

   Sludge wasting method _____ (eg. Batch or continous, daily or weekly)

   Sludge wasting frequency _____ (eg. Daily, weekly, other)

   Sludge wasting location _____ (eg. From membrane tank, aeration tank, surface wasting)

6. Total Volume _____ MG _____ m3

   Anoxic tank volume _____ MG _____ m3

   Anaerobic tank volume _____ MG _____ m3

   Aerobic tank volume _____ MG _____ m3

   Membrane tank volume _____ MG _____ m3

WateReuse Foundation Project No. WRF-06-007

Investigation of Membrane Bioreactor Effluent Water Quality and Technology

MEMBRANE BIOREACTOR PLANT QUESTIONNAIRE

Plant name: _____

IV. MEMBRANE DESIGN AND OPERATIONAL CHARACTERISTICS

1. Manufacturer / Model ID: _____

2. Membrane module type _____ flat sheet _____ hollow fiber _____ tubular

3. Membrane configuration: _____ submerged _____ external

4. Nominal pore size of membrane _____ µm

5. Membrane area _____ ft2 _____ m2

6. Filtration cycle duration _____ minutes

7. Backwash (Y/N) _____ Relaxation (Y/N) _____

8. Backwash / Relaxation duration _____ seconds

9. Backwash flux _____ gfd _____ lmh

10. Scouring air per unit membrane area

Average	_____	scfm	_____	m3/h
Minimum	_____	scfm	_____	m3/h
Maximum	_____	scfm	_____	m3/h

11. What is the total unit power consumption of your MBR plant? Please specify units (kWh/1000 gallons of permeate). If possible, please provide break down of total power requirement i.e. % of total power consumption related to membrane air scour, activated sludge and treatment of waste activated sludge (if applicable).

_____

12. Design flux _____ gfd _____ lmh

13. Operational flux _____ gfd _____ lmh

14. Transmembrane Pressure (TMP) range _____ psi _____ kPa

15. Maintenance cleans
    Frequency (for eg. 1/week) _____
    Chemical and dose (for eg. 2000 mg/L NaOCl) _____

16. Recovery cleans (Soak cleans)
    Frequency (for eg. 1/year) _____
    Chemical and dose (for eg. 500 mg/L NaOCl), soak time, temperature _____

17. Membrane age: _____ years (warrantied) _____ years (actual)

V. WATER QUALITY GOALS / PERFORMANCE

1. Effluent water quality permit name & no. _____

2. Water quality goals

		Additional info
Turbidity, NTU		
TSS, mg/L		
BOD_5, mg/L		
COD, mg/L		
TOC, mg/L		
Ammonia, mg-N/L		
TKN, mg-N/L		
TIN, mg-N/L		
Total nitrogen, mg-N/L		
Total phosphorus, mg-P/L		
Total coliform bacteria, CFU/100 mL		
Fecal coliform bacteria, CFU/100 mL		
Viruses, PFU/100 mL		
Others (i.e. Metals, EDC/PPCPs)		

3. Please complete MBR influent and effluent water quality tables with annual average, minimum and maximum values during most recent 12-month period. If data is not available for any particular parameter, enter "NA". If data is below the detection limit, please enter "ND" and specify the detection limit; for eg: ND, <2 mg/L)
If a full year worth of data is not available for a particular parameter, use data which is available.

MBR Treatment Performance				
	Influent	Effluent		
Parameter	Average	Average	Minimum	Maximum
Turbidity, NTU				
TSS, mg/L				
BOD_5, mg/L				
COD, mg/L				
TOC, mg/L				
Ammonia, mg-N/L				
TKN, mg-N/L				
TIN, mg-N/L				
Total nitrogen, mg-N/L				
Total phosphorus, mg-P/L				
Total coliform bacteria, CFU/100 mL				
Fecal coliform bacteria, CFU/100 mL				
Viruses, PFU/100 mL				
Others (i.e. Metals, EDC/PPCPs)				

VI. LESSONS LEARNED

Please comment on following questions:

