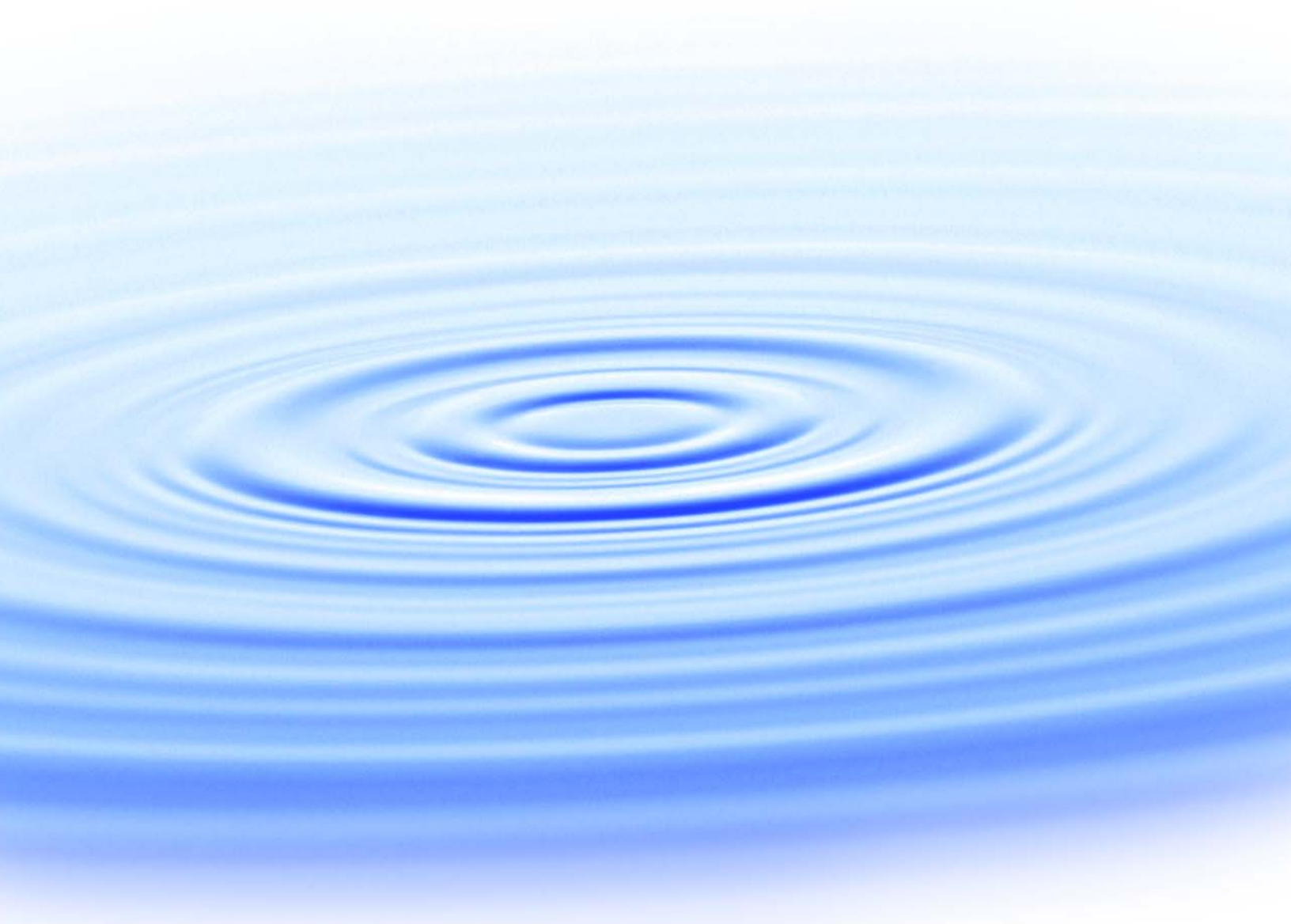
Disinfection Guidelines for Satellite Water Recycling Facilities



WateReuse Research Foundation

Disinfection Guidelines for Satellite Water Recycling Facilities

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.

Disinfection Guidelines for Satellite Water Recycling Facilities

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Acronyms

APHA	American Public Health Association
AWWARF	American Water Works Association Research Foundation
BOD	biochemical oxygen demand
CDPH	California Department of Public Health
CFU	colony-forming units
COD	chemical oxygen demand
CT	concentration × contact time
DI	deionized water
DNA	deoxyribonucleic acid
DO	dissolved oxygen
FDEP	Florida Department of Environmental Protection
HAdV	human adenovirus
HAV	hepatitis A virus
HRT	hydraulic retention time
IEUA	Inland Empire Utilities Agency
LRV	log removal value
MBR	membrane bioreactor
MF	microfiltration
MGD	million gallons per day
MLSS	mixed liquor suspended solids
MPN	most probable number
NDMA	nitrosodimethylamine
NELAP	National Environmental Laboratory Accreditation Program
NTU	nephelometric turbidity unit
NWRI	National Water Research Institute
PCR	polymerase chain reaction
PES	polyethersulfone
PET	polyethylene terephthalate
PFU	plaque-forming unit
PVDF	polyvinylidene fluoride
QA/QC	quality assurance/quality control
RNA	ribonucleic acid
RP#5	Reclamation Plant #5
RPM	revolutions per minute
RT-PCR	reverse transcription−polymerase chain reaction
SBR	sequencing batch reactor
SRT	solid retention time

TDS	total dissolved solids
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
USEPA	U.S. Environmental Protection Agency
UV	ultraviolet light
UVT	ultraviolet light transmittance

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:

- Definition of 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 primary goal of this study was to assess membrane bioreactor (MBR) effluent water quality and plant operational requirements necessary to allow consideration by regulatory agencies to lower disinfection requirements. Results from the study demonstrated that, when properly designed and operated, satellite MBR facilities can produce oxidized, fully nitrified effluents that have low concentrations of particles and microbial indicators. On the basis of the results from the bench-scale microbial inactivation studies conducted on MBR effluents, a free chlorine CT value of 30 mg-min/L was sufficient to achieve a 5-log removal of seeded male-specific bacteriophage and a total coliform bacterial concentration at or below 2.0 CFU/100 mL when filtrate turbidity was ≤ 1.0 NTU.

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Executive Summary

Use of recycled water to augment surface water and groundwater supplies has increased substantially in arid and semi-arid states in the United States. Recycled water is typically obtained from large centralized water recycling facilities and is conveyed to end users through recycled water conveyance lines. This approach requires large investments in conveyance infrastructure and is feasible only for nearby end users with high water demands. In order to increase the use of recycled water by non-centrally situated end users with smaller water demands, satellite water recycling facilities situated near the end users are often considered to minimize the cost of conveyance infrastructure.

The United States does not have federal effluent quality or treatment standards for reclaimed water. Each state has adopted regulations and guidelines differently, with California (under Title 22) recognized as one of the states with a comprehensive set of high effluent water quality treatment process requirements. In terms of disinfection, the chlorine disinfection requirements in this state for utilizing filtered effluent for unrestricted public access applications are specified as a CT value (the product of total chlorine residual and modal contact time measured at the same point) of not less than 450 mg-min/L at all times with a modal contact time (time for highest concentration to pass through contact basin) of at least 90 min, on the basis of peak dry weather design flow. Other states with well-developed recycled water requirements include Florida, Washington, Arizona, and Texas.

Membrane bioreactors (MBRs) are often the technology of choice for water recycling facilities. This technology has the capability to produce effluent water quality superior to that from more-conventional wastewater plants with tertiary treatment, particularly with respect to ammonia, organics, particles, and microorganisms. However, the lack of data on real-world performance of MBR facilities has precluded the potential to lower the disinfection requirements for effluents produced. Thus, the primary goal of this study was to assess MBR effluent water quality and plant operational requirements necessary to allow consideration by regulatory agencies to lower disinfection requirements. As part of the study, specific CT values were developed for various water qualities. A white paper on disinfection guidelines for satellite water recycling facilities was developed as part of this project and is presented in the final chapter.

MBR effluent water quality data were collected from a wide range of satellite facilities (38 facilities) to allow proper characterization of MBR effluents with respect to inorganic, organic, physical, and microbial parameters. The MBR facilities sampled during the study utilized different process configurations (submerged and external), membrane geometries (hollow-fiber, flat-sheet, and tubular), fouling control strategies (relaxation and backwash), and membranes of various ages. The MBR facilities sampled were spread across six different states and three different U.S. Environmental Protection Agency regions; flow rates at these facilities ranged from 0.001 to 1.8 MGD. Results from the reconnaissance survey demonstrated that satellite MBR facilities are capable of producing oxidized, nitrified effluents that have a lower concentration of particles and microbial indicators but are not always operated or maintained to ensure high performance, primarily because of lack of regulatory requirements in the state where they are situated.

A more detailed sampling program at nine of the initial 38 satellite facilities surveyed was subsequently conducted. The results demonstrated consistently high nitrification efficiency with filtrate ammonia concentrations mostly below 0.1 mg of N/L for most facilities and below 1 mg of N/L for all facilities. Ammonia concentrations were consistently lower for all the three samples collected from these facilities, which indicated that, when properly designed and operated, satellite MBR facilities can achieve complete nitrification. Satellite facilities consistently produced oxidized effluent with filtrate total organic carbon concentrations mostly below 6 mg/L (ranging from 3.3 to 10.5 mg/L); these levels were consistent during the three sampling events for each facility. Filtrate turbidities were below 0.2 NTU for the majority of satellite facilities sampled and were also consistent during the three sampling events.

In order to assess the appropriate chlorine CT values for MBR effluents, bench-scale free available chlorine microbial inactivation studies were conducted on effluents from satellite facilities and MBR pilot systems operating under routine and stressed conditions. Based on the results, to achieve a 5-log removal of seeded male-specific bacteriophage and a total coliform bacterial concentration at or below 2.0 CFU/100 mL

- a free available chlorine CT of 10 mg-min/L was sufficient for effluents from satellite water recycling facilities;
- a free available chlorine CT of 5 mg-min/L was sufficient for effluents collected from MBR pilot systems after chemical cleaning of the membranes; and
- a free available chlorine CT of 30 mg-min/L was sufficient for effluents collected from MBR pilot systems with breached membranes when filtrate turbidity was ≤ 1.0 NTU. Greater CTs were necessary as turbidities from breaches increased.

Results from the study demonstrated the ability of the MBR process to produce oxidized, nitrified effluents that have very low concentrations of particles and pathogens. Microbial inactivation studies conducted on effluents from satellite MBR facilities and pilot MBR systems showed that a free available chlorine CT of 30 mg-min/L and turbidity of ≤ 1.0 were sufficient to achieve a 5-log removal of seeded male-specific bacteriophage and total coliform bacterial concentrations at or below 2.0 CFU/100 mL. In order to employ these low CT values at satellite facilities, implementing a process control strategy that will ensure production of high-quality effluent by the MBR process with respect to particles and ammonia is critical. Figure ES1 presents a process control strategy to implement lower CT values to achieve a desired level of disinfection at satellite water recycling facilities.

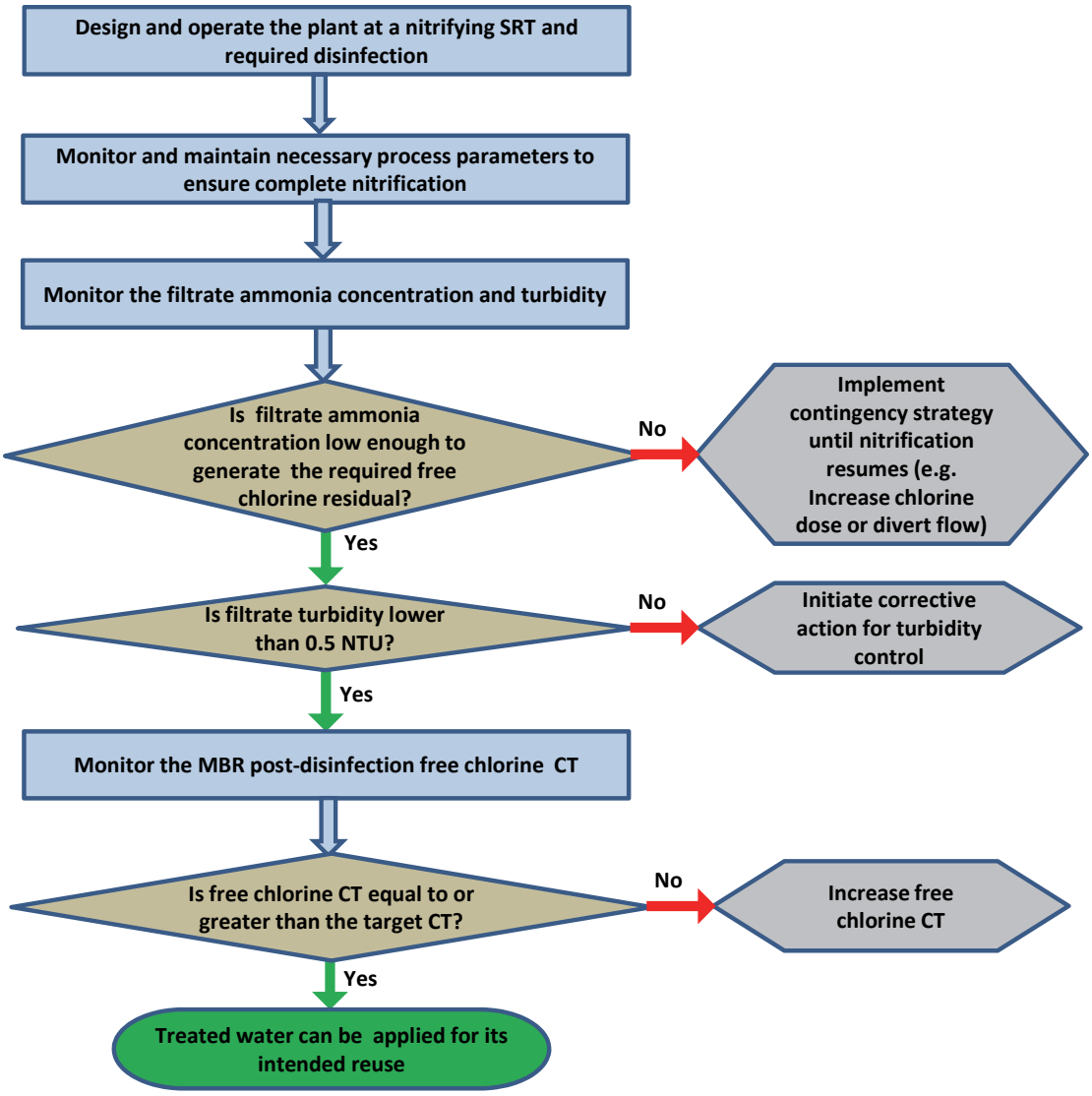


Figure ES1. Process control strategy for the satellite water recycling facilities to implement lower free chlorine CT values.

Three future research areas were identified as part of this study. They included (1) demonstrating the effectiveness of proposed CT values and monitoring requirements at a full-scale water recycling facility in meeting current disinfection regulations; (2) studying the occurrence and removal of adenoviruses by the MBR process while treating municipal wastewater; and (3) identifying surrogates for detecting presence of microbial indicators in the MBR filtrate and evaluating online sensors for detection of pathogens.

Chapter 1

Introduction

1.1 Project Background

Use of recycled water for nonpotable applications has increased dramatically in the United States, especially in water-scarce states such as California, Florida, and Texas. Recycled water is now used in many applications that include landscape irrigation, fire protection, toilet and urinal flushing, agricultural irrigation, cooling, and air conditioning. Most of these applications require a small flow of water, and because the points of application are usually disperse, it becomes cost prohibitive to install conveyance pipelines to transfer recycled water from a centralized water reclamation facility to these points of application. Satellite or decentralized treatment facilities allow treatment of wastewater for local reuse applications and minimize the cost of conveyance infrastructure. Installation of satellite and decentralized facilities as a viable water recycling solution has been increasing because of their demonstrated reliability, minimal footprint, elimination of new recycled water distribution pipelines, and postponement of central treatment capital improvement projects (Davis, 2009).

1.1.1 Satellite Water Recycling Facilities

Satellite water recycling facilities "scalp" or "mine" wastewater from a sewer collection system and reuse the treated water for local recycling applications while returning the treatment process residuals to the collection system for processing at the centralized treatment facility (Metcalf and Eddy, 2007). Satellite facilities can obtain the wastewater for local treatment and recycling in three specific ways: (1) interception type, where the wastewater is intercepted in a high-rise building prior to the collection system; (2) extraction type, where the water is pumped from the centralized collection system in a process referred to as "sewer mining" or "sewer scalping;" and (3) upstream type, where the water is obtained from developments at the extremities of a centralized collection system (Metcalf and Eddy, 2007). Satellite facilities differ from decentralized systems in that the latter are not connected to a centralized collection facility (Crites and Tchobanoglous, 1998). Because of this operational distinction, decentralized facilities have greater design demands in addressing solid-handling issues and can have greater considerations related to flow equalization.

Water recycling applications with unrestricted access require treatment to eliminate pathogens because the effluent is often utilized for irrigation of green space with unrestricted public access. This goal is achieved when the water is oxidized, solids are removed, and ammonia that can interfere with the disinfection process are minimized prior to disinfection. As shown in Table 1.1, more than half of the recycled water applications in California and Florida require tertiary treatment followed by disinfection. For many satellite applications, this treatment needs to occur with a small footprint because of site constraints. Therefore, footprint minimization and higher effluent quality are usually key drivers for satellite facilities.

Table 1.1. Treatment Levels Specified for Recycled Water Applications in Select States

Types of Use	Treatment Level		
	California	Florida	Washington
Urban uses and Landscape Irrigation			
Fire protection	DT	DT (HLD)	DT
Toilet & urinal flushing	DT	DT (HLD)	DT
Irrigation of parks, schoolyards, residential landscaping	DT	DT (HLD)	DT
Irrigation of cemeteries highway landscaping	DS	DT (HLD)	DS
Irrigation of nurseries	DT or DS	DT (HLD)	DS
Landscape impoundment	DT or DS[a]	DT (HLD)	DS
Agricultural Irrigation			
Pasture for milk animals	DS	DS (BD)	DS
Fodder and fiber crops	US	DS (BD)	DS
Orchards (no contact between fruit and recycled water)	US	DT (HLD)	DS
Vineyards (no contact between fruit and recycled water)	US	DT (HLD)	DS
Non-food bearing trees	US	DS (BD)	DS
Food crops eaten after processing	DS	DT (HLD)	DS
Food crops eaten raw	DT	DT (HLD)[b]	DT
Commercial/Industrial			
Cooling & air conditioning - w/cooling towers	DT or DS[a]		DT or DS
Structural fire fighting	DT	DT (HLD)	DS
Commercial car washes	DT	DT (HLD)	
Commercial laundries	DT	DT (HLD)	
Artifical snow making	DT	DT (HLD)	
Soil compaction, concrete mixing	DS	DT (HLD)	
Environmental and Other Uses			
Recreational ponds with body contact (swimming)	DT		
Wildlife habitat/wetland	DS		DT or DS
Aquaculture	DT or DS		
Rapid Infiltration Basins		DS (BD)	
Groundwater Recharge			
Seawater intrusion barrier	DT[a]	DT (HLD)[c]	
Replenishment of potable aquifers	DT[a]	DT (HLD)[c]	DT

NS - Treatment not specified by state regulations
DT indicates disinfected tertiary effluent
DS indicates disinfected secondary effluent
US indicates undisinfected secondary effluent
DT (HLD) indicates disinfected tertiary effluent with high level of disinfection
DT (BD) indicates disinfected tertiary effluent with basic disinfection

[a]Restrictions may apply

[b]Special permit required from Department of Health as well

[c]Must also meet drinking water standards

Source. Adapted partially from California Department of Water Resources, 2004.