1 Based on your observation, what factors (if any) have impacted effluent water quality of your plant?

2 Based on your observation, what factors (if any) have impacted operational performance of your plant?

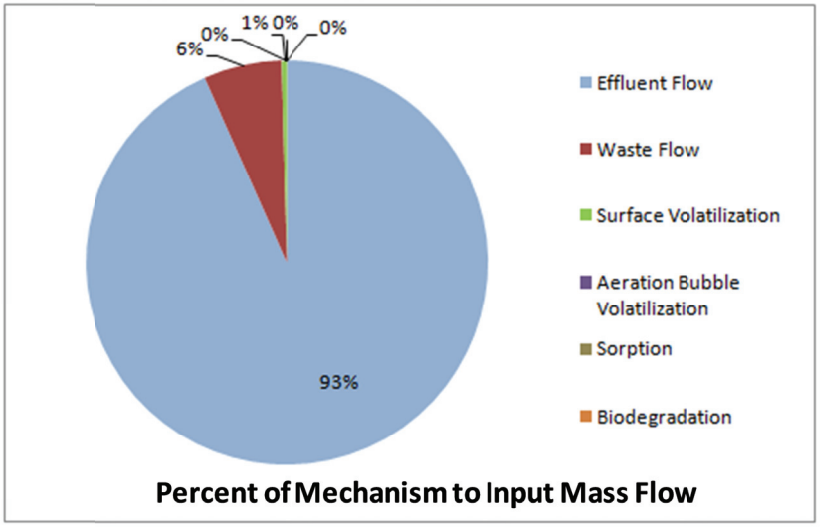
3 Has your plant consistently met or exceeded water quality goals? If not, then what were the factors behind it?

4 What operational and water quality differences (if any) did you observe between pilot scale and full scale?

Appendix B

Model Output Scenarios

INPUT PARAMETER	Units		Values	
Biodegradation Rate	L/mg COD-d	0	0.1	2
Sorption Coefficient	L/mg COD	0	10	1000
Henry's Constant	L H_2O/L gas	0.0001	0.1	100
Surface Mass Transfer Coef.	day^{-1}	0.1	1	10
SRT	days	2	15	50
Reactor Volume	L	125000	330000	1000000
Influent COD	mg COD/L	170	370	570
BAP small fraction	-	0.5	0.7	0.9
DO	mg O_2/L	1	3	6
Influent Micropollutant Concentration (mg/L):			5	



Percent of Mechanism to Input Mass Flow

Scenario 1

GENERAL OUTPUT

Effluent COD (mg COD/L):	15.7
Wasted Sludge (L/d):	62500
Wasted Sludge (kg/d):	111
Power for Aeration (kW):	1
Aeration Alpha (kg O_2/kWh):	0.86
FOTE (kg O_2/kWh):	1.4
HRT (days):	0.13
MLSS (mg COD/L):	1774
MLVSS (mg COD/L):	1524
X_a (mg COD/L):	438
EPS (mg COD/L):	270
Q^w/Q^0:	0.06

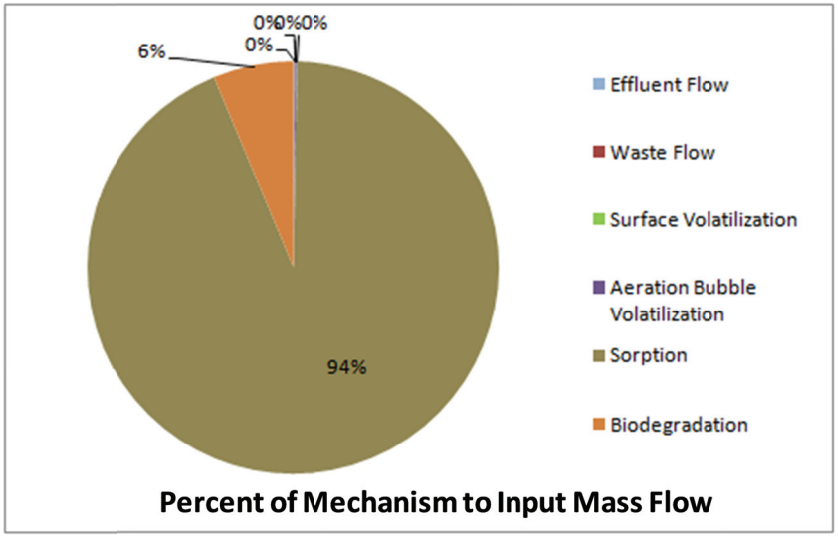
MICROPOLLUTANT OUTPUT

Effluent Concentration (mg/L)	5.0
Mass in Influent Flow (mg/d):	5.0E+06
Mass in Effluent Flow (mg/d):	4.7E+06
Mass in Waste Flow (mg/d):	3.1E+05
Mass Volatilized, Water Surface (mg/d):	2.1E+04
Mass Volatilized, Aeration Bubbles (mg/d):	8.3E+02
Mass Sorbed (mg/d):	0.0E+00
Mass Biodegraded (mg/d):	0.0E+00

All parameters are set on the lowest values of the selected range. 91% of the influent COD is removed by the MBR under these parameters. None of the micropollutant in the influent is removed.

Scenario 2

INPUT PARAMETER	Units		Values	
Biodegradation Rate	L/mg COD-d	0	0.1	2
Sorption Coefficient	L/mg COD	0	10	1000
Henry's Constant	L H_2O/L gas	0.0001	0.1	100
Surface Mass Transfer Coef.	day^{-1}	0.1	1	10
SRT	days	2	15	50
Reactor Volume	L	125000	330000	1000000
Influent COD	mg COD/L	170	370	570
BAP small fraction	-	0.5	0.7	0.9
DO	mg O_2/L	1	3	6
Influent Micropollutant Concentration (mg/L):			5	



Percent of Mechanism to Input Mass Flow

GENERAL OUTPUT

Effluent COD (mg COD/L):	26.6
Wasted Sludge (L/d):	22000
Wasted Sludge (kg/d):	106
Power for Aeration (kW):	9
Aeration Alpha (kg O_2/kWh):	0.65
FOTE (kg O_2/kWh):	1.1
HRT (days):	0.33
MLSS (mg COD/L):	4830
MLVSS (mg COD/L):	4142
X_a (mg COD/L):	1850
EPS (mg COD/L):	717
Q^w/Q^0:	0.02

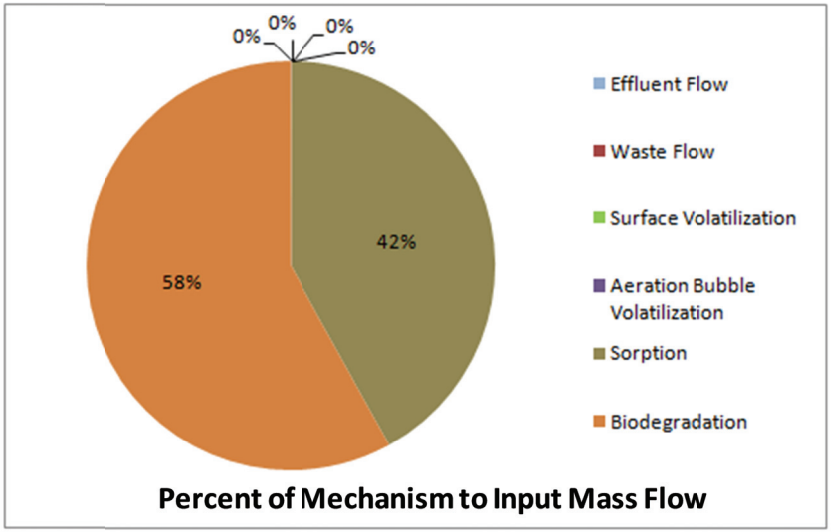
MICROPOLLUTANT OUTPUT

Effluent Concentration (mg/L)	0.0
Mass in Influent Flow (mg/d):	5.0E+06
Mass in Effluent Flow (mg/d):	5.0E+03
Mass in Waste Flow (mg/d):	1.1E+02
Mass Volatilized, Water Surface (mg/d):	5.6E+02
Mass Volatilized, Aeration Bubbles (mg/d):	7.8E+03
Mass Sorbed (mg/d):	4.7E+06
Mass Biodegraded (mg/d):	3.1E+05

All parameters are set on the middle values of the selected range. 93% of the influent COD is removed. 100% of the micropollutant in the influent is removed, predominantly by sorption. The power required for aeration increases 9 times that of Scenario 1.

Scenario 5

INPUT PARAMETER	Units	Values		
Biodegradation Rate	L/mg COD-d	0	0.1	**2**
Sorption Coefficient	L/mg COD	0	**10**	1000
Henry's Constant	L H_2O/L gas	**0.0001**	0.1	100
Surface Mass Transfer Coef.	day^{-1}	**0.1**	1	10
SRT	days	2	**15**	50
Reactor Volume	L	125000	330000	**1000000**
Influent COD	mg COD/L	170	**370**	570
BAP small fraction	-	0.5	**0.7**	0.9
DO	mg O_2/L	1	3	**6**
Influent Micropollutant Concentration (mg/L):		5		



Percent of Mechanism to Input Mass Flow

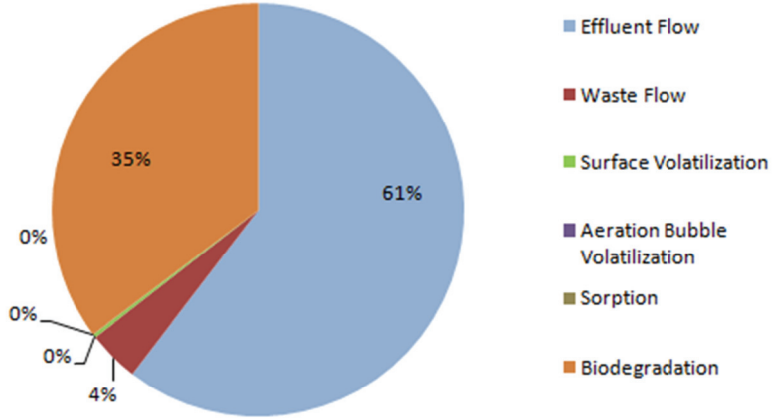
GENERAL OUTPUT	
Effluent COD (mg COD/L):	25.1
Wasted Sludge (L/d):	66667
Wasted Sludge (kg/d):	120
Power for Aeration (kW):	7
Aeration Alpha (kg O_2/kWh):	0.85
FOTE (kg O_2/kWh):	1.4
HRT (days):	1.00
MLSS (mg COD/L):	1806
MLVSS (mg COD/L):	1558
X_a (mg COD/L):	719
EPS (mg COD/L):	241
Q^w/Q^0:	0.07