The two most viable activated sludge technologies for satellite water recycling facilities are sequencing batch reactors (SBRs) and membrane bioreactors (MBRs). Although both SBRs and MBRs are suspended growth processes, they rely on different solid separation processes that result in different volumetric loading rate tolerances. Use of membrane filtration for solid separation in the MBR process allows operation at a high mixed liquor suspended solids (MLSS) concentration in the range of 8000–12,000 mg/L. Alternatively, reliance on gravity settling for solid separation in SBRs requires the process to operate at a lower MLSS concentration of 2000–5000 mg/L, because the ability of the sludge to settle within the SBR reduces drastically at high MLSS concentrations. Operation at a lower MLSS concentration requires a longer hydraulic retention time (HRT) and subsequently results in a larger footprint for SBRs than for MBRs. The SBR systems typically require an HRT of 15 to 40 h (Metcalf and Eddy, 2007), whereas MBR systems require HRTs of 4 to 11 h for municipal wastewater treatment (Hirani et al., 2007).

In addition, most of the satellite facilities are not staffed for 24 h a day, and so a high level of automation is usually desired for such facilities. MBR systems are also highly automated and require little or no supervision, which makes them a more attractive option for satellite facilities. Because the MBR process can achieve higher effluent water quality with a much smaller footprint than do conventional treatment processes and requires little or no supervision, it is the most widely used process for satellite facilities.

1.1.2 Effluent Quality Requirements for Reuse

Water reuse is defined as utilization of wastewater following treatment to achieve effluent quality standards appropriate to the water's designated beneficial use. The United States does not have federal effluent quality or treatment standards for reclaimed water, but the U.S. Environmental Protection Agency (USEPA) issued updated guideline recommendations (USEPA, 2004). Each state has adopted regulations and guidelines differently, with California (under Title 22) recognized as one of the states with a comprehensive set of high effluent water quality treatment process requirements (O'Connor et al., 2008). Other states with well-developed recycled water requirements include Florida, Washington, Arizona, and Texas. Their requirements are summarized in the following.

In California, the chlorine disinfection requirement for utilizing filtered effluent for unrestricted public access applications is specified as a CT (the product of total chlorine residual and modal contact time measured at the same point) value of not less than 450 mg-min/L at all times with a modal contact time (time for highest concentration to pass through contact chamber) of at least 90 min, on the basis of peak dry weather design flow (California Department of Public Health [CDPH], 2009). Approval of an alternative disinfection process (UV or ozone) requires a demonstration that the combined filtration and disinfection process will inactivate or remove 99.999% of f-specific bacteriophage MS-2 or poliovirus in the wastewater. This alternate process must still produce disinfected effluent for which the median concentration of total coliform bacteria does not exceed a most probable number (MPN) of 2.2 per 100 mL, utilizing the bacteriological results of the last 7 days for which analyses have been completed. In addition, the number of total coliform bacteria should not exceed an MPN of 23 per 100 mL in more than one sample in any 30-day period and no sample may exceed an MPN of 240 total coliform bacteria per 100 mL.

In Florida, reclaimed water is defined as that receiving at least secondary treatment and basic disinfection and that is reused after flowing out of a domestic wastewater treatment facility. Low-rate land applications for irrigation of public access areas, residential irrigation, or edible crops

require tertiary treatment that can provide a total-suspended-solids (TSS) level at or below 5 mg/L prior to disinfectant application. Such applications also require high-level disinfection that results in fecal coliform concentrations (per 100 mL of sample) below detectable limits for 75% of the values acquired over a 30-day period with any one sample not to exceed 25 fecal coliform bacteria per 100 mL of sample nor to exceed 5.0 mg/L of TSS at the point of disinfectant application. The total chlorine CT requirement is based on the fecal coliform bacterial concentrations before disinfection and is specified at 25 mg-min/L CT for a fecal coliform bacterial concentration of <1000 MPN/100 mL, 40 mg-min/L CT for a fecal coliform bacterial concentration of 1000 to <10,000 MPN/100 mL, and 120 mg-min/L CT for a fecal coliform bacterial concentration of 10,000 MPN/100 mL and higher.

In Washington, reclaimed water used for spray irrigation of food crops, irrigation of public access areas, and fire hydrants and sprinkler systems must be coagulated and filtered prior to disinfection. Washington is presently reevaluating its guidelines, but existing chlorine disinfection requirements cite a minimum residual of 1 mg/L of free chlorine following a contact time of at least 30 min measured as t_{10} (time required for 10% of the disinfectant to pass through the contact chamber).

In Arizona, reclaimed water used for irrigation of food crops, recreational impoundments, public access landscape irrigation, toilet flushing, fire protection systems, spray irrigation of orchards and vineyards, closed-loop air conditioning systems, vehicle and equipment washing, and snow making must be Class A reclaimed water that has been subjected to secondary treatment, filtration, and disinfection. Class A reclaimed water just prior to disinfection achieves a 24-h average turbidity of 2 NTU and never exceeds 5 NTU. There must also not be any detectable fecal coliform bacteria in four of the last seven monthly reclaimed water samples collected, nor is a single sample at or above 23 organisms per 100 mL permissible.

In Texas, reclaimed water can be used for residential and urban use irrigation, fire protection, irrigation of food crops that come into direct contact with human skin, irrigation of pastures for milking animals, maintenance of water bodies with possibility of recreational activities, and toilet flushing. Such applications, where there is a potential for public contact, require a 30-day average quality of 5 mg/L for 5-day biochemical oxygen demand (BOD_5) or carbonaceous BOD_5 ($CBOD_5$), turbidity of 3 NTU, a fecal coliform or *Escherichia coli* 30-day geometric mean of 20 CFU/100 mL and a maximum single grab sample value of 75 CFU/100 mL, and an *Enterococcus* 30-day geometric mean of 4 CFU/100 mL and a maximum single grab sample value of 9 CFU/100 mL. There is also a recommendation to carry out periodic fecal coliform bacterial sampling in certain reclaimed water distribution piping systems.

Because California has the most comprehensive set of regulations for recycled water among all the states, evaluating satellite treatment technology with respect to California regulations is important. Recycled water regulations for the state of California are stated under Title 22 of the California Code of Regulations.

1.1.3 California's Title 22 Regulations for Reuse

Title 22 defines categories of reclaimed water through designated effluent criteria for total coliform bacteria and turbidity (CDPH, 2009). Title 22 relies on medium or membrane filtration to condition the water for effective disinfection. Filtration performance is monitored by using turbidity, whereas the disinfection performance is monitored by using total coliform bacterial concentration in the disinfected effluent. Treatment requirements deemed necessary to meet the

most stringent disinfected tertiary recycling criteria include medium or membrane filtration to reduce turbidity to less than 2 or 0.2 NTU, respectively, followed by chlorine disinfection to ensure a minimum CT of 450 mg-min/L at all times. This treatment scheme is expected to achieve a 5-log reduction of virus. If an alternative disinfectant is to be used, then a 5-log inactivation/removal of virus should be demonstrated by using the disinfection process when combined with the filtration process.

The goal of the most stringent disinfected tertiary recycling criteria, shown in Table 1.2, is the production of essentially enteric-virus-free water for applications with unrestricted access. Although there have not been sufficient data generated to demonstrate virus-free water from a risk-based analysis, the criteria in Table 1.2 rely on the findings of the Pomona Virus Study (Sanitation Districts of Los Angeles County, 1977). This study demonstrated through pilot evaluations of media filtration systems that the Title 22-required treatment, when performed to successfully meet the required turbidity and total coliform bacteria effluent criteria, also reduced the concentration of seeded poliovirus by 5 logs. The work helped establish the chlorine disinfection standard at a CT of 450 mg-min/L with a modal contact time of not less than 90 min on the basis of peak dry weather flow. When the hydraulics in the chlorine contact basins allow for a perfect plug flow, then the t_{10} is similar to the modal contact time. UV light irradiation is also allowed if the process can be demonstrated to comply with the stipulations of the Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse (NWRI/AWWARF, 2003).

Table 1.2. California Recycling Criteria

Total Coliform Criteria (MPN/100 mL)	Turbidity Criteria (NTU)
<2.2 for median of 7 days of consecutive samples; 23 allowed once in any 30-day period.	≤2 for daily average; AND ≤5 for 95% of the time in a 24-h period; AND ≤10 at any time for granular media filtration OR ≤ 0.2 more than 95% of time in a 24-h period AND ≤0.5 NTU at any time for membrane filtration

1.1.4 Modification of Disinfectant Requirements for Satellite Facilities

California's Title 22 regulations specify different filtrate turbidity requirements for medium and membrane filters, but the chlorine disinfection requirements are the same for medium-filtered and membrane-filtered effluents. In addition, the regulations do not differentiate between nitrified and non-nitrified effluents. Because the presence of ammonia would result in formation of chloramines, which have a lower disinfection efficacy than does free chlorine, treatment processes that produce nitrified effluents should require either a lower chlorine dose or a shorter contact time or both.

Satellite facilities employing MBR technology use micro- or ultrafiltration membranes for solid separation and achieve a high-quality effluent that has a very low concentration of particles and pathogens, if any. Figure 1 presents the filtrate turbidity for five different MBR systems evaluated over 3500 h each, and as shown, the filtrate turbidities were below 0.2 NTU for 95% of the time (Hirani et al., 2007). Effluents with such low levels of particles would allow the downstream disinfection process to be more effective; therefore, the disinfection requirements for such effluents should be lower to achieve the same level of disinfection.

Use of membranes for solid separation also allows the MBR process to operate at a higher MLSS concentration (8000–12,000 mg/L), because the ability of sludge to settle does not impact the membrane filtration performance as it impacts clarification in conventional activated sludge processes. Operation at high MLSS concentration is typically achieved by operation at a longer SRT, which results in production of a fully nitrified effluent (Hirani et al., 2010). Operation at a higher MLSS concentration also results in a smaller bioreactor volume due to a higher volumetric loading rate. These features allow the MBR process to produce a high-quality fully nitrified effluent with a small footprint. Because ammonia is either absent or present at very low levels in MBR effluents, it allows use of free chlorine instead of chloramine as the disinfectant, and because of the higher disinfection efficacy of free chlorine, a much lower disinfectant concentration for a shorter contact time should be adequate to achieve the same level of disinfection.

Existing water reuse disinfection guidelines were established before development and implementation of these newer technologies that are currently employed at satellite installations. Understanding the manner in which new technologies improve effluent quality compared to more traditional treatment approaches is therefore important. Understanding ways to monitor this improved effluent quality in real time and the type of verification data that would be necessary in order to enable regulators to reduce subsequent disinfection requirements is also important. Implementing lower disinfection requirements that are still protective of human health is an important consideration as society minimizes the generation of potentially carcinogenic disinfection by-products, as well as cutting energy use that produces greenhouse gas emissions that contribute to climate change. Examining the presence of new or emerging pathogens in effluents of satellite facilities also is necessary, because these microorganisms were not considered when the Title 22 requirements were developed in the late 1970s. Although there was some consideration of emerging pathogens when the disinfection sections of Title 22 were revised in 2000, the current Title 22 requirements are based on total coliform bacteria and MS-2 bacteriophage. The new organisms of concern include bacteria (for example, *E. coli* O157:H7, *Listeria*, and *Heliocobacter*), viruses (for example, poliovirus, coxsackievirus, echovirus, hepatitis A virus, rotavirus, norovirus, and adenovirus), and parasites (for example, *Cryptosporidium*, *Cyclospora*, *Toxoplasma*, *Microsporidia*, and *Giardia*) (Gerba and Smith, 2005). Therefore, although first establishing new satellite disinfection standards relative to the existing standards for conventional treatment is important, so is revisiting these standards in the future as additional organisms are studied and incorporated into new risk-based standards.

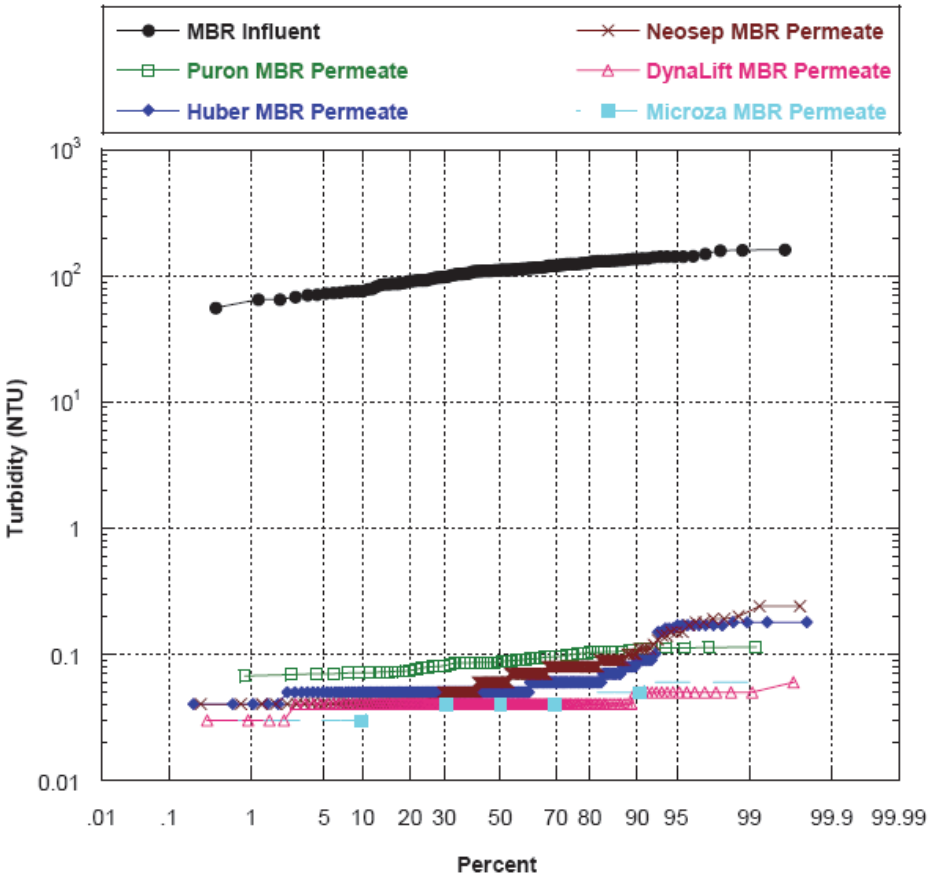


Figure 1.1. Filtrate turbidity for various MBR systems

Source: Hirani et al., 2007

The higher quality effluent from an MBR process has the potential for a considerably lower CT requirement than what is needed for conventional filtration processes. Although the superiority of membrane separation to conventional filtration has been demonstrated for lowering UV light disinfection dose requirements, sufficient data have not been generated to demonstrate lowering chlorination disinfection requirements. Such a demonstration is contingent upon defining MBR operating parameters needed to ensure adequate effluent water quality conditions that would support a lower disinfection requirement. California requires an MBR system to meet the most restrictive Title 22 requirements with respect to effluent turbidity. Although performance within these turbidity standards does not indicate the absence of pathogens or pathogen indicator organisms, it should produce an effluent quality that requires a much lower subsequent disinfectant dose and shorter contact time. Another important consideration is the consistency in the nitrification efficiency of the MBR process and resulting effluent ammonia concentration in the MBR effluent, because the passage of residual ammonia will convert free chlorine to the less effective disinfectant, chloramine.

1.2 Project Objectives

The primary goal of this study is the characterization of MBR effluent water quality requirements necessary for operation with lower disinfection requirements. In order to achieve this goal, a research study was designed to accomplish the following objectives:

- Characterize satellite MBR effluent water qualities through a reconnaissance survey of a wide range of satellite facilities.
- Assess satellite MBR effluent water quality variability at selected satellite facilities.
- Assess worst-case scenarios on satellite MBR effluent water quality.
- Develop disinfection requirements for MBR effluents produced under routine and stressed operating conditions.
- Conduct monitoring of the nitrification process consistency at a full-scale MBR water recycling facility and identify potential causes for reduction in nitrification efficiency of the biological process.

Chapter 2

Project Approach

2.1 Research Approach

The research study consisted of multiple sequential tasks to characterize satellite MBR effluents and determine subsequent disinfection requirements for these effluents (Figure 2.1). This approach consisted of the following tasks, each of which is discussed in detail in the following subsections:

- Initial screening of 38 satellite recycling facilities:
    - Characterization of effluent water qualities from satellite facilities
    - Binning of satellite facilities based on water quality performance
    - Rationale for selection of satellite facilities for detailed water quality evaluations
    - Selection of satellite facilities for detailed water quality evaluations
- Detailed water quality evaluations of nine selected satellite facilities
- Detailed water quality evaluations for samples from MBR pilot study to assess impacts of cleaned and breached membranes on effluent water quality
- Determination of CT values for effluents from systems operating under routine and stressed conditions
- Online full-scale nitrification monitoring program

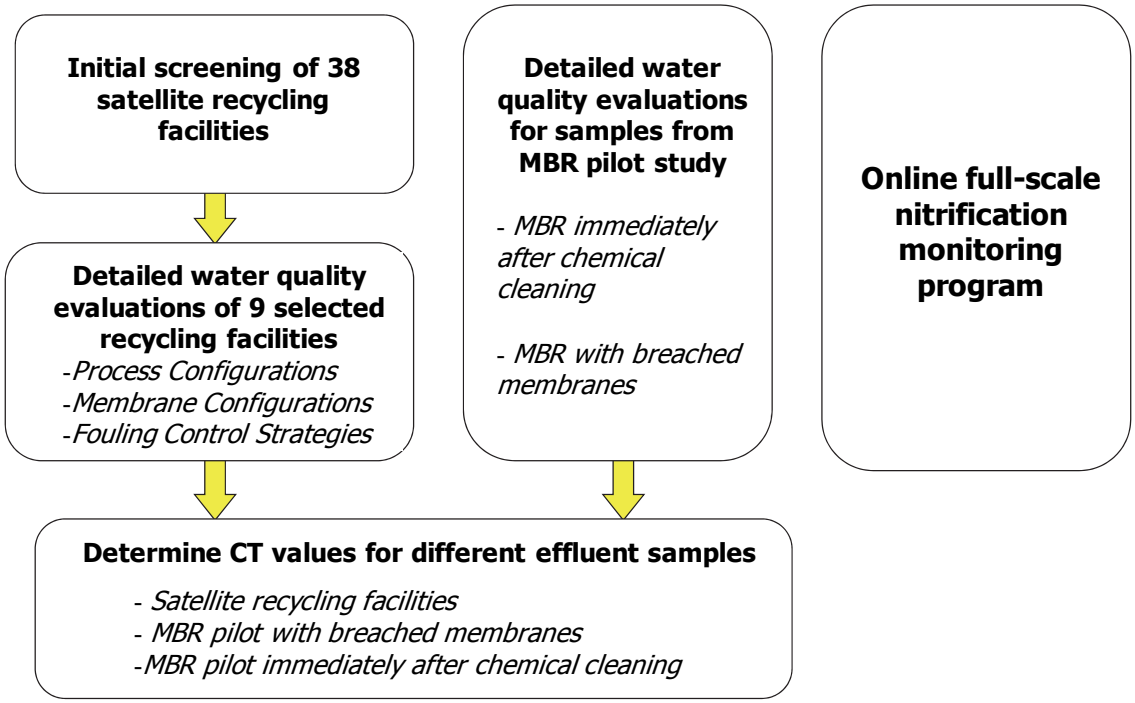


Figure 2.1. Research approach to derive the disinfectant requirements for effluents from satellite MBR facilities.