MICROPOLLUTANT OUTPUT	
Effluent Concentration (mg/L)	0.0
Mass in Influent Flow (mg/d):	5.0E+06
Mass in Effluent Flow (mg/d):	1.9E+03
Mass in Waste Flow (mg/d):	1.3E+02
Mass Volatilized, Water Surface (mg/d):	6.7E+01
Mass Volatilized, Aeration Bubbles (mg/d):	2.2E+00
Mass Sorbed (mg/d):	2.1E+06
Mass Biodegraded (mg/d):	2.9E+06

A micropollutant that is easily biodegraded, sorbable, and minimally volatile may have a fate similar to that depicted above. The SRT value chosen is moderate, while the HRT is relatively high – conditions that would support biodegradation and sorption.

Scenario 6

INPUT PARAMETER	Units	Values		
Biodegradation Rate	L/mg COD-d	0	**0.01**	2
Sorption Coefficient	L/mg COD	**0**	10	1000
Henry's Constant	L H_2O/L gas	**0.0001**	0.1	100
Surface Mass Transfer Coef.	day^{-1}	**0.1**	1	10
SRT	days	**2**	15	50
Reactor Volume	L	**125000**	330000	1000000
Influent COD	mg COD/L	**170**	370	570
BAP small fraction	-	**0.5**	0.7	0.9
DO	mg O_2/L	**1**	3	6
Influent Micropollutant Concentration (mg/L):		5		



Percent of Mechanism to Input Mass Flow

PROCESS OUTPUT

Effluent COD (mg COD/L):	15.7
Wasted Sludge (L/d):	62500
Wasted Sludge (kg/d):	111
Power for Aeration (kW):	1
Aeration Alpha (kg O_2/kWh):	0.86
FOTE (kg O_2/kWh):	1.4
HRT (days):	0.13
MLSS (mg COD/L):	1774
MLVSS (mg COD/L):	1524
X_a (mg COD/L):	438
EPS (mg COD/L):	270
Q^w/Q^0:	0.06

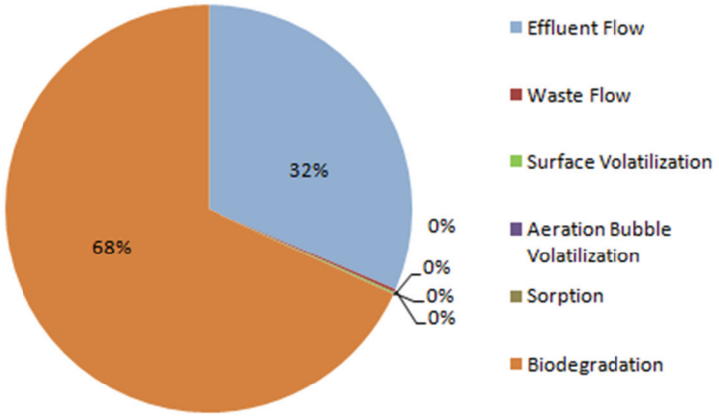
MICROPOLLUTANT OUTPUT

Effluent Concentration (mg/L)	3.2
Mass in Influent Flow (mg/d):	5.0E+06
Mass in Effluent Flow (mg/d):	3.0E+06
Mass in Waste Flow (mg/d):	2.0E+05
Mass Volatilized, Water Surface (mg/d):	1.3E+04
Mass Volatilized, Aeration Bubbles (mg/d):	5.4E+02
Mass Sorbed (mg/d):	0.0E+00
Mass Biodegraded (mg/d):	1.8E+06

The next 3 slides (Scenarios 6, 7, and 8) demonstrate of the effect of increasing SRT. In these cases, biodegradation is the dominant loss mechanism. Note that for these 3 scenarios, the biodegradation rate was set at 0.01 rather than 0.1 L/mg COD-d .

Scenario 7

INPUT PARAMETER	Units	Values		
Biodegradation Rate	L/mg COD-d	0	**0.01**	2
Sorption Coefficient	L/mg COD	**0**	10	1000
Henry's Constant	L H_2O/L gas	**0.0001**	0.1	100
Surface Mass Transfer Coef.	day^{-1}	**0.1**	1	10
SRT	days	2	**15**	50
Reactor Volume	L	**125000**	330000	1000000
Influent COD	mg COD/L	**170**	370	570
BAP small fraction	-	**0.5**	0.7	0.9
DO	mg O_2/L	**1**	3	6
Influent Micropollutant Concentration (mg/L):		5		



Percent of Mechanism to Input Mass Flow

PROCESS OUTPUT

Effluent COD (mgCOD/L):	14.3
Wasted Sludge (L/d):	8333
Wasted Sludge (kg/d):	61
Power for Aeration (kW):	4
Aeration Alpha (kg O_2/kWh):	0.52
FOTE (kg O_2/kWh):	0.8
HRT (days):	0.13
MLSS (mg COD/L):	7345
MLVSS (mg COD/L):	6071
X_a (mg COD/L):	1717
EPS (mg COD/L):	734
Q^w/Q^0:	0.01

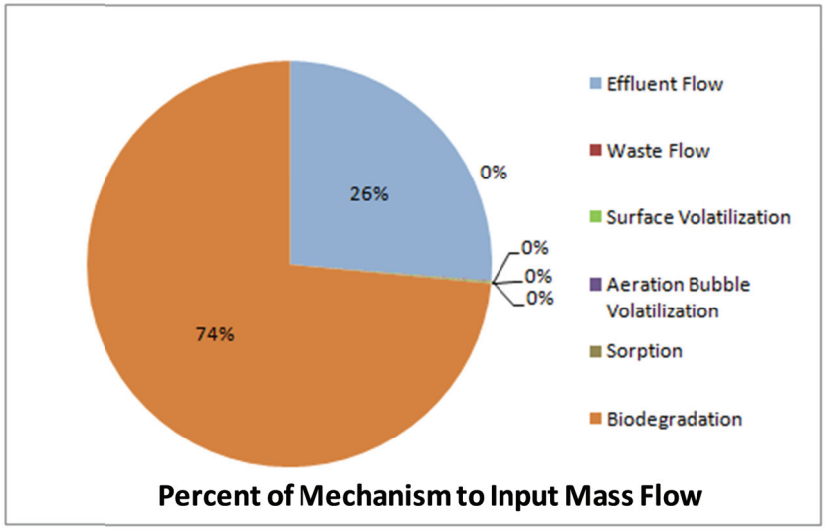
MICROPOLLUTANT OUTPUT

Effluent Concentration (mg/L)	1.6
Mass in Influent Flow (mg/d):	5.0E+06
Mass in Effluent Flow (mg/d):	1.6E+06
Mass in Waste Flow (mg/d):	1.3E+04
Mass Volatilized, Water Surface (mg/d):	6.5E+03
Mass Volatilized, Aeration Bubbles (mg/d):	1.1E+03
Mass Sorbed (mg/d):	0.0E+00
Mass Biodegraded (mg/d):	3.4E+06

As SRT increases, power required for aeration increases; micropollutant in effluent decreases while becoming increasingly biodegraded, and effluent COD decreases.

Scenario 8

INPUT PARAMETER	Units		Values	
Biodegradation Rate	L/mg COD-d	0	0.01	2
Sorption Coefficient	L/mg COD	0	10	1000
Henry's Constant	L H_2O/L gas	0.0001	0.1	100
Surface Mass Transfer Coef.	day^{-1}	0.1	1	10
SRT	days	2	15	50
Reactor Volume	L	125000	330000	1000000
Influent COD	mg COD/L	170	370	570
BAP small fraction	-	0.5	0.7	0.9
DO	mg O_2/L	1	3	6
Influent Micropollutant Concentration (mg/L):		5		



Percent of Mechanism to Input Mass Flow

PROCESS OUTPUT

Effluent COD (mg COD/L):	14.5
Wasted Sludge (L/d):	2500
Wasted Sludge (kg/d):	27
Power for Aeration (kW):	8
Aeration Alpha (kg O_2/kWh):	0.39
FOTE (kg O_2/kWh):	0.6
HRT (days):	0.13
MLSS (mg COD/L):	10743
MLVSS (mg COD/L):	7869
X_a (mg COD/L):	2233
EPS (mg COD/L):	875
Q^w/Q^0:	0.00

MICROPOLLUTANT OUTPUT

Effluent Concentration (mg/L)	1.3
Mass in Influent Flow (mg/d):	5.0E+06
Mass in Effluent Flow (mg/d):	1.3E+06
Mass in Waste Flow (mg/d):	3.3E+03
Mass Volatilized, Water Surface (mg/d):	5.4E+03
Mass Volatilized, Aeration Bubbles (mg/d):	1.7E+03
Mass Sorbed (mg/d):	0.0E+00
Mass Biodegraded (mg/d):	3.7E+06

Operating with the highest SRT value and the lowest HRT value in the selected ranges, 26% of a moderately biodegradable compound treated in an MBR remains in the reactor effluent. The effluent COD is approximately the same as in Scenario 7.