2.1.1 Characterization of Effluent Water Qualities from Satellite Facilities

The objective of this task was to characterize effluents from a wide range of satellite MBR facilities and to classify these facilities into three different bins on the basis of water quality performance. To achieve this goal, detailed survey questionnaires were sent to each satellite facility to collect necessary operational and water quality data before initiating the water quality sampling program. After acquisition of the necessary information, influent and MBR filtrate samples were collected from 38 satellite facilities. Filtrate samples were analyzed for a list of parameters described in Section 3.5, whereas influent samples were analyzed for total coliform bacteria and male-specific bacteriophage to determine removal levels of these microorganisms. Results obtained from this task provide decision makers with an effluent water quality database for a wide range of satellite MBR facilities. These results also provide an insight on typical concentrations of water quality parameters that can impact disinfection of MBR effluents.

2.1.2 Binning of Satellite Facilities Based on Water Quality Performance

The effluent water quality data obtained from the reconnaissance survey of the 38 satellite facilities were used to segregate the satellite facilities into one of three different bins. The objective of the binning process was to facilitate selection of nine satellite facilities for additional detailed water quality evaluations and also to allow selection of three satellite facilities (one from each bin) for disinfection studies. The process for selection of satellite facilities for detailed water quality evaluations is demonstrated in Figure 2.2 and described in detail below.

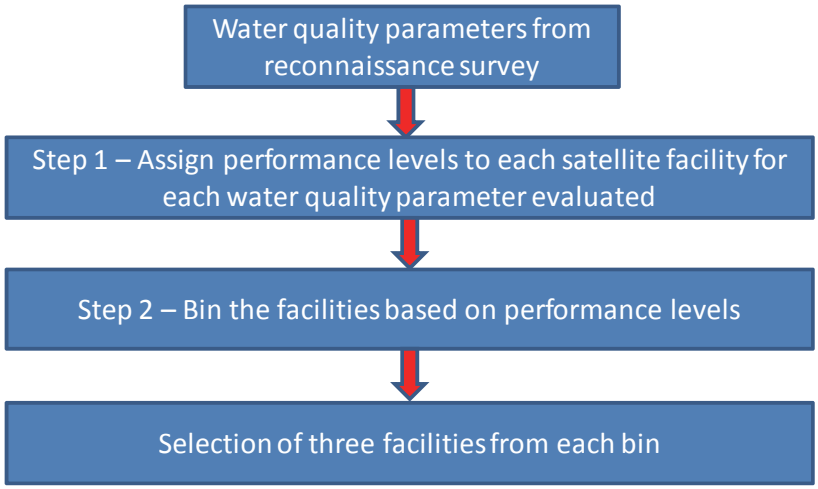


Figure 2.2. Process for selection of satellite facilities for detailed water quality sampling.

Step 1—Assign performance level to each satellite facility for each water quality parameter evaluated.

Level 1: <=50th percentile concentration among facilities sampled

Level 2: >50th to 90th percentile concentration among facilities sampled

Level 3: >90th percentile concentration among facilities sampled

Once the performance levels were assigned to individual water quality parameters by using Step 1, the satellite facilities were binned as listed in Step 2.

Step 2—Bin the facilities on the basis of performance levels

On the basis of average performance levels observed for the six parameters—TOC, ammonia, turbidity, total coliform bacteria, UV absorbance at 254 nm (UV-254), and total particle counts:

Bin A—Average of performance levels is <= 33rd percentile value

Bin B—Average of performance levels is > 33rd and up to 66th percentile value

Bin C—Average of performance levels is > 66th percentile value

Binning results were then used for selection of facilities for detailed water quality evaluations.

2.1.3 Rationale for Selection of Satellite Facilities for Detailed Water Quality Evaluations

Results obtained from the binning process allowed segregation of satellite facilities based on different levels of water quality performance. Because the satellite MBR facilities use different process configurations and membrane systems, ensuring that those selected for detailed water quality evaluations not only represent a wide range of water quality performance but also utilize different process configurations and membrane systems is critical. Three satellite facilities were selected from each performance bin to represent facilities that employed

- Different process configurations (submerged or external)
- Membrane geometries (hollow-fiber, flat-sheet, or tubular)
- Fouling control strategies (relaxation or backwash)

In addition, the selected facilities were situated in different geographical areas, represented a wide range of flow rates, and utilized membranes with different ages.

2.1.4 Detailed Water Quality Evaluations of Selected Satellite Facilities

The objective of the detailed water quality evaluations was to assess the filtrate water qualities produced from satellite facilities with respect to a broad range of water quality parameters as well as to assess the variability in water qualities during multiple sampling events. Because the reconnaissance survey was conducted by using a single grab sampling event for each facility, the detailed water quality evaluation consisted of three sampling events spread over 3 months. These samples were also analyzed for additional microbial parameters such as *Cryptosporidium*, *Giardia*, and a range of viruses (hepatitis A virus, adenovirus, rotavirus, and enterovirus) to provide insight on the presence of these organisms in the MBR filtrates. Such water quality data would help identify potential challenges not only for chlorine disinfection but also for UV disinfection, because both disinfectants are utilized at satellite facilities. Assessment of the water quality data obtained during the detailed water evaluations is presented in Section 3.5. Data obtained from the evaluations helped to assess the consistency in effluent water qualities produced by these facilities.

2.1.5 Assessment of Impact of Cleaned and Breached Membranes on Effluent Water Quality

The objective of this task was to assess the impact of membrane integrity loss on effluent water quality and subsequent disinfection requirements. Because of regulatory requirements, it was not feasible to intentionally engineer membrane failure at a full-scale water recycling facility. Thus, two different pilot systems were utilized during the study period, and membrane cleaning and breaching events were conducted.

2.1.5.1 Assessing the Impact of Cleaned Membranes

Periodic chemical cleanings were conducted on the pilot MBR systems to remove organic foulants and to recover membrane permeability. Organic foulants responsible for pore blocking and cake layer formation on the membrane surface reduce the effective pore size of the membrane. Chemical cleaning to remove these foulants from the membrane pores and surfaces also reduces the effectiveness of the MBR process in rejecting microbial contaminants. Therefore, the objective of this task was to (a) assess the impact of chemical cleaning on microbial rejection by the MBR process and (b) determine the subsequent impact on disinfection efficacy. MBR influent and effluent samples were collected immediately before and after chemical cleaning. Samples spanning the entire filtration cycle were collected over two consecutive filtration cycles to determine the log removal of coliform bacteria and indigenous male-specific bacteriophage. Details on the water quality parameters assessed during this task are presented in Section 3.5. Data obtained from this task determined whether membrane cleaning had any impact on effluent water quality with respect to passage of microbial indicators and how such changes in water quality impacted the subsequent disinfection capability.

2.1.5.2 Assessing the Impact of Breached Membranes

Passage of particles through the membrane can occur because of membrane breach. This loss of integrity can result in a spike in both effluent turbidity and microorganisms in the MBR filtrate. Typically, the effluent turbidity increases immediately after relaxation or backwash and gradually shrinks to a previously observed value once the membrane plugs with activated sludge after a few minutes of filtration. This phenomenon occurs during each filtration cycle. Therefore, the objective of this task was to assess the impact of membrane breach on microbial rejection by the MBR process and subsequent disinfection efficacy. A membrane plate of a flat-sheet pilot MBR system was slit by using a knife to create a membrane breach (3 cm long and 2–4 mm wide). Because MBR installations are required by the CDPH to maintain a filtrate turbidity of <0.5 NTU at all times (but typically operate at <0.1 NTU), a membrane sheet in a pilot system was intentionally compromised to an extent that filtrate turbidity exceeded 0.5 NTU. Samples spanning the entire filtration cycle were collected over two consecutive filtration cycles to determine the log removal of coliform bacteria and indigenous male-specific bacteriophage. Details on the water quality parameters assessed during this task are presented in Section 3.5. Data obtained from this task can help in determining the impact of membrane breach on effluent water quality with respect to passage of particles and microbial indicators and subsequent disinfection efficacy.

2.1.6 Determination of CT Values for Effluents from Systems Operating Under Routine and Stressed Conditions

The objective of this task was to determine the chlorine disinfection requirements for effluents from MBR systems operating under routine and stressed conditions. Water samples were collected from three different satellite facilities and a pilot system. Three filtrate samples were collected from each satellite facility during separate sampling events and disinfection studies were conducted on each of these effluents to account for variability in effluent water quality and its impact on subsequent disinfection requirements.

The three satellite facilities sampled for the disinfection studies produced water qualities that were moderate to poor on the basis of the results obtained from the binning process. Conducting CT studies on these effluents provided a better understanding of the impact of water quality on disinfectant efficacy for worse-performing facilities operating under routine conditions that still met the water quality goals established for their reuse applications.

Disinfection studies were also conducted on effluents from a pilot MBR system after chemical cleaning and after membrane breach. Such studies simulated poorer-water-quality scenarios for disinfection under stressed operating conditions because the concentrations of pathogens and particles were much higher under these scenarios than what would be expected from an MBR facility operating under routine conditions.

2.1.7 Online Effluent Ammonia Monitoring at a Water Recycling Facility

The presence of ammonia in effluents from satellite facilities can result in formation of chloramines, which have lower disinfection efficacy than does free chlorine. If free chlorine is to be utilized for disinfection of satellite facilities, ensuring that effluent ammonia concentrations are consistently low is critical. Operation at longer SRTs allows satellite MBR facilities to produce effluents with very low ammonia concentrations (<0.5 mg of N/L). Although daily or weekly effluent grab samples can be used to measure nitrification efficiency of the satellite facilities, they provide only a small window into data variability. Increasing the monitoring frequency (for example, 30 min, 1 h, etc.) using online instrumentation can be useful to better understand the variability in effluent ammonia concentrations.

Factors that can potentially impact the effluent ammonia concentration include diurnal changes in influent ammonia concentration, dissolved oxygen concentration in the reactor basins during the peak ammonia loading conditions, operational issues with the dissolved-oxygen sensors, and corresponding response from the process air blowers, etc.

The objective of this task was to assess the consistency in effluent ammonia concentration at an MBR facility by continuously monitoring the effluent ammonia concentration. An online ammonia analyzer was installed at a water recycling facility in California, details of which are provided in Section 3.4. Ammonia concentrations in the MBR filtrate were measured and recorded every 30 min. In addition, dissolved oxygen concentrations in the aerobic reactor basins were also measured and recorded to trouble-shoot any potential spikes in the effluent ammonia concentration. Data obtained from this task showed the consistency in nitrification efficiency of MBR facilities, which could provide additional assurance in potentially lowering the disinfection requirements for satellite MBR facilities. They also provided a better understanding of the impact of operating conditions, upsets in bioreactor basins, and operational issues on effluent ammonia.

2.2 Development of a White Paper on Disinfection Guidelines

The objective of developing a white paper on disinfection guidelines was to summarize the findings of the study in a document that could serve as a starting point for regulators to consider lowering the disinfection requirements for MBR effluents. The key components of the white paper include the findings from the characterization of the effluents from the satellite facilities, the proposed CT values based on the results from the disinfection studies, the process and effluent water quality monitoring requirements needed for implementation of lower CT values, and further research needs identified from the key project findings.

Chapter 3

Materials and Methods

3.1 Participating Satellite Water Recycling Facilities

To characterize the effluent water qualities of satellite water recycling facilities, 38 satellite MBR facilities were sampled during the study period. The capacity of these satellite facilities ranged from 0.001 to 1.8 million gallons per day (MGD), and effluents from these facilities were used for various reuse applications such as irrigation, aquifer recharge, toilet flushing, cooling tower use, groundwater recharge, and industrial applications. Table 3.1 presents a list of the satellite facilities that were sampled during the study; the facilities were spread across six different states and three different USEPA regions.

Table 3.1. List of Satellite Water Recycling Facilities Participating in the Study

No.	Plant Identifier	State	Design Capacity (gpd)	Avg. Flow Reported (gpd)	Max. Flow Reported (gpd)	Reuse Application
1	MA-01	MA	84,000	NA	NA	Toilet flushing, aquifer recharge
2	MA-02	MA	16,000	10,500	15,500	Toilet flushing, aquifer recharge
3	MA-03	MA	11,000	NA	NA	Aquifer recharge
4	CT-01	CT	20,000	10,205	19,500	Toilet flushing, aquifer recharge
5	MA-04	MA	250,000	NA	NA	Toilet flushing, cooling water
6	CT-02	CT	18,000	7250	8400	Aquifer recharge
7	CT-03	CT	12,000	3920	16,500	Aquifer recharge
8	RI-01	RI	85,000	NA	NA	Irrigation, aquifer recharge
9	NJ-01	NJ	22,000	12,010	26,000	Aquifer recharge
10	NJ-02	NJ	16,000	7600	10,000	Aquifer recharge
11	NJ-03	NJ	70,000	NA	NA	Aquifer recharge
12	NJ-04	NJ	7000	4450	18,520	Aquifer recharge
13	NJ-05	NJ	29,000	2560	8360	Aquifer recharge
14	NJ-06	NJ	18,000	3580	12,480	Aquifer recharge
15	NJ-07	NJ	18,000	8000	18,420	Aquifer recharge
16	NJ-08	NJ	2000	2400	2460	Aquifer recharge
17	NJ-09	NJ	2000	4000	8640	Aquifer recharge
18	NJ-10	NJ	244,000	158,490	235,200	Aquifer recharge
19	NJ-11	NJ	13,000	71,670	106,010	Aquifer recharge
20	NJ-12	NJ	50,000	29,600	45,520	Aquifer recharge
21	NJ-13	NJ	140,000	18,000	140,000	Aquifer recharge
22	NJ-14	NJ	324,000	220,000	324,000	Aquifer recharge
23	NJ-15	NJ	NA	NA	NA	Aquifer recharge

No.	Plant Identifier	State	Design Capacity (gpd)	Avg. Flow Reported (gpd)	Max. Flow Reported (gpd)	Reuse Application
24	NJ-16	NJ	NA	NA	NA	NA
25	NJ-17	NJ	3000	NA	NA	Direct reuse, aquifer recharge
26	NJ-18	NJ	3000	NA	NA	Direct reuse, aquifer recharge
27	NJ-19	NJ	2000	NA	NA	Direct reuse, aquifer recharge
28	NJ-20	NJ	1000	NA	NA	Aquifer recharge
29	NJ-21	NJ	3000	NA	NA	Direct reuse, aquifer recharge
30	NJ-22	NJ	2000	1000	2000	Direct reuse, aquifer recharge
31	NJ-23	NJ	2000	200	2000	Direct reuse, aquifer recharge
32	NJ-24	NJ	2000	500	700	Aquifer recharge
33	CA-01	CA	1,800,000	1,100,000	1,800,000	Irrigation, aquifer recharge, Industrial applications
34	NY-01	NY	NA	35,000	50,000	NA
35	NY-02	NY	29,000	8000	15,000	Toilet flushing, irrigation, cooling water
36	NY-03	NY	4000	NA	NA	Direct reuse, aquifer recharge
37	NY-04	NY	14,000	10,000	18,000	Toilet flushing, irrigation, cooling water
38	NY-05	NY	25,000	22,000	35,000	Toilet flushing, irrigation, cooling water

Note. NA = information not available.

Table 3.2 summarizes the available influent wastewater quality for the satellite facilities. As shown, the BOD_5 concentration among these facilities varied from 127 to 294 mg/L, representing a wide range of municipal wastewater strength. The total Kjeldahl nitrogen (TKN) concentration for these facilities varied from 31 to 103 mg of N/L, whereas the TSS concentration varied from 57 to 234 mg/L. These facilities also utilized different process configurations and membrane geometries.

Table 3.2. Influent Wastewater Quality for Satellite Water Recycling Facilities

Parameter (*n*)	Units	Median	Min.	Max.
Ammonia-N (2)	mg of N/L	26	25	27
TKN (12)	mg of N/L	44	31	103
COD (1)	mg/L	700	700	700
BOD (13)	mg/L	162	127	294
TSS (13)	mg/L	179	57	234

3.2 Pilot MBR Systems Utilized for Membrane Cleaning and Breaching Studies

Two different MBR pilot systems were used during the study to determine the impact of stressed conditions on membrane performance with respect to effluent water quality and subsequent disinfection requirements. Pilot systems were used to simulate membrane cleaning and breaching events because it was not feasible to conduct membrane breach experiments in a full-scale satellite facility.

3.2.1 Pilot Testing Site

The pilot testing for this project was conducted at the Inland Empire Utilities Agency (IEUA)'s Reclamation Plant #5 (RP#5) in Chino, California. The treatment process at RP#5 is a conventional activated sludge process that includes influent screening, grit removal, primary clarification, nitrification/denitrification, secondary clarification, and media filtration. Primary effluent, after being screened by a 0.75 mm-pore-size rotary-drum screen (Waste-Tech, Inc.), was fed to the pilot MBR systems. A process flow diagram of RP#5 showing the major unit processes appears in Figure 3.1.

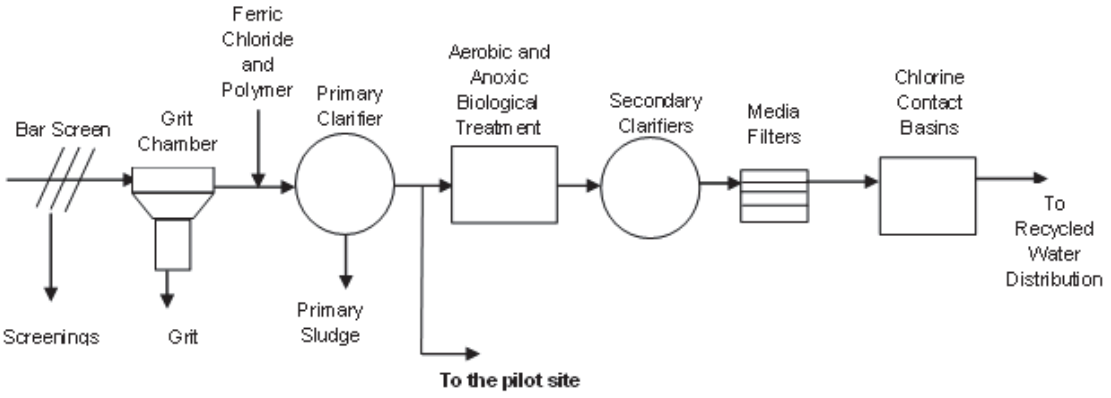


Figure 3.1. Process flow diagram of the IEUA RP#5.

3.2.2 Influent Wastewater Quality for Pilot Systems

During the study period, the MBR systems were operated on primary effluent obtained from primary effluent collector/splitter at RP#5. Influent wastewater (screened primary effluent) quality for the MBR pilot systems is presented in Table 3.3. The COD concentrations ranged from 170–330 mg/L with a median concentration of 250 mg/L, which is typical of primary effluent obtained from municipal wastewater applications. The median ammonia concentration was 37 mg of N/L and varied from 27–47 mg of N/L.

The operating parameters for the pilot systems are provided in Table 3.4. Pilot systems A and B were operated at solid retention times (SRTs) of 28 and 41 days, respectively; operation at such long SRTs ensured complete nitrification. Operating parameters for the pilot systems were typical of a full-scale MBR facility.

Table 3.3. Influent Wastewater Quality for Satellite Water Recycling Facilities

Parameter	Unit	No. of Analyses	Median	Min.	Max.
Ammonia-N	mg of N/L	27	37	27	47
COD	mg/L	25	250	170	330
BOD	mg/L	16	99	51	130
TSS	mg/L	25	52	37	85

Table 3.4. Operating Parameters for the MBR Pilot Systems

Parameter	Value	
	Pilot System A	Pilot System B
Design SRT (days)	28	41
HRT (h)	4.5	7.0
Flow rate (gpm)	4.0	5.6
Biological process configuration	Nitrification and partial denitrification	Nitrification and partial denitrification
Membrane gross flux (gfd)	21.8	15.0
Length of filtration cycle (min)	9	9
Transmembrane pressure range (psi)	1.0–3.0	0.5–3.0

3.2.3 Pilot System A

Pilot system A was designed with aerobic and anoxic zones to allow for nitrification and denitrification. The system consisted of a 219 gal (0.8 m^3) anoxic tank, 280 gal (1.1 m^3) aerobic tank, and 497 gal (1.9 m^3) membrane tank that contained one membrane module. As shown in Figure 3.2, primary effluent was screened by using a 0.75 mm pore-size fine screen and was fed to the anoxic tank. The feed pump to the pilot was regulated by a level switch in the aeration tank to maintain the desired water level. Mixed liquor from the anoxic tank overflowed to the aeration tank. Nitrified mixed liquor from the aerobic tank was pumped to the anoxic tank at a rate of two

times the net filtrate flow rate for denitrification. Mixed liquor from the aerobic tank was pumped to the membrane tank for filtration at five times the net filtrate flow rate. Mixed liquor from the membrane tank overflowed to the aeration tank at four times the net filtrate flow rate to return solids to the bioreactors. Sludge wasting was performed automatically from an internal recycle line to maintain the target MLSS concentration in the aerobic tank.

The membrane tank of pilot system A was equipped with one membrane module (with one membrane cassette). The membrane cassette held 18 membrane sheets with a total membrane area of 269 ft^2 (25 m^2) per module. The membrane module used a polyvinylidene fluoride (PVDF) flat-sheet membrane with a nominal pore size of 0.1 μm. Figure 3.3 shows a photograph of MBR pilot system A, whereas Figure 3.4 shows a photograph of the membrane module.

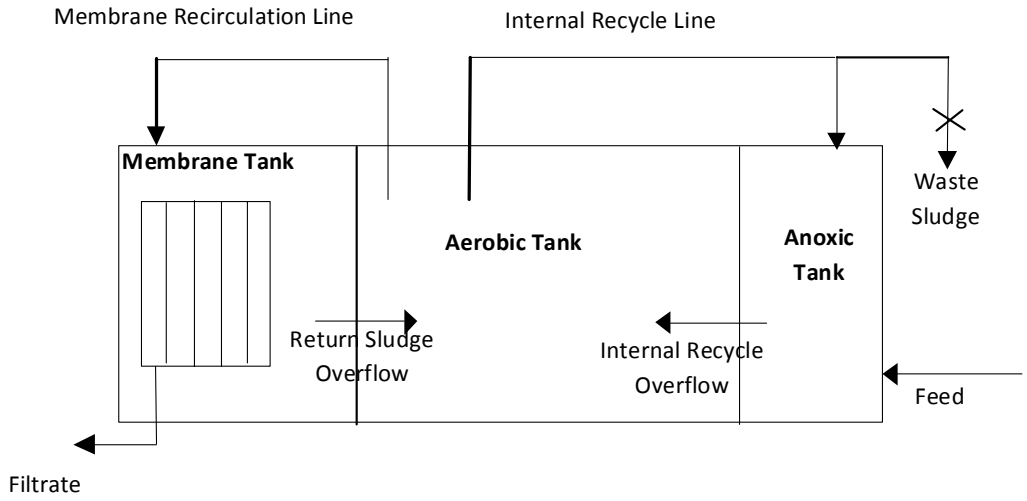


Figure 3.2. Process schematic of MBR Pilot System A.

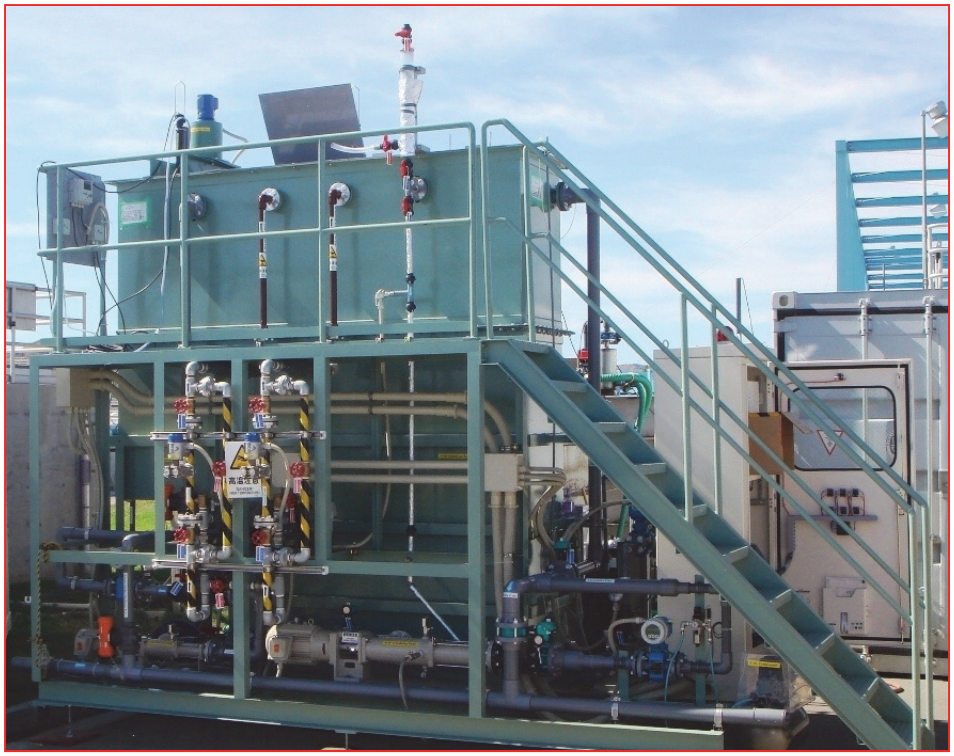


Figure 3.3. Photograph of MBR Pilot System A.

Figure 3.4. Photograph of the Pilot System A membrane module.

3.2.4 Pilot System B

Pilot system B was designed with aerobic and anoxic zones to allow for nitrification and denitrification. The pilot system consisted of a 396 gal (1.5 m^3) anoxic tank, 1200 gal (4.5 m^3) aerobic tank, and 370 gal (1.4 m^3) membrane tank that contained one membrane module. The process schematic of the pilot system is shown in Figure 3.5. As shown, primary effluent was screened by using a 0.75 mm pore-size fine screen and was fed to the anoxic tank. A feed pump to the pilot system was regulated by a level switch in the anoxic tank to maintain the desired water level. Mixed liquor from the anoxic tank was pumped to the aerobic tank at a rate of three times the filtrate flow rate to provide internal recycle flow between the aerobic and anoxic tanks for denitrification. Nitrified mixed liquor from the aerobic tank overflowed back to the anoxic tank through a weir for denitrification. Mixed liquor from the aerobic tank was pumped to the membrane tank for filtration at five times the filtrate flow rate as well as to return solids from the membrane tank to the bioreactors. Sludge wasting was done automatically from an aerobic to membrane recirculation line to maintain the target MLSS in the aerobic tank.

The membrane tank of pilot system B was equipped with one membrane module, which consisted of two cassettes. Each of the membrane cassettes held 25 membrane sheets with a total membrane area of 540 ft^2 (50 m^2) per module. The membrane module used a polyethersulfone (PES) flat-sheet ultrafiltration membrane with a nominal pore size of 0.04 µm. Figure 3.6 shows a photograph of the pilot, whereas Figure 3.7 shows a photograph of the membrane module.

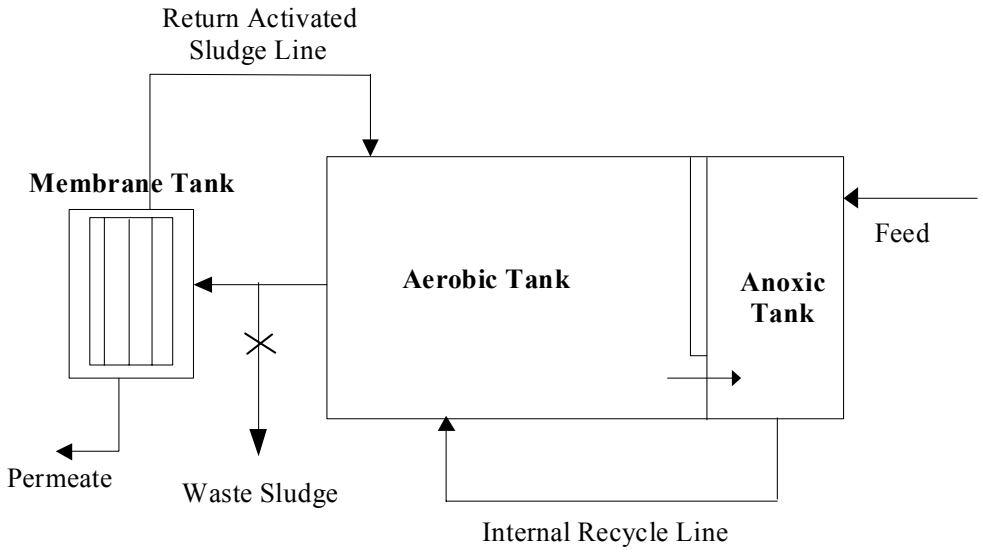


Figure 3.5. Process schematic of MBR Pilot System B.

Figure 3.6. Photograph of MBR Pilot System B.

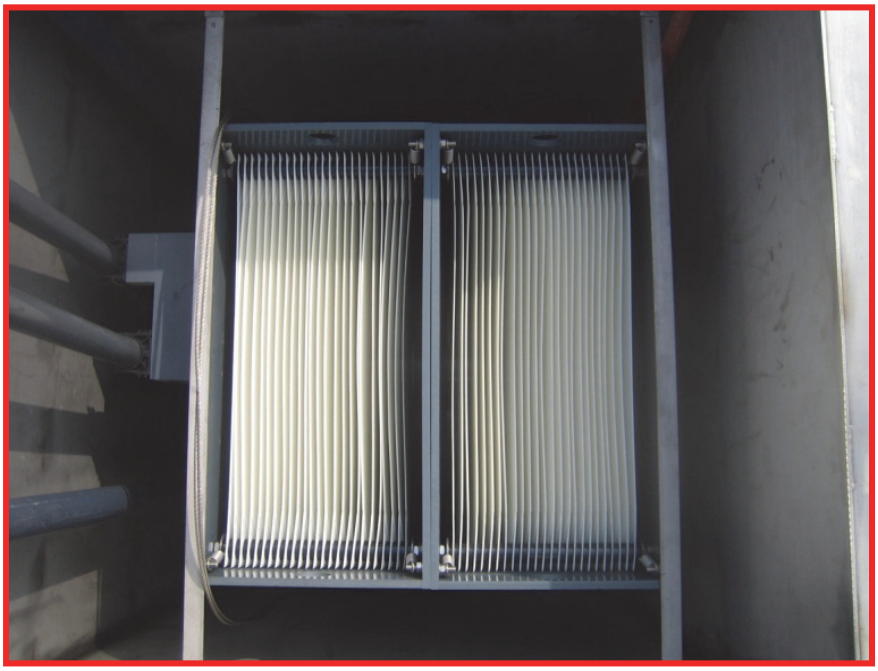


Figure 3.7. Photograph (top view) of the Pilot System B membrane module.

3.3 Bench-Scale Apparatus for Microbial Inactivation Studies

The bench-scale disinfection studies were conducted on filtrate samples collected from the satellite facilities as well as the MBR pilot systems. Three samples were collected at different times from each satellite facility to conduct the disinfection studies. Upon receipt of samples, water quality parameters such as turbidity, ammonia, and temperature were measured and recorded. A chlorine demand study was then conducted on each sample. Chlorine control experiments were conducted to assure that no chlorine decay occurred over the period when the target chlorine dose was added to the deionized (DI) water. Male-specific bacteriophage control experiments were conducted to monitor the decay in male-specific bacteriophage over time. Figure 3.8 presents the schematic for the protocol utilized for the bench-scale disinfection studies, details of which are discussed in the following.

3.3.1 Chlorine Demand Study on the Filtrate Samples

A chlorine demand study was conducted on each filtrate sample before beginning the disinfection studies by using a 1 L aliquot of the 7 L filtrate sample collected from each MBR system. The ammonia concentration in the filtrate sample was measured and recorded by using the Nessler Method (USEPA Method 380). A chlorine stock solution containing approximately 500 mg of free chlorine/L was prepared from a sodium hypochlorite solution (containing 5% chlorine) and stored in an amber bottle. A single 200 mL aliquot of the sample to be tested was poured into a clean glass bottle. An appropriate volume of chlorine stock solution was then added to the bottle containing the sample to achieve the target free chlorine concentration of 11 mg/L in the sample bottle. At 0, 1, 3, 5, 8, and 10 min after addition of stock solution to the sample, the free and total chlorine concentrations in the prepared samples were measured by using a spectrophotometer (USEPA Method 80). Free and total chlorine concentrations were plotted with respect to time to determine the chlorine demand from the rate of decay of free and total chlorine concentrations.

3.3.2 Male-Specific Bacteriophage Control on the Filtrate Samples

The objective of this experiment was to determine if the male-specific bacteriophage concentration remained constant over the test period. The baseline concentrations of coliform bacteria and male-specific bacteriophage in the filtrate sample were measured. The filtrate samples were seeded by using a concentrated stock suspension of male-specific bacteriophage to achieve a concentration of approximately 10^8 PFU/100 mL. Filtrate samples were collected immediately after seeding and at the longest contact time for the experiment; samples were then analyzed for male-specific bacteriophage.

3.3.3 Chlorine Control using DI Water and Target Chlorine Doses

The objective of this experiment was to determine the decay in the chlorine concentration when the chlorine stock solution was added to DI water. The chlorine control test was performed for each target chlorine dose. The chlorine stock solution was added to two different samples of DI water to achieve a target chlorine concentration of 3 and 5 mg/L, respectively, in these samples. Each sample was analyzed for free and total chlorine at 0, 1, 3, 5, and 10 min after addition of the chlorine stock solution to determine any decay in the chlorine concentration.

3.3.4 Microbial Inactivation Studies on the Filtrate Samples

The objective of the microbial inactivation studies was to determine the free chlorine residual−response curve for inactivation of total coliform bacteria and male-specific bacteriophage. A 7 L MBR filtrate sample was collected for each stream. The sample was analyzed for ammonia, turbidity, temperature, total coliform bacteria, and male-specific bacteriophage. A 6 L volume of the filtrate sample was seeded with male-specific bacteriophage stock to achieve a target concentration of 10^8 PFU/100 mL. The filtrate sample was split into six 1 L containers. Chlorine stock solution was added to three of the 1 L containers simultaneously to achieve the target chlorine dose. The remaining three 1 L bottles were used for different contact times and/or a different dose. Free and total chlorine concentrations in each of the 1 L containers were measured at a target contact time for that particular container. Immediately after collection of the sample, residual chlorine in the 1 L container was quenched with sodium thiosulfate. Samples were analyzed for male-specific bacteriophage and total coliform bacteria. These steps were repeated for all six CT samples.