Appendix C

Removal of Trace Organic Compounds as Reported in Literature

Acetaminophen

- Greater than 99% removal for 8 to 10-day SRT (Yu et al., 2006)
- Greater than 99% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m^3/day pilot-scale MBR systems (Bernhard et al., 2006)
- Approximately 96% removal for unspecified operations (Radjenovic et al., 2007)

Androstenedione

- Greater than 92% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m^3/day pilot-scale MBR systems (Bernhard et al., 2006)

Atrazine

- Approximately 9% removal observed for greater than 400-day SRT MBR system (Bernhard et al., 2006)

Atenolol

- Approximately 66% removal observed for unspecified operating conditions (Radjenovic et al., 2007).

Benzfibrate

- Good removal (80–97%) observed for MBR operated for SRT range of 11–41 days (Clara et al., 2004)
- Approximately 80–95% removal observed for 10- to 55-day SRT MBR system, with lowest removal observed for highest SRT (Clara et al., 2005a).
- Approximately 91% removal observed for 37-day SRT MBR system (Quintana et al., 2005)
- Approximately 78–95% removal observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)
- Approximately 76–96% removal observed for unspecified operating conditions (Radjenovic et al., 2007)

Bisphenol a

- Approximately 1.3 log reduction from dumpsite leachate utilizing external tubular UF module operated in cross-flow mode with cross-flow velocity of approximately 5 m/s and transmembrane pressure differential of 6 bar (Wintgens et al., 2002)
- Greater than 95% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)

- Approximately 93–99% removal observed for 22- to 82-day SRT MBR system (Clara et al. 2005b)
- Approximately 94% removal observed for synthetic influent with seeded real sludge for 350-day SRT (Chen et al., 2008)

Caffeine

- Greater than 98% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m^3/day pilot-scale MBR systems (Bernhard et al., 2006)

Carbamezapine

- No removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernhard et al., 2006)
- No removal observed for MBR operated for SRT range of 11–41 days (Clara et al., 2004)
- Almost no removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)
- Almost no removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)
- Almost no removal observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)
- Approximately 13% removal observed for greater than 400 day SRT MBR system (Bernhard et al., 2006)
- Range of 0–12% removal for unspecified operations (Radjenovic et al., 2007)
- 9% removal observed for spiked synthetic wastewater at 72-day SRT (Reif et al., 2008)

Celestolide

- Approximately 0% removal (maximum) and 33% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Approximately 52% removal for spiked synthetic wastewater with 72-day SRT (Reif et al., 2008)

Clofibric Acid

- Approximately 75% removal observed for pilot-scale hybrid MBR composed of precoagulation/sedimentation ahead of the hollow fiber MBR operated in constant flow rate mode and membrane flux fixed at 0.4 m3/m2/d and 9-h hydraulic retention time (HRT). Performance without precoagulation/sedimentation was better (Kimura et al., 2005)
- Approximately 88% removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system (Kimura et al., 2005)
- Approximately 54% removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)
- Observed range of 73–86% observed for unspecified operating conditions (Radjenovic et al., 2007)

DEET

- No removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Removals between 45% and 83% in the pilot submerged MBR exceeded the 0% to 50% removal in the parallel full-scale activated sludge process (Bernard et al., 2006)
- Approximately 62% removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)

Diazepam

- 26% removal observed for spiked synthetic wastewater for 72-day SRT (Reif et al., 2008)

Diclofenac

- No removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Approximately 20% removal observed for pilot-scale hybrid MBR composed of precoagulation/sedimentation ahead of the hollow fiber MBR operated in constant flow rate mode and membrane flux fixed at 0.4 m3/m2/d and 9-h hydraulic retention time (HRT). Performance without precoagulation/sedimentation was similar (Kimura et al., 2005)
- Little removal observed for MBR operated for SRT range of 11–41 days; better performance with conventional activated sludge plant because of longer operating SRTs.
- No removal observed for 10-day SRT and approximately 50% removal for 27-day SRT and 67% removal for 55-day SRT MBR system (Clara et al., 2004)
- Approximately 15–35% removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)
- Approximately 20% removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system (Kimura et al., 2005)
- Approximately 23% removal observed for 37-day SRT MBR system (Quintana et al., 2005)
- No removal observed for 22-day SRT, 30% removal observed for 40-day SRT, and 50% removal observed for 82-day SRT MBR system (Clara et al., 2005b)
- Approximately 58% removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)
- Approximately 18% removal for 8- to 10-day SRT (Yu et al., 2006)
- Approximately 26% removal (maximum) and 5% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Range of 16–87% removal observed for unspecified operations (Radjenovic et al., 2007)
- Removal range of 8 ± 53% for SRT in excess of 100 days (Wever et al., 2007)
- No removal observed for spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