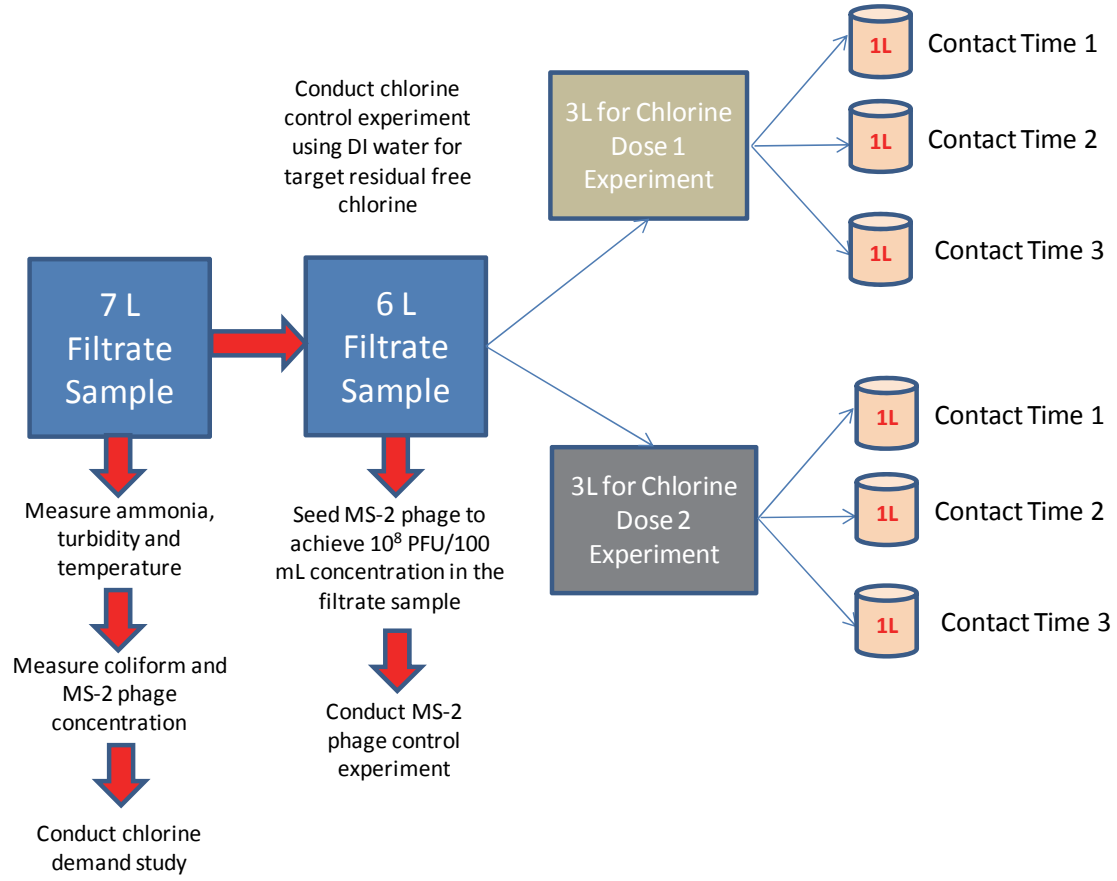


Figure 3.8. Protocol for the bench-scale disinfection studies.

3.4 Online Ammonia Analyzer

An online ammonia analyzer from Endress+Hauser was utilized to monitor the MBR effluent ammonia concentration at a water recycling facility in California. The specifications of the analyzer are shown in Table 3.5. The StamoLys CA 71 AM ammonia analyzer is a photometric analysis system that is designed for almost continuous monitoring of the ammonia content in

wastewater. Figure 3.9 shows the location of the analyzer installed at the water recycling facility, whereas Figure 3.10 shows photographs of the analyzer.

Table 3.5. Specifications of the Online Ammonia Analyzer

Parameter	Value
Product name	StamoLys CA 71 AM
Name of the manufacturer	Endress+Hauser
Measuring range	0.02–5.0 mg of N/L
Wavelength	660 nm
Sample requirement	15 mL/measurement
Measuring interval	2–120 min
Ambient temp	5–40 ºC
Sample flow rate	Min 5 mL/min
Sample solid content	<50 mg/L

Figure 3.9. Online ammonia analyzer installed at the CA-01 facility.

Figure 3.10. Photographs of the online ammonia analyzer installed at the CA-01 facility.

3.5 Sampling Protocols and Water Quality Analysis

Water quality sampling for the study consisted of filtrate samples collected from the satellite water recycling facilities and the pilot MBR systems as well as samples collected during the bench-scale disinfection studies. Samples collected during the study were analyzed for the different sets of parameters listed in Table 3.6. Filtrate samples from the reconnaissance survey of 38 satellite facilities were analyzed for the parameters listed in Set B. Filtrate samples for the detailed water quality evaluations of the selected nine satellite facilities and pilot systems were analyzed for the parameters listed in Set A. Influent samples collected from the satellite facilities and pilot systems were analyzed for the parameters listed in Set C. Filtrate samples from the bench-scale disinfection studies were also analyzed for the parameters listed in Set C.

Table 3.6. Water Quality Parameters Analyzed During the Study

Set A	Set B	Set C
Total coliform bacteria	Total coliform bacteria	Total coliform bacteria
Male-specific bacteriophage	Male-specific bacteriophage	Male-specific bacteriophage
TOC	TOC	
Ammonia-N	Ammonia-N	
Turbidity	Turbidity	
Particle counts	Particle counts	
Enterovirus		
Rotavirus		
Hepatitis A virus		
Adenovirus		
Cryptosporidium/*Giardia*		
UV-254		

Table 3.7 shows the laboratory analytical methods and corresponding method detection limits for each water quality parameter analyzed during the study. Analysis for TOC, ammonia, turbidity, particle counts, and UV-254 was conducted at the American Water (AW) laboratories, whereas microbial analysis was conducted at the AW, MWH, and BioVir laboratories. Details on the laboratory methods used for analysis of *Giardia*, *Cryptosporidium*, and viruses are attached in Appendix B.

Table 3.7. Analytical Methods/Instruments Used for Water Quality Parameters

Water Quality Parameter	Analytical Method/Instrument	Detection Limit
Total coliform bacteria	Standard Method 9222B	1 per 100 mL
Male-specific bacteriophage	USEPA Method 1602	1 per 100 mL
TOC	Standard Method 5310B	0.001 mg/L
Ammonia-N	Method 380 and Method 8155	0.02 mg of N/L
Turbidity	Hach 2100N Turbidimeter	0.001 NTU
Particle counts	Met One WGS-267 Particle Counter	> 2 μm particles
Viruses (rotavirus, hepatitis A virus, adenovirus, enterovirus)	PCR and RT-PCR	10^3 per 25 μl reaction
Cryptosporidium/*Giardia*	USEPA Method 1623	1 per 10 L
UV-254	Hach DR 5000 UV-Vis Spectrophotometer	0.001 cm^{-1}

The following section provides a general description of the quality assurance/quality control (QA/QC) procedures employed during the study: Sampling QA/QC and laboratory QA/QC.

To ensure data accuracy, a QA/QC protocol was implemented for the sampling program. Before collection of effluent samples, sampling lines and ports were flushed for a few seconds to ensure that the samples collected represented water quality produced by the recycling facilities and minimized the possibility of including biological regrowth from the stationary sampling lines. For systems employing backwash as a fouling control strategy, contamination in the backwash tank of effluent samples from MBR facilities was avoided, whenever possible, by disinfecting the filtrate piping and by collecting the samples during the middle of the filtration cycle.

Appropriate chain-of-custody labels accompanied all samples and sample isolates. Sample sites were identified using facility identifiers/codes. All samples were stored with ice and refrigerated until processed. Samples were always transported to the local laboratory within 6 h after collection or were shipped via overnight delivery to outside laboratories.

Standard laboratory practices for positive and negative controls, sterility checks, and daily recording of incubator, refrigerator, and freezer temperatures, technician performance, laboratory pure water quality, and reagent purity were followed as outlined in the 21st edition of *Standard Methods* (Eaton et al., 2005), the USEPA manual *Handbook for Certification of Bacteriological Laboratories*, or the ASTM procedure. Positive and negative controls were utilized to ensure the precision of laboratory analyses. Complete enumeration of all reactions was noted and recorded. Completeness of the experimental protocols was addressed by including all relevant parameters. Comparability of the data was determined by the intralaboratory evaluation of the procedures.

All QA/QC procedures were documented and recorded in laboratory notebooks. All data were collected and stored electronically, with backup copies made routinely. All hard copies of original sample sheets were stored in each laboratory as a reference. The central AW laboratory at Belleville, IL, is NELAP certified and USEPA certified for *Giardia* and *Cryptosporidium* monitoring. MWH Laboratories and BioVir Laboratories are also NELAP certified.

Chapter 4

Effluent Water Qualities Produced from 38 Satellite Facilities

4.1 Introduction and Objective

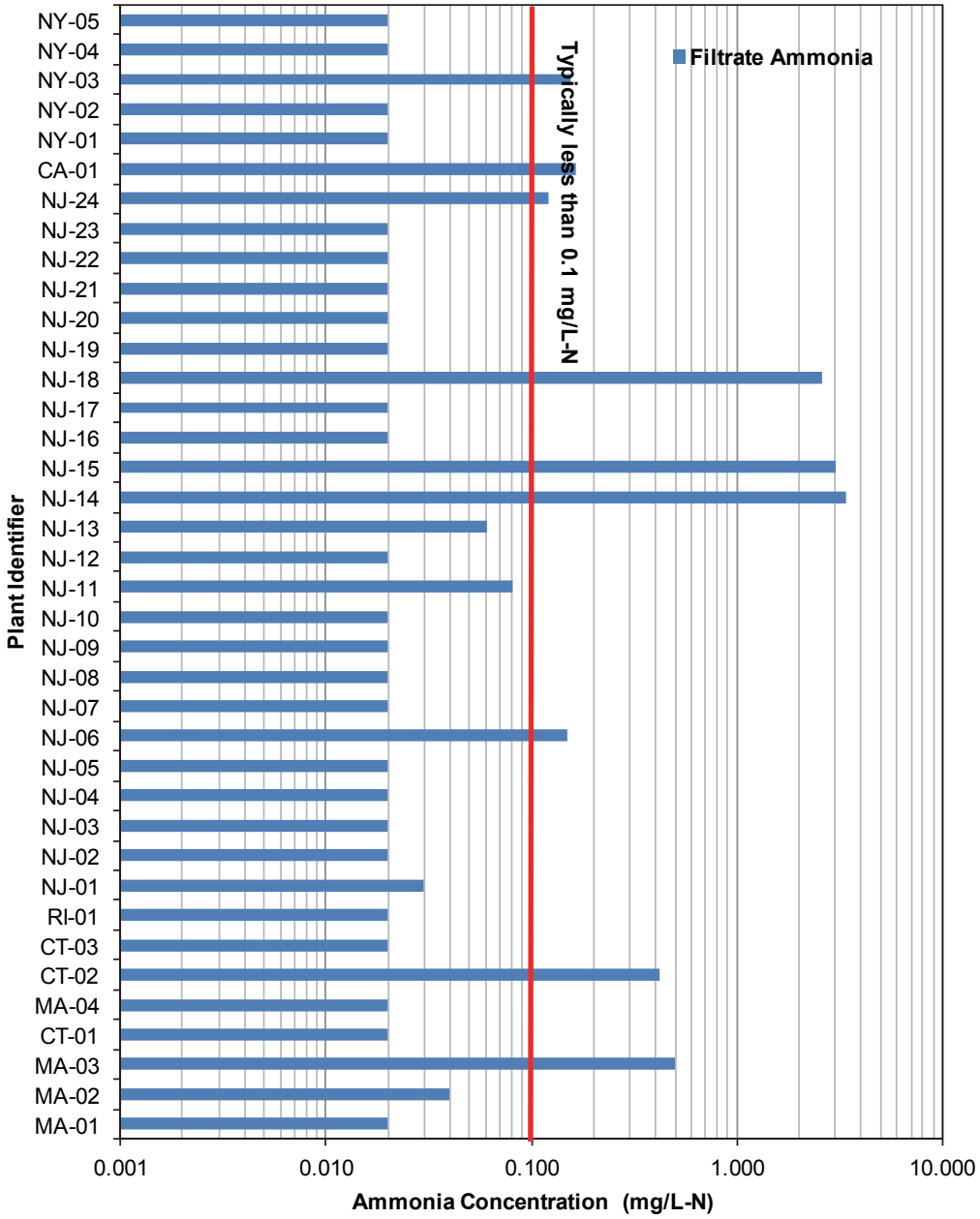
Satellite MBR facilities are expected to produce high-quality effluent with respect to organics, ammonia, particles, and microorganisms because of their operation, a longer SRT, and their use of membranes for solid separation. Although production of high-quality effluent is anticipated from these facilities, operational issues related to the bioreactors and membranes can lead to differences in the quality of water produced by these facilities. Therefore, the objective of the reconnaissance survey was to characterize the effluents from a wide range of satellite MBR facilities. Effluent water quality data obtained from the reconnaissance survey were used for binning the satellite facilities on the basis of water quality performance.

Grab samples collected from the 38 satellite facilities were analyzed for TOC, ammonia, turbidity, UV-254, particle counts, total coliform bacteria, and male-specific bacteriophage. The satellite facilities are referenced by using plant identifiers that consist of an abbreviation for the state followed by a number. Effluent water qualities observed for the satellite facilities sampled during the study are discussed in the following sections.

4.2 Inorganic Parameter (Ammonia)

The effluent ammonia concentrations for the satellite facilities are presented in Figure 4.1. As shown, the ammonia concentrations varied from 0.01 (method detection limit) to 3.4 mg of N/L. Typically, MBR systems are designed to operate at a high MLSS concentration to take advantage of a smaller footprint; this is usually achieved by designing the systems at long SRTs (typically longer than 12 days). Operation at a long SRT typically results in complete nitrification and subsequently very low effluent ammonia concentrations, as observed for most of these facilities. Ninety percent of the facilities sampled produced effluents with ammonia concentrations below 0.44 mg of N/L, and the median concentration was reported at the method detection limit (Figure 4.2). Although the majority of the facilities produced fully nitrified effluents, MBR facilities NJ-14, NJ-15, and NJ-18 reported effluent ammonia concentrations of 3.4, 3.0, and 2.6 mg of N/L, respectively. NJ-14 and NJ-15 facilities utilize UV light for disinfection so the presence of ammonia did not impact the downstream disinfection process at these facilities. Also, NJ-15 does not have a discharge limit for ammonia, although it is required to meet a total nitrogen limit.

Effluent ammonia concentration of <0.5 mg of N/L and > 97% removal of ammonia have been reported in many MBR studies (Adham and DeCarolis, 2004; Hirani et al., 2007; Innocenti et al., 2002; Lesjean et al., 2002; Qin et al., 2006; Wintgens et al., 2002). Several MBR studies have demonstrated effluent ammonia concentrations ranging from <0.5 to 7.1 mg of N/L, feed ammonia concentrations ranging from 10.5 to 54 mg of N/L, and SRT ranging from 4 to 68 days (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).



Method's detection limit was 0.02 mg/L-N.

Figure 4.1. Ammonia concentrations measured in the effluents of satellite facilities.

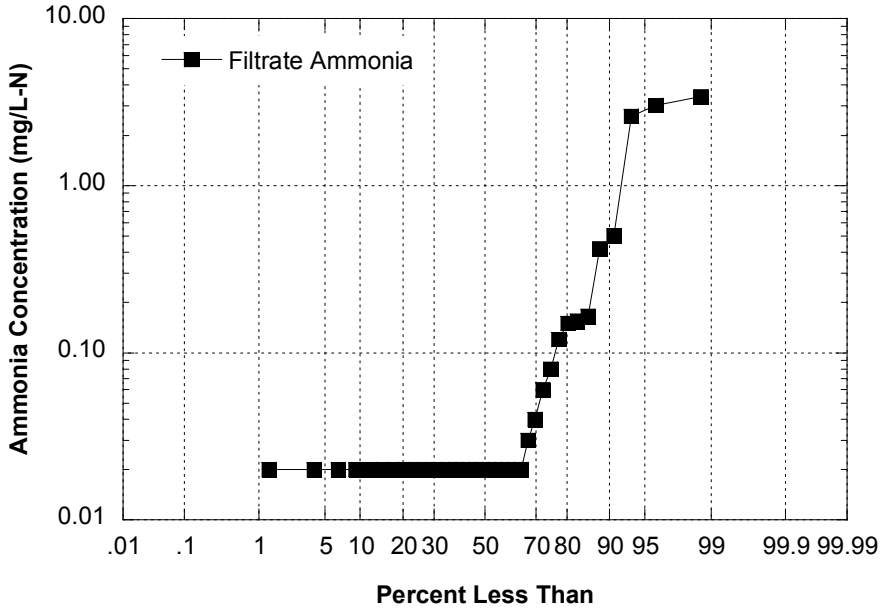


Figure 4.2. Cumulative probability distribution for the ammonia concentrations measured in the effluents of satellite facilities.

4.3 Organic Parameters

4.3.1 Total Organic Carbon (TOC)

Figure 4.3 presents the TOC concentrations measured in the MBR filtrate at various satellite facilities. As shown, the effluent TOC concentrations for these facilities varied from 1.7 to 26.7 mg/L. Typically, the TOC concentration in the effluent of MBR systems treating municipal wastewater is less than 7 mg/L (Qin et al., 2006; Ottoson et al., 2006; Kang et al., 2007), which was observed for most of these facilities. The three satellite facilities with the highest effluent TOC concentrations were MA-01 (9.1 mg/L), MA-02 (10.6 mg/L), and NJ-18 (26.7 mg/L). As shown in Figure 4.4, 90% of the satellite facilities sampled produced effluent with TOC concentrations below 8.1 mg/L; the median concentration was 4.0 mg/L.

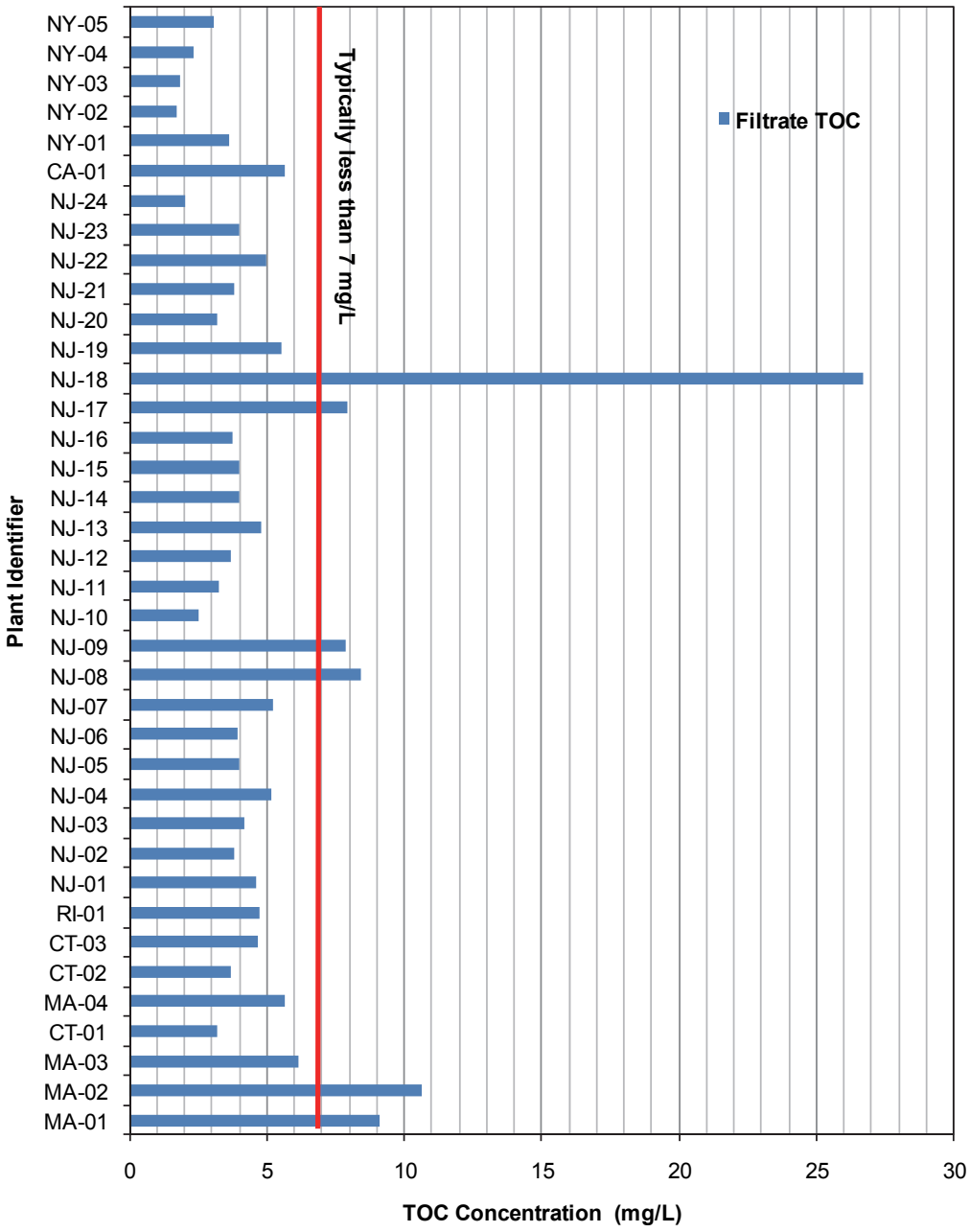


Figure 4.3. TOC concentration measured in the effluents of satellite facilities.

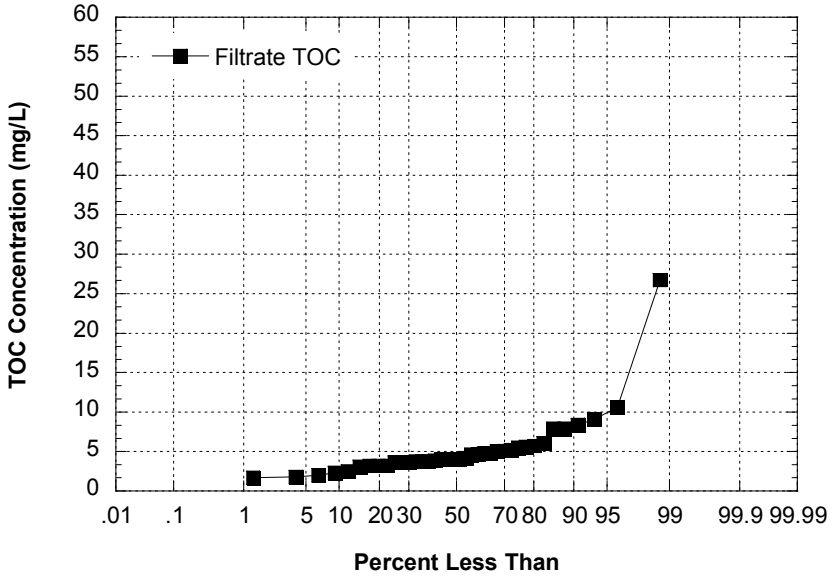


Figure 4.4. Cumulative probability distribution for TOC concentrations measured in the effluents of satellite facilities.

4.3.2 UV-254

Water quality samples collected from the satellite facilities were also analyzed for UV-254, and the results were utilized to calculate the percent transmittance for these samples. As shown in Figure 4.5, the UV-254 for effluents ranged from 0.06 to 0.35 cm^{-1} with corresponding transmittance values ranging from 88% to 45%. Ninety percent of the satellite facilities sampled produced effluents with UV-254 below 0.22 cm^{-1} (Figure 4.6), with the highest absorbance reported for an effluent from facility NJ-18 (0.35 cm^{-1}). The National Water Research Institute (NWRI) guidelines for UV disinfection of drinking water and water reuse recommend filtrate UV transmittance values of 65% or greater at 254 nm for low-pressure membrane (microfiltration and ultrafiltration) filtered effluent (NWRI/AWWARF, 2003). Lower transmittance reduces the efficacy of UV disinfection, and the NWRI's recommended UV dose for membrane-filtered effluent (80 mJ/cm^2) may not suffice for satellite facilities producing effluents with UV transmittance values below 65%.

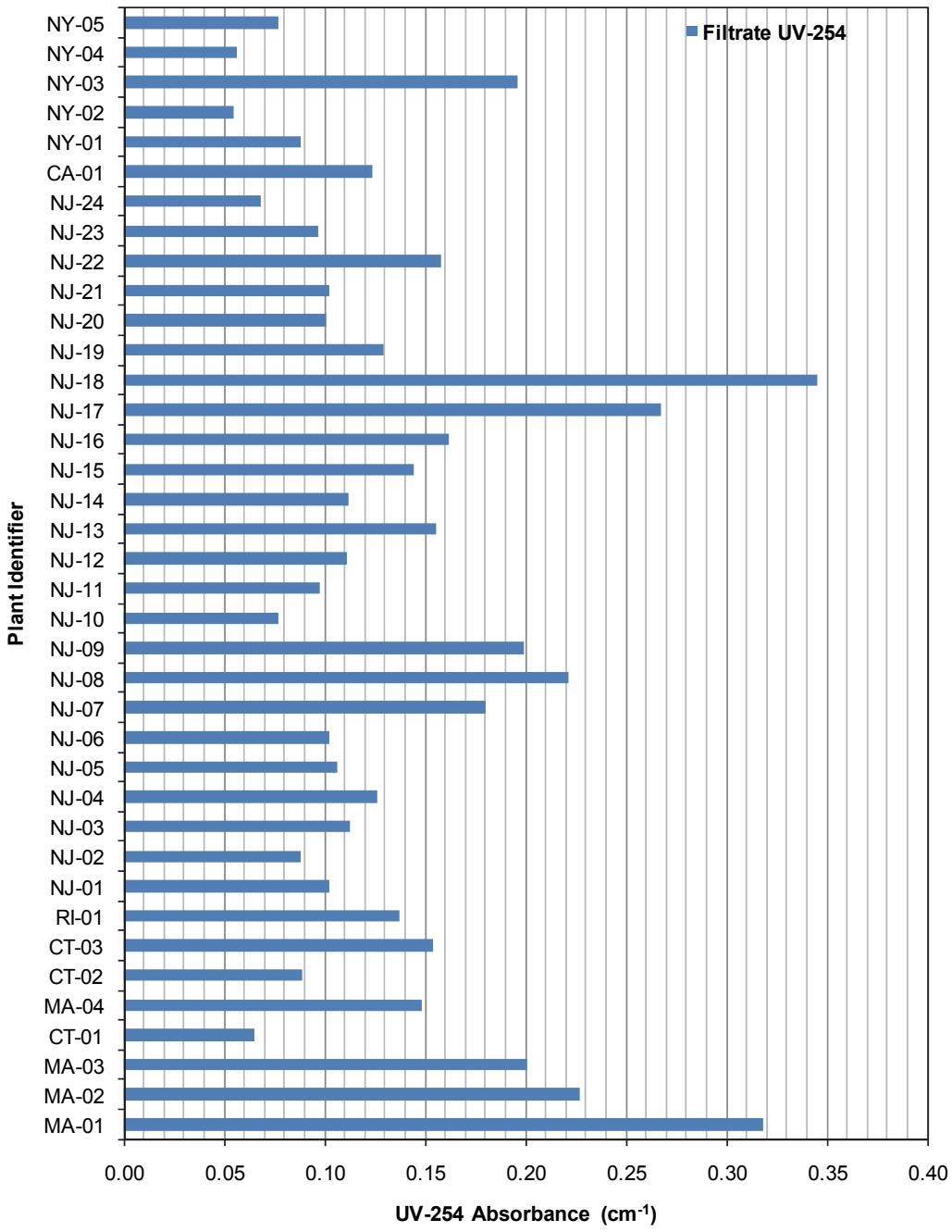


Figure 4.5. UV-254 measured in the effluents from satellite facilities.

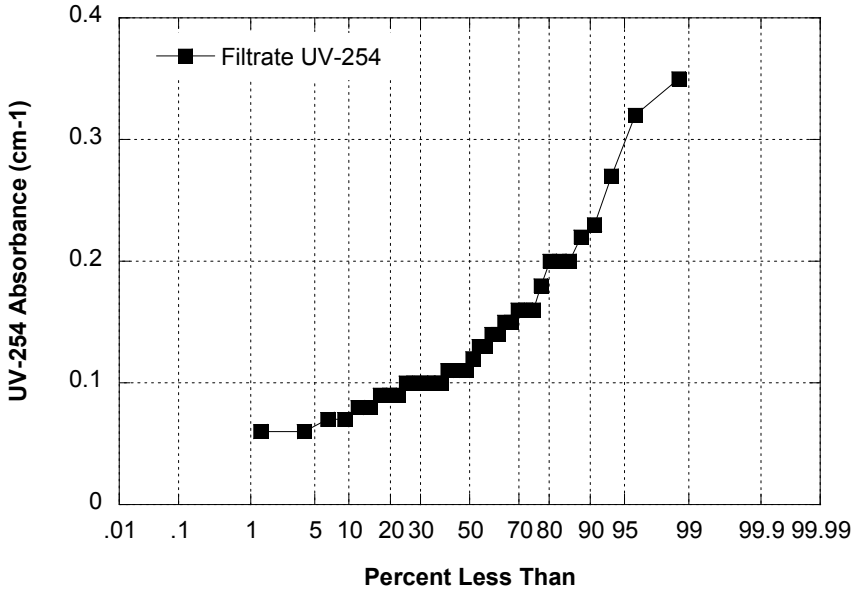


Figure 4.6. Cumulative probability distribution for the UV-254 measured in the effluents of satellite facilities.

4.4 Physical Parameters

4.4.1 Turbidity

Figure 4.7 shows the filtrate turbidity for the satellite facilities sampled. Because MBR systems utilize microfiltration or ultrafiltration membranes for solid separation, they can achieve high removal of particles and are expected to produce effluents with a turbidity typically below 0.2 NTU (Hirani et al., 2007). Although the median effluent turbidity for these facilities was 0.2 NTU, 10% of the facilities sampled produced effluents with a turbidity above 0.7 NTU (Figure 4.8), indicating that some of these facilities may be operating with breached membranes or may have regrowth occurring in the filtrate line. The filtrate turbidity for treatment facilities NJ-06, NJ-07, NJ-24, and NY-03 were measured at exceptionally high levels of 1.1, 3.5, 2.6, and 8.6 NTU, respectively. The NJ-06, NJ-07, and NJ-24 facilities were not required to meet any filtrate turbidity limits. Although the membranes used at the NJ-06 facility are old (5.5 years), those at the NJ-07 facility are relatively new (1 year old) and are less likely to have membrane integrity problems. The oldest membrane modules used at the NJ-24 facility were reported to be about 10 years old, whereas the membrane age for the NY-03 facility could not be confirmed. Unlike California, many other states do not require continuous monitoring of filtrate turbidity and mandatory shutdown of MBR facilities if the filtrate turbidity exceeds 0.5 NTU. Therefore, many of these satellite facilities in other states do not measure or record filtrate turbidity continuously.

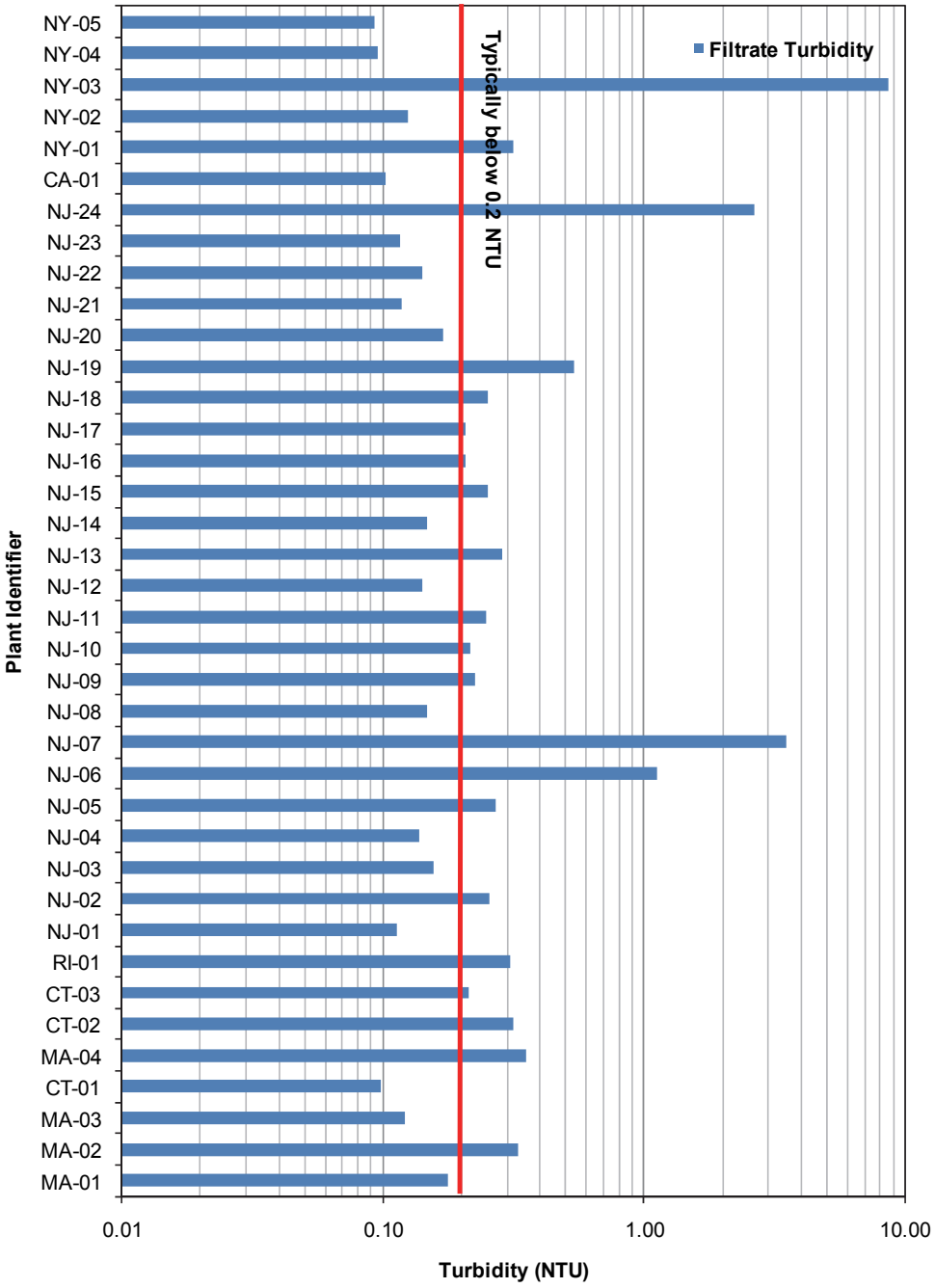


Figure 4.7. Turbidity measured in the effluents from satellite facilities.

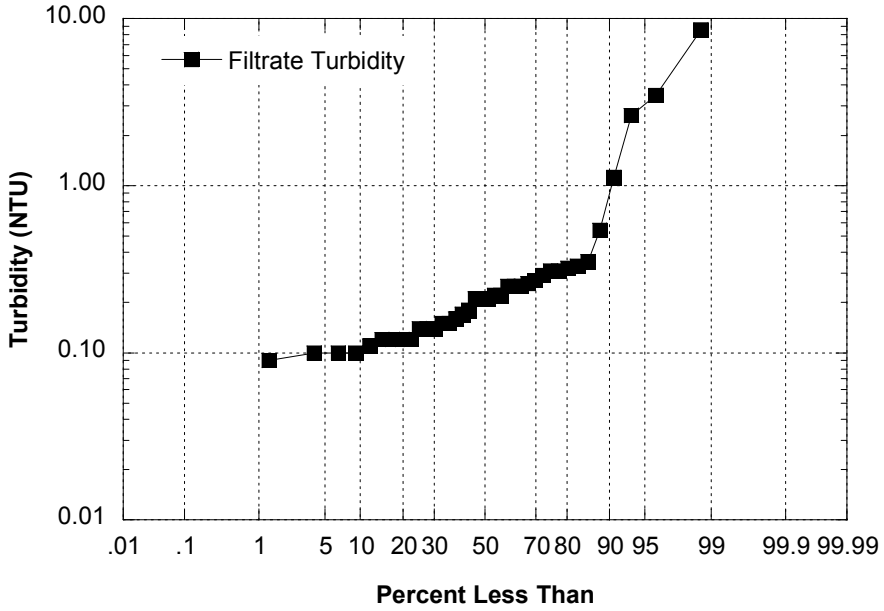


Figure 4.8. Cumulative probability distribution for the turbidity measured in the effluents of satellite facilities.

4.4.2 Particle Counts

Figure 4.9 presents the total particle counts (>2 μm) measured in effluents from the satellite facilities, whereas Figure 4.10 shows the cumulative probability distribution for these counts. The total particle count for the satellite facilities ranged from 2600 to more than 2×10^6 per 100 mL, and 90% of these facilities produced effluents with total particle counts of less than 146,000 per 100 mL. The median concentration was 26,700 particles per 100 mL. The presence of particles affects the disinfection efficacy because particles shield pathogens from inactivation; disinfection efficacy has been shown to decrease with increasing particle size (Winward et al., 2008).