Dicloprop

- No removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system and 50% removal observed when precoagulation and sedimentation MBR hybrid system used (Quintana et al., 2005)

EDTA

- No removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)
- -14% ± 40% removal for SRT in excess of 100 days (Wever et al., 2007)

Erythromycin

- Less than 10% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m^3/day pilot-scale MBR systems (Bernard et al., 2006)
- Approximately 69% removal for unspecified operations (Radjenovic et al., 2007)
- 91% removal observed for spiked synthetic wastewater with 72-day SRT (Reif et al., 2008)

17-α Estradiol

- 60–70% removal observed for MBR operated for SRT range of 11to 41 days, but poor (<10%) removal observed at 20 days (5°C instead of 22–27°C) (Clara et al. 2005b)

17- β Estradiol (E2)

- Greater than 99% removal observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)

17- α Ethinylestradiol (EE2)

- Unexpected poor removals observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)

17-β Ethinylestradiol

- 60–80% removal observed for MBR operated for SRT range of 11 to 41 days, but poor (<10%) removal observed at 20 days (5°C instead of 22–27°C) (Clara et al., 2004)

Estriol (E3)

- Greater than 95% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Greater than 99% removal observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)

Estrone (E1)

- Almost complete removal observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)

- Approximately 22% removal (maximum) and 74% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)

Galoxolide (HHCB)

- 80–90% removal observed for MBR operated for SRT range of 11 to 41 days, even during 5°C instead of 22–27°C sampling (Clara et al. 2004)
- Approximately 85% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)
- Approximately 30–55% removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)
- Approximately 65% removal (maximum) and 63% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Approximately 50% removal observed for spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

Gemfibrozil

- Approximately 68% removal for 8- to 10-day SRT (Yu et al., 2006)
- Approximately 55% removal (maximum) and 46% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Approximate removal of 87% observed for unspecified operation conditions (Radejenovic et al., 2007)

Hydrocodone

- No removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)

Iopromide

- Approximately 42–75% removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)

Ibuprofen

- Greater than 98% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Greater than 95% removal observed for pilot-scale hybrid MBR composed of precoagulation/sedimentation ahead of the hollow fiber MBR operated in constant flow rate mode and membrane flux fixed at 0.4 m3/m2/d and 9-h hydraulic retention time (HRT). Performance without precoagulation/sedimentation was similar (Kimura et al., 2005)
- Complete removal observed for MBR operated for SRT range of 11–41 days as well as for conventional activated sludge system (Clara et al., 2004)
- Greater than 99% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)
- Approximately 90–95% removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)

- Approximately 95% removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system (Kimura et al., 2005)
- Approximately 97% removal observed for 37-day SRT MBR system (Quintana et al., 2005)
- Approximately 97–99% removal observed for 22- to 82-day SRT MBR system (Clara et al., 2005b)
- Approximately 99% removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)
- Approximately 87% removal for 8- to 10-day SRT (Yu et al., 2005)
- Approximately 95% removal (maximum) and 95% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2005)
- Approximately 96–100% removal observed for unspecified operations (Radjenovic et al., 2007)
- 98% removal observed for spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

Indomethacin

- Approximately 21% removal (maximum) and 17% (mean) based on values obtained for 36 feed and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Approximately 46% removal observed for unspecified operating conditions (Radjenovic et al., 2007)

Ketoprofen

- Greater than 95% removal observed for pilot-scale hybrid MBR composed of precoagulation/sedimentation ahead of the hollow fiber MBR operated in constant flow rate mode and membrane flux fixed at 0.4 m3/m2/d and 9-h hydraulic retention time (HRT). Performance without precoagulation/sedimentation was slightly worse (Kimura et al., 2005)
- Approximately 95% removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system (Kimura et al., 2005)
- Approximately 62% removal observed for 37-day SRT MBR system (Quintana et al., 2005)
- Approximately 77% removal for 8- to 10-day SRT (Yu et al., 2006)
- Approximately 27% removal (maximum) and 14% (mean) based on values obtained for 36 feeds and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Observed range of 63–97% observed for unspecified operating conditions (Radjenovic et al., 2007)