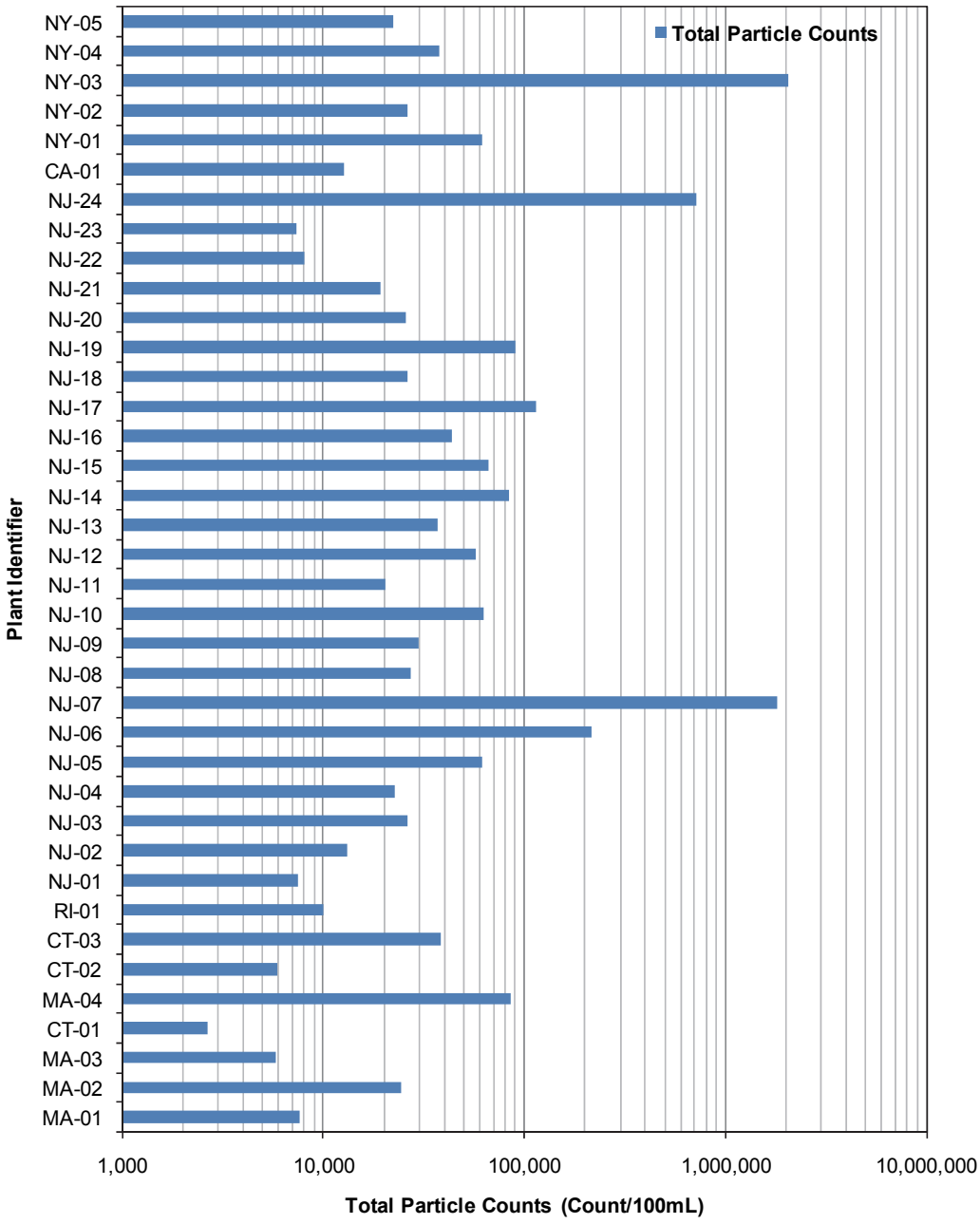


Figure 4.9. Total particle counts measured in the effluents of satellite facilities.

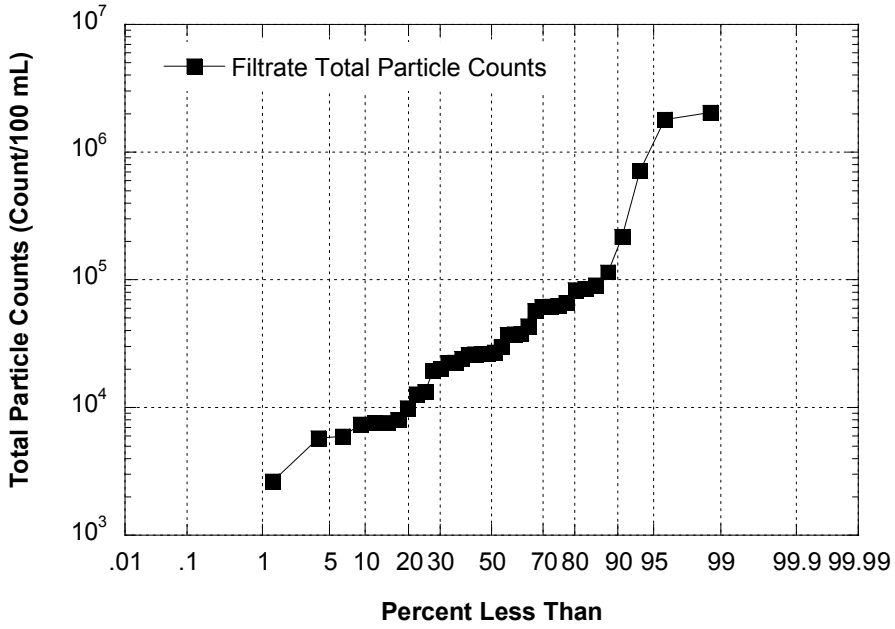
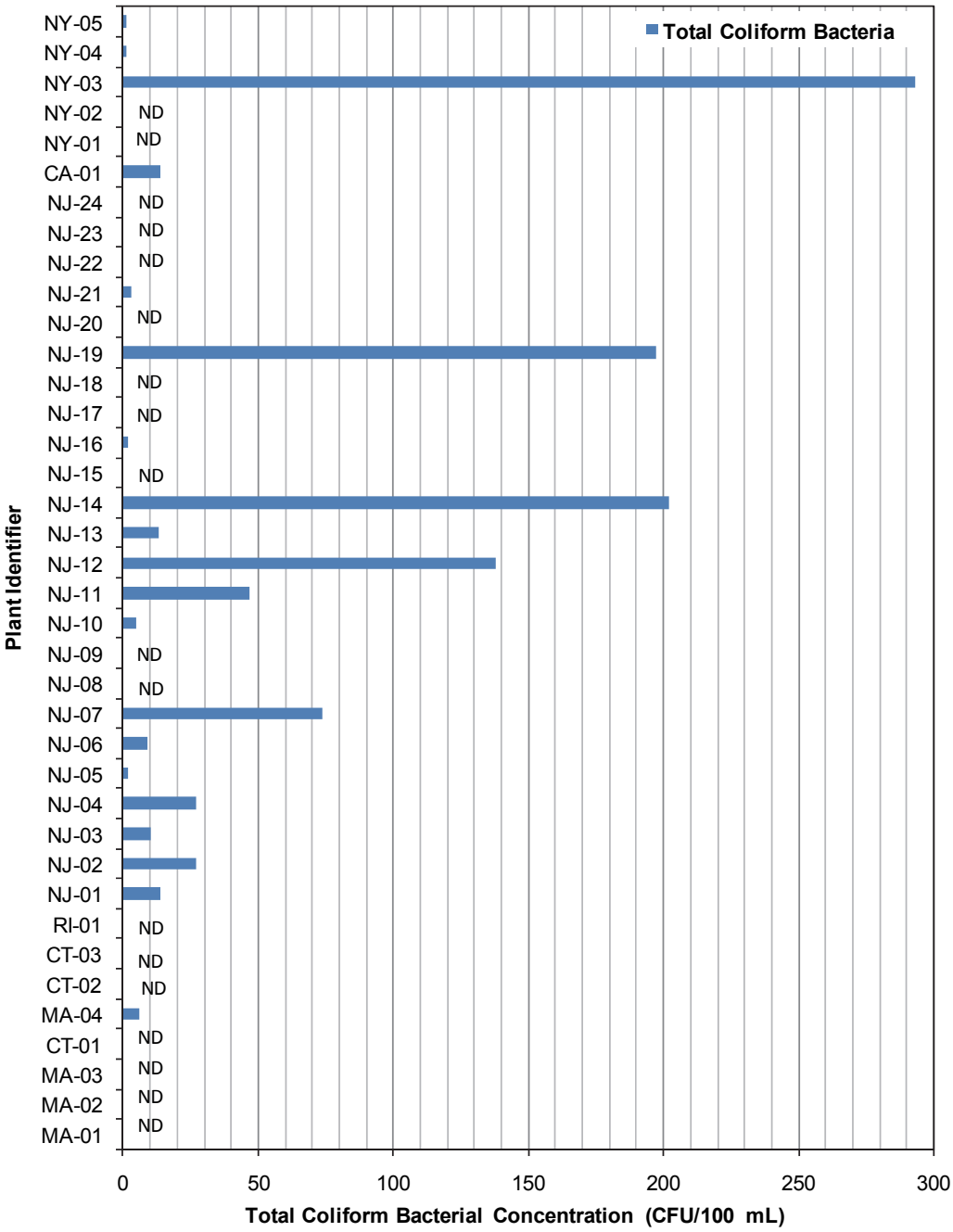


Figure 4.10. Cumulative probability distribution for total particle counts measured in the effluents of satellite facilities.

4.5 Microbial Parameters

4.5.1 Total Coliform Bacteria

Figure 4.11 presents the effluent total coliform bacterial concentrations for the satellite facilities. As shown, the bacterial concentration ranged from <1 to 293 CFU/100 mL, and the median concentration was measured at 1 CFU/100 mL. Ninety percent of the facilities sampled produced effluents with total coliform bacterial concentration below 100 CFU/100 mL (Figure 4.12). Because the effluent total coliform bacterial concentration is usually monitored after the disinfection process for meeting regulatory requirements, it is typically not monitored frequently for MBR effluents. The presence of coliform bacteria at a high concentration in an MBR effluent might be an indication of membrane breach or postmembrane regrowth. The total coliform bacterial concentration in the influent ranged from 1.0×10^3 to 1.6×10^8 CFU/100 mL, and the log removal values (LRVs) ranged from 2.8 to 7.4 logs with a median LRV of 5.7 logs. MBRs utilize membranes for solid separation; therefore, total coliform bacteria are expected to be removed to a high extent because of, at least in part, size exclusion. Several studies have shown greater than 5-log removal of total coliform bacteria by MBRs (Ueda and Horan, 2000; Adham and DeCarolis, 2004; Ottoson et al., 2006; Zhang and Farahbakhsh, 2007; Hirani et al., 2010).



ND indicates non-detect (0 CFU/100 mL)

Figure 4.11. Total coliform bacterial concentrations measured in the effluents of satellite facilities.

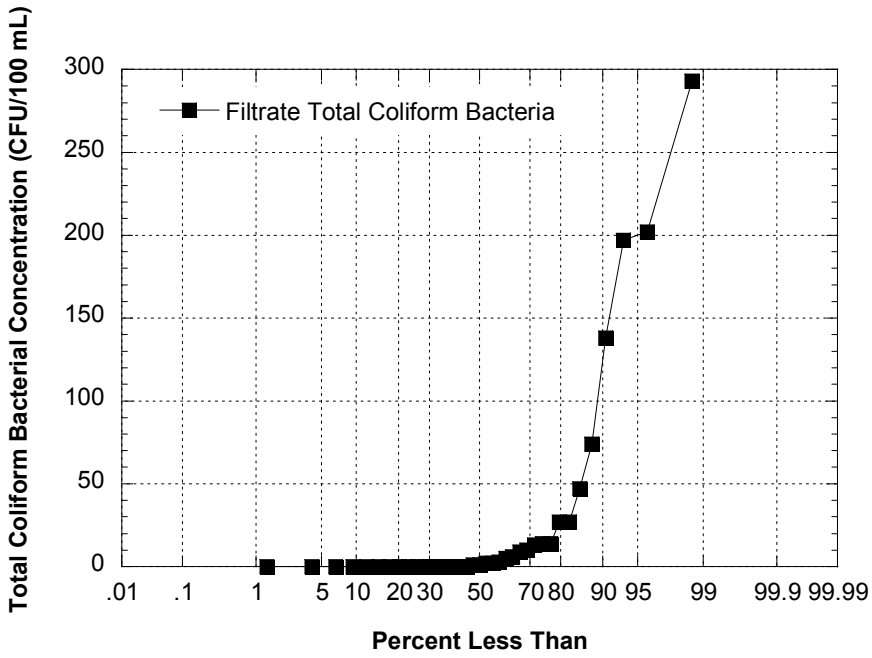
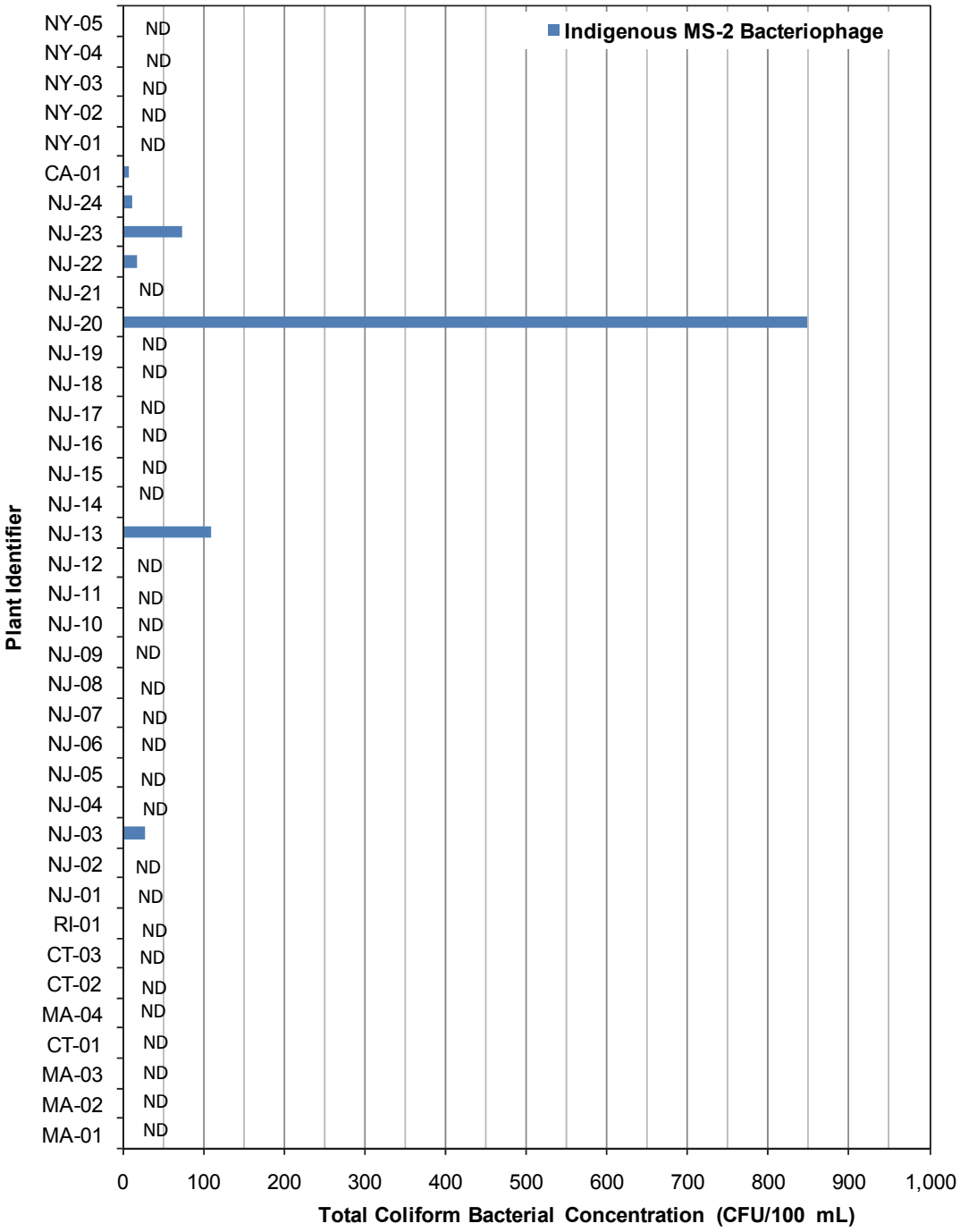


Figure 4.12. Cumulative probability distribution for total coliform bacterial concentrations measured in the effluents of satellite facilities.

4.5.2 Indigenous Male-Specific Bacteriophage

Figure 4.13 presents the indigenous male-specific bacteriophage concentration in the filtrate samples collected from the satellite facilities. Although male-specific bacteriophage concentrations in the samples from facilities NJ-13 and NJ-20 were high (110 and 848 PFU/100 mL, respectively), these organisms were not detected in most of the filtrate samples. The male-specific bacteriophage concentrations in the filtrate samples ranged from <1 to 848 PFU/100 mL, while the median concentration was below the detection limit (1 PFU/100 mL). Among the 38 facilities sampled, 90% of the facilities had filtrate male-specific bacteriophage concentration below 21 PFU/100 mL (Figure 4.14). Several studies have reported complete removal of indigenous male-specific bacteriophage from wastewater by MBR systems (Adham and DeCarolis, 2004; Zhang and Farahbakhsh, 2007; Hirani et al., 2010). Because indigenous male-specific bacteriophage are mostly particle associated and the membranes retain all particulate matter in the reactor, indigenous male-specific bacteriophage are expected to be removed to a high extent by the MBRs.



ND indicates non-detect (0 CFU/100 mL)

Figure 4.13. Indigenous male-specific bacteriophage concentrations in the effluents of satellite facilities.

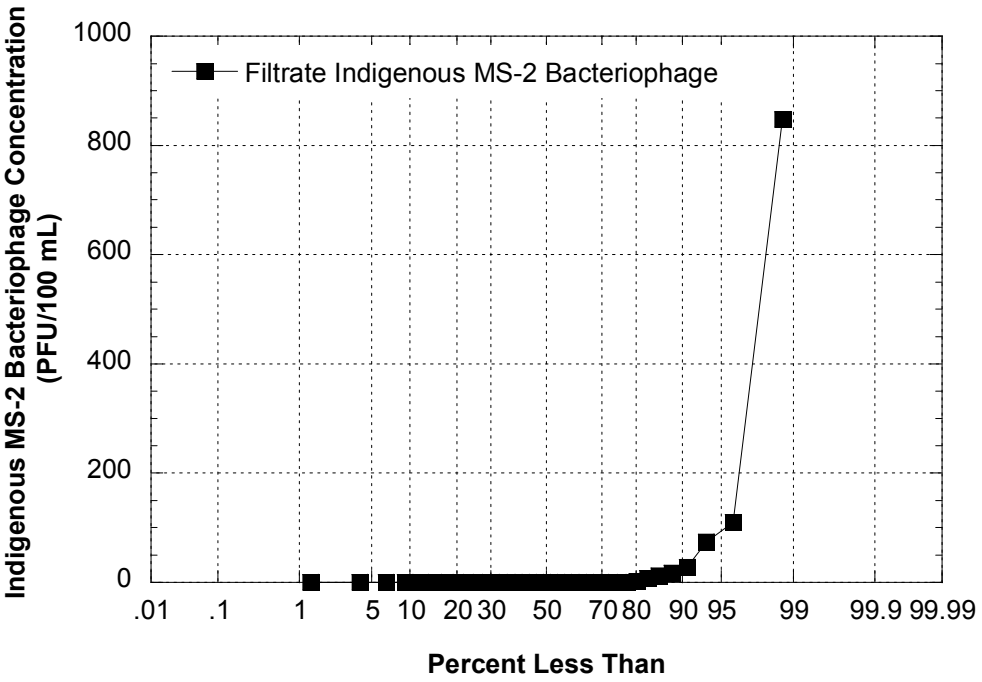


Figure 4.14. Cumulative probability distribution for indigenous male-specific bacteriophage concentrations measured in the effluents of satellite facilities.