Mefenamic Acid

- Approximately 85% removal observed for pilot-scale hybrid MBR composed of precoagulation/sedimentation ahead of the hollow fiber MBR operated in constant flow rate mode and membrane flux fixed at 0.4 m3/m2/d and 9-h hydraulic retention time (HRT). Performance without precoagulation/sedimentation was slightly worse (Kimura et al., 2005)
- Approximately 70% removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system (Kimura et al., 2005)

- Range of 71–76% removal observed for unspecified operating conditions (Radjenovic et al., 2007)

Naproxen

- Approximately 35% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Greater than 90% removal observed for pilot-scale hybrid MBR composed of precoagulation/sedimentation ahead of the hollow fiber MBR operated in constant flow rate mode and membrane flux fixed at 0.4 m3/m2/d and 9-h hydraulic retention time (HRT). Performance without precoagulation/sedimentation was slightly less (Bernard et al., 2006)
- Approximately 73–83% removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)
- Approximately 85% removal observed for 10,000 mg/L MLSS and 9-day HRT MBR system (Kimura,K. et al., 2005)
- Approximately 70% removal observed for 37-day SRT MBR system (Quintana et al., 2005)
- Approximately 88% removal for 8- to 10-day SRT (Yu et al., 2006)
- Approximately 93% removal (maximum) and 92% removal (mean) based on values obtained for 36 feeds and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Approximately 69–99% removal for unspecified operations (Radjenovic et al., 2007)
- 84% removal observed for spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

Nonylphenol (NP)

- Approximately 85% removal from dumpsite leachate utilizing external tubular UF module operated in cross-flow mode with cross-flow velocity of approximately 5 m/s and transmembrane pressure differential of 6 bar. TSS within bioreactors maintained at approximately 22 g/L and little removal of NP (approximately 2%) via solids partitioning because sludge wasting rate quite low. The percentage of the reactor reduction that was due to biodegradation and the percentage that was due to stripping was not measured (Bernard et al., 2006)
- Approximately 85–90% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)
- Approximately 20% removal observed (Vogelsang et al., 2006)

Nonylphenol Monoethoxylate

- Approximately 97–99% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Nonylphenol Diethoxylate

- Approximately 85–95% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Nonylphenoxy acetic acid

- Effluent levels are 3 to 6 times higher than influent levels for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Nonylphenoxyethoxy acetic acid

- Effluent levels are 2 to 10 times higher than influent levels for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Octylphenol

- Approximately 65 to greater than 99% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Octylphenol monethoxylate

- Approximately 95 to greater than 98% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Octylphenol diethoxylate

- Approximately 58 to greater than 92% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)

Oxybenzone

- Approximately 45% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)

Roxithromycin

- Approximately 65% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005)
- 77% removal observed for spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

Salicylic Acid

- Approximately 99% removal (maximum) and 99% removal (mean) based on values obtained for 36 feeds and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)

Sulfamethoxazole

- Approximately 65% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Approximately 40% removal observed for 10-day SRT MBR system (Clara et al., 2005a)
- Approximately 60–90% removal for unspecified operations (Radjenovic et al., 2007)
- 52% removal observed for spiked synthetic wastewater run at 72-day SRT (Reif et al., 2008)

TCEP

- No removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Approximately 37% removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)

TCPP

- Approximately 12% removal observed for greater than 400-day SRT MBR system (Bernard et al., 2006)

Testosterone

- Greater than 83% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)

Tonalide (AHTN)

- 80–90% removal observed for MBR operated for SRT range of 11 to 41 days, even during 5°C instead of 22–27°C sampling (Clara et al., 2004)
- Approximately 85–95% removal observed for 10- to 55-day SRT MBR system (Clara et al., 2005a)
- Approximately 35–55% removal observed for 10- to 12-day SRT MBR system (Joss et al., 2005)
- Approximately 70% removal (maximum) and 66% (mean) based on values obtained for 36 feeds and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)
- Approximately 45% removal observed for spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

Traseolide

- Approximately 90% removal (maximum) and 73% (mean) based on values obtained for 36 feeds and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)

Triclosan

- Approximately 45% removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- Approximately 69% removal for 8- to 10-day SRT (Yu et al., 2006)
- Approximately 92% removal (maximum) and 94% (mean) based on values obtained for 36 feeds and 39 effluents for 3- to 30-day SRT values (Lishman et al., 2006)

Trimethoprim

- No removal observed for plate and frame (Pure-Envitech Co.) and hollow fiber (Kolon Co.) 1 m3/day pilot-scale MBR systems (Bernard et al., 2006)
- 36% removal observed spiked synthetic wastewater and 72-day SRT (Reif et al., 2008)

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