4.6 Summary of Reconnaissance Survey Results

Table 4.1 summarizes the water quality data for each satellite facility sampled during the reconnaissance survey. Results showed that 90% of the satellite facilities produced effluent TOC concentrations less than 8.1 mg/L, ammonia concentrations less than 0.44 mg of N/L, turbidities less than 0.7 NTU, UV-254 values less than 0.22 cm^{-1}, total particle counts less than 145,840/100 mL, total coliform bacterial concentrations less than 100 CFU/100 mL, and indigenous male-specific bacteriophage concentrations less than 21 PFU/100 mL. Effluent TOC concentrations did not correlate with UV-254 values, indicating that the characteristics of the organics may be different for different satellite facilities. Total particle counts did not always correlate with turbidity, and total coliform bacteria were not always detected in the samples in which male-specific bacteriophage were present and vice versa.

Table 4.1. Effluent Water Quality Data for Satellite Facilities

Number ID	Plant Identifier	Effluent Water Quality						
		TOC (mg/L)	Ammonia (mg/L-N)	Turbidity (NTU)	UV-254 (cm^{-1})	Total Particle Counts (Count / 100 mL)	Total Coliform Bacteria (CFU/100 mL)	Indigenous Male Specific Bacteriophage (PFU/100 mL)
1	MA-01	9.1	0.01	0.18	0.32	7,604	0	0
2	MA-02	10.6	0.04	0.33	0.23	24,251	0	0
3	MA-03	6.1	0.50	0.12	0.20	5,767	0	2
4	CT-01	3.2	0.01	0.10	0.07	2,648	0	0
5	MA-04	5.6	0.01	0.35	0.15	85,343	6	0
6	CT-02	3.7	0.42	0.32	0.09	5,955	0	0
7	CT-03	4.7	0.01	0.21	0.15	38,059	0	0
8	RI-01	4.7	0.01	0.31	0.14	9,955	0	0
9	NJ-01	4.6	0.03	0.11	0.10	7,542	14	0
10	NJ-02	3.8	0.01	0.26	0.09	13,247	27	NA
11	NJ-03	4.2	0.02	0.16	0.11	26,296	10	28
12	NJ-04	5.1	0.01	0.14	0.13	22,460	27	0
13	NJ-05	4.0	0.01	0.27	0.11	61,785	2	0
14	NJ-06	3.9	0.15	1.12	0.10	217,547	9	0
15	NJ-07	5.2	0.01	3.48	0.18	1,799,703	74	0
16	NJ-08	8.4	0.01	0.15	0.22	27,101	0	0
17	NJ-09	7.9	0.01	0.22	0.20	29,841	0	0
18	NJ-10	2.5	0.01	0.22	0.08	63,122	5	0
19	NJ-11	3.2	0.08	0.25	0.10	20,171	47	0
20	NJ-12	3.7	0.01	0.14	0.11	56,894	138	0
21	NJ-13	4.8	0.06	0.29	0.16	37,138	13	110
22	NJ-14	4.0	3.41	0.15	0.11	83,126	202	0
23	NJ-15	4.0	3.02	0.25	0.14	66,147	0	0
24	NJ-16	3.8	0.01	0.21	0.16	43,460	2	0
25	NJ-17	7.9	0.02	0.21	0.27	115,108	0	0
26	NJ-18	26.7	2.60	0.25	0.35	26,328	0	0
27	NJ-19	5.5	0.01	0.54	0.13	90,771	197	0
28	NJ-20	3.2	0.01	0.17	0.10	25,934	0	848
29	NJ-21	3.8	0.01	0.12	0.10	19,411	3	0
30	NJ-22	5.0	0.01	0.14	0.16	7,997	NA	18
31	NJ-23	4.0	0.01	0.12	0.10	7,394	0	74
32	NJ-24	2.0	0.12	2.64	0.07	716,310	0	12
33	CA-01	5.7	0.17	0.10	0.12	12,730	14	8
34	NY-01	3.6	0.01	0.31	0.09	61,425	0	0
35	NY-02	1.7	0.01	0.12	0.06	26,321	0	0
36	NY-03	1.8	0.16	8.58	0.20	2,044,564	293	0
37	NY-04	2.3	0.01	0.10	0.06	37,628	1	0
38	NY-05	3.1	0.01	0.09	0.08	22,371	1	0
NA indicates not available								
90th Percentile Conc.		8.1	0.44	0.71	0.22	145,840	100	21

4.7 Binning of Satellite Facilities

The objective of binning was to place these facilities into three performance categories on the basis of their effluent water quality. Binning of the satellite facilities also helped facilitate additional water quality evaluation for subsequent selection of representative satellite facilities from each performance bin for additional detailed water quality analyses and the performance of bench-scale microbial inactivation studies. Based on the method discussed in Section 2.1.2, performance levels were assigned to each water quality parameter from each satellite facility (Table 4.2).

Table 4.2. Performance Levels for Individual Water Quality Parameters for Satellite Facilities

No. ID	Plant Identifier	Performance Level						Avg. of Performance Levels for 6 Parameters
		TOC	NH_3	Turbidity	UV-254	Total Particle Counts	Total Coliform Bacteria	
1	MA-01	3	1	1	3	1	1	1.67
2	MA-02	3	2	2	3	1	1	2.00
3	MA-03	2	3	1	2	1	1	1.67
4	CT-01	1	1	1	1	1	1	1.00
5	MA-04	2	1	2	2	2	2	1.83
6	CT-02	1	2	2	1	1	1	1.33
7	CT-03	2	1	2	2	2	1	1.67
8	RI-01	2	1	2	2	1	1	1.50
9	NJ-01	2	2	1	1	1	2	1.50
10	NJ-02	1	1	2	1	1	2	1.33
11	NJ-03	2	2	1	1	1	2	1.50
12	NJ-04	2	1	1	2	1	2	1.50
13	NJ-05	1	1	2	1	2	2	1.50
14	NJ-06	1	2	3	1	3	2	2.00
15	NJ-07	2	1	3	2	3	2	2.17
16	NJ-08	3	1	1	2	2	1	1.67
17	NJ-09	2	1	2	2	2	1	1.67
18	NJ-10	1	1	2	1	2	2	1.50
19	NJ-11	1	2	2	1	1	2	1.50
20	NJ-12	1	1	1	1	2	3	1.50
21	NJ-13	2	2	2	2	2	2	2.00
22	NJ-14	1	3	1	1	2	3	1.83
23	NJ-15	1	3	2	2	2	1	1.83
24	NJ-16	1	1	1	2	2	2	1.50
25	NJ-17	2	2	1	3	2	1	1.83
26	NJ-18	3	3	2	3	1	1	2.17
27	NJ-19	2	1	2	2	2	3	2.00
28	NJ-20	1	1	1	1	1	1	1.00
29	NJ-21	1	1	1	1	1	2	1.17
30	NJ-22	2	1	1	2	1	1	1.33
31	NJ-23	2	1	1	1	1	1	1.17
32	NJ-24	1	2	3	1	3	1	1.83
33	CA-01	2	2	1	2	1	2	1.67
34	NY-01	1	1	2	1	2	1	1.33
35	NY-02	1	1	1	1	1	1	1.00
36	NY-03	1	2	3	2	3	3	2.33
37	NY-04	1	1	1	1	2	1	1.17
38	NY-05	1	1	1	1	1	1	1.00

On the basis of performance levels, the satellite facilities were binned into three different performance bins as stated in Step 2 in Section 2.1.2. Through use of the binning results (Table 4.3), three satellite facilities were selected from each performance bin to represent facilities that utilized different process configurations (submerged or external), membrane geometries (hollow-fiber, flat-sheet, or tubular), and fouling control strategies (relaxation or backwash).

The process configuration, membrane geometry, fouling control strategy, and membrane age for the selected satellite facilities are presented in Table 4.4; whereas effluent water quality results for these facilities (from the reconnaissance survey), along with the 50th and 90th percentile concentration among the facilities sampled, are shown in Table 4.5. As shown, the selected satellite facilities utilize different process configurations, membrane geometries, and fouling control strategies, as well as membrane ages between 1 and 6 years.

Table 4.3. Results from the Binning Process

Avg. Performance Level for 6 Parameters Evaluated (TOC, Ammonia, Turbidity, UV-254, Total Particle Counts, Total Coliform Bacteria)

<= 33rd percentile Bin A	>33rd–66th percentile Bin B	>66th percentile Bin C
CT-01 *(HF, Sub)*	MA-01	MA-02 *(HF, Sub)*
CT-02 *(HF, Sub)*	MA-03	MA-04
NJ-02 *(HF, Sub, BW)*	CT-03 *(FS, Sub, RX)*	NJ-06 *(FS, Sub, RX)*
RI-02	NJ-08 *(TB, Ext, BW)*	NJ-07 *(HF, Sub, BW)*
NJ-01 *(HF, Sub, BW)*	NJ-09 *(TB, Ext, BW)*	NJ-13 *(HF, Sub, BW)*
NJ-03 *(HF, Sub, BW)*	CA-01 *(HF, Sub, RX)*	NJ-14 *(HF, Sub, BW)*
NJ-04 *(HF, Sub, BW)*		NJ-15 *(FS, Sub, RX)*
NJ-05 *(HF, Sub, BW)*		NJ-17 *(TB, Ext)*
NJ-10 *(HF, Sub, BW)*		NJ-18 *(TB, Ext)*
NJ-11 *(HF, Sub, BW)*		NJ-19 *(TB, Ext)*
NJ-12 *(HF, Sub, BW)*		NJ-24 *(Ext)*
NJ-16 *(HF, Sub)*		NY-03
NJ-20 *(TB, Ext)*		
NJ-21 *(HF, Sub)*		
NJ-22 *(HF, Sub, BW)*		
NJ-23 *(TB, Ext)*		
NY-01 *(HF, Sub, BW)*		
NY-02 *(HF, Sub, BW & RX)*		
NY-04 *(HF, Sub, BW)*		
NY-05 *(HF, Sub, BW)*		

HF = hollow-fiber membranes;

FS = flat-sheet membranes;

TB = tubular membranes;

Sub = submerged process configuration;

Ext = external process configuration;

BW = backwash utilized as fouling control strategy;

RX = relaxation utilized as fouling control strategy.

Table 4.4. Satellite Facilities Selected for Detailed Water Quality Evaluations

	Name of Facility	Avg./Max. Flow (gpd)	Process Configuration	Membrane Geometry	Fouling Control Strategy	Membrane Age (Yrs)
Bin A	NJ-05	2600/8400	Submerged	Hollow-fiber	Backwash	5
	NJ-04	4500/18,500	Submerged	Hollow-fiber	Backwash	5+
	NJ-23	200/2000	External	Tubular	Backwash	6
Bin B	CA-01	1,100,000/1,800,000	Submerged	Hollow-fiber	Relaxation	1
	CT-03	3900/16,500	Submerged	Flat-sheet	Relaxation	6
	NJ-08	2400/2400	External	Tubular	Backwash	5
Bin C	NJ-07	8000/18,400	Submerged	Hollow-fiber	Backwash	1
	NJ-06	3600/12,500	Submerged	Flat-sheet	Relaxation	5.5
	NJ-14	220,000/324,000	Submerged	Hollow-fiber	Backwash	1.5–6

Table 4.5. Effluent Water Quality for Selected Satellite Facilities

	Plant Identifier	Ammonia (mg/L-N)	TOC (mg/L)	Turbidity (NTU)	Total Coliform Bacteria (CFU/100 mL)	UV-254 (cm^{-1})	Total Particle Counts/100 mL (>2 µm)	Indigenous Male-Specific Bacteriophage (PFU/100 mL)
Bin A	NJ-05	0.01	4.0	0.27	2	0.11	61,785	0
	NJ-04	0.01	5.1	0.14	27	0.13	22,460	0
	NJ-23	0.01	4.0	0.12	0	0.10	7,394	74
Bin B	CA-01	0.17	5.7	0.10	14	0.12	12,730	8
	CT-03	0.01	4.7	0.21	0	0.15	38,059	0
	NJ-08	0.01	8.4	0.15	0	0.22	27,101	0
Bin C	NJ-07	0.01	5.2	3.48	74	0.18	1,799,703	0
	NJ-06	0.15	3.9	1.12	9	0.10	217,547	0
	NJ-14	3.41	4.0	0.15	202	0.11	83,126	0
50th Percentile Conc.		0.01	4.0	0.21	1	0.12	26,175	0
90th Percentile Conc.		0.44	8.1	0.71	100	0.22	145,840	21

Chapter 5

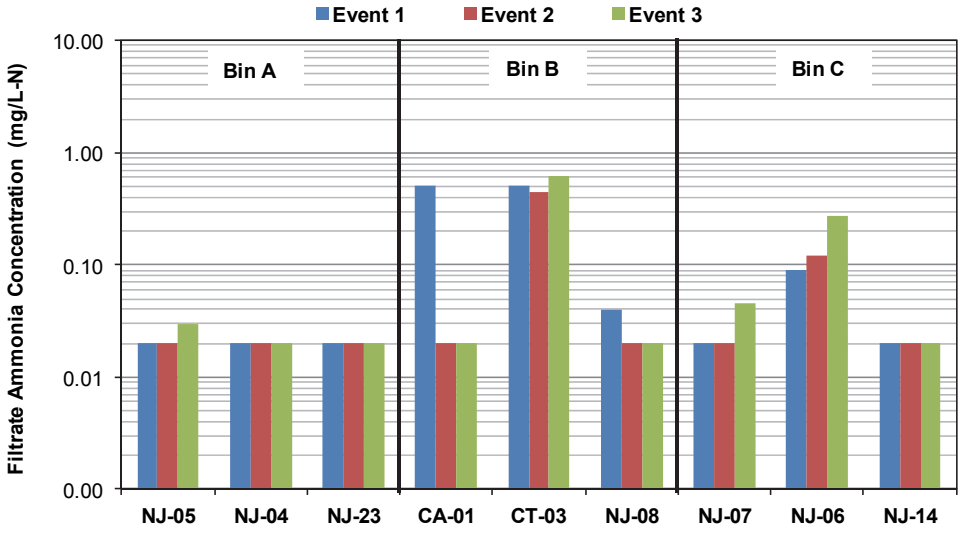
Variability in Water Qualities Produced from Selected Satellite Facilities

5.1 Introduction and Objective

The objective of Task 2.1.2 was to assess the variability in effluent water quality produced by the selected satellite facilities (from the binning process) over several months. In order to accomplish this objective, three sampling events were conducted for each of the nine selected facilities spanning 3 months (Event 1, April 5; Event 2, May 18; and Event 3, June 6).

5.2 Inorganic Parameter (Ammonia)

Figure 5.1 presents the filtrate ammonia concentrations for the selected satellite facilities. The filtrate ammonia concentrations for these facilities were consistently below 1 mg of N/L and varied from <0.02 to 0.61 mg of N/L. Although the NJ-14 facility produced effluent with a high ammonia concentration during the initial reconnaissance survey, issues with the biological reactor were later resolved, which allowed the facility to achieve a high level of nitrification during the subsequent detailed water quality evaluations. Filtrate ammonia concentrations for the selected satellite facilities were mostly below 0.1 mg of N/L, with the exception of the CT-03 facility, which produced effluent with a higher ammonia concentration during all three sampling events. When properly designed and operated, satellite MBR facilities can achieve complete nitrification, although any upset in the bioreactor basins can result in a temporary spike in effluent ammonia concentration.



Method's detection limit was 0.02 mg/L-N.

Figure 5.1. Filtrate ammonia concentrations for the selected satellite facilities.

5.3 Organic Parameters

5.3.1 Total Organic Carbon (TOC)

Filtrate TOC concentrations amongst the selected satellite facilities varied from 3.3 to 10.5 mg/L (Figure 5.2). With a few exceptions, filtrate TOC concentrations for these facilities were fairly consistent during the three sampling events, demonstrating the capability of these facilities to produce oxidized effluent over an extended period of sampling. The CT-03 facility had a higher effluent TOC concentration (10.5 mg/L) during the first sampling event, which may be attributed to a temporary upset in the bioreactor basin.

5.3.2 UV-254

Filtrate UV-254 for selected satellite facilities varied from 0.10 to 0.32 cm^{-1} (Figure 5.3) and was found to vary substantially during the three sampling events. The corresponding filtrate transmittance values (based on UV-254) for the effluents ranged from 79% to 48%. The TOC concentrations for these facilities were fairly consistent, although the UV-254 values varied substantially during the three sampling events, indicating that the characteristics of the residual organic matter in the effluent varied. Because these satellite facilities treat wastewater from shopping malls, hotels, schools, golf clubs, and other small complexes, they are likelier to experience variation in wastewater quality depending on the time of day when the samples were collected.

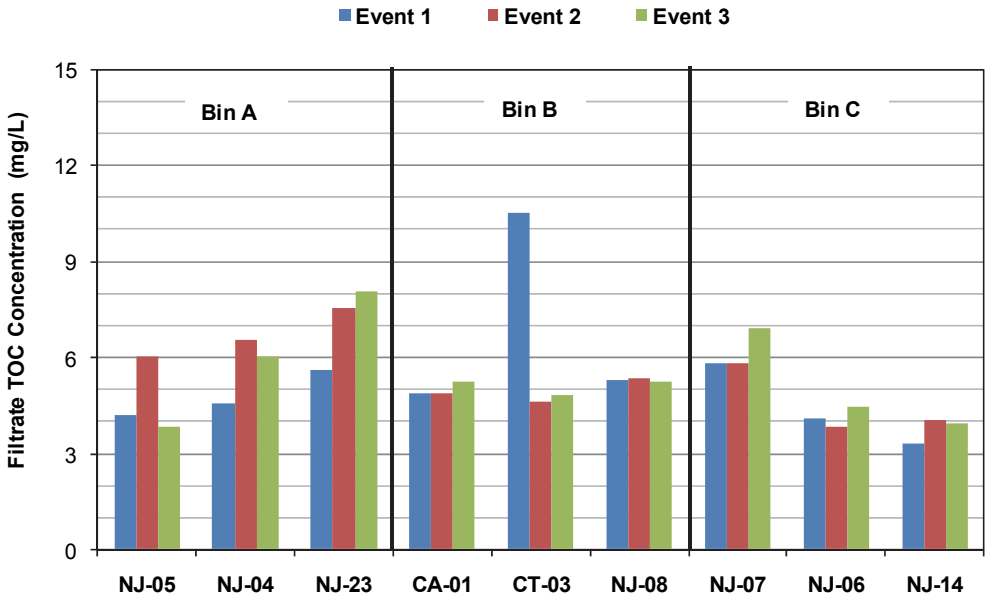


Figure 5.2. Filtrate TOC concentrations for the selected satellite facilities.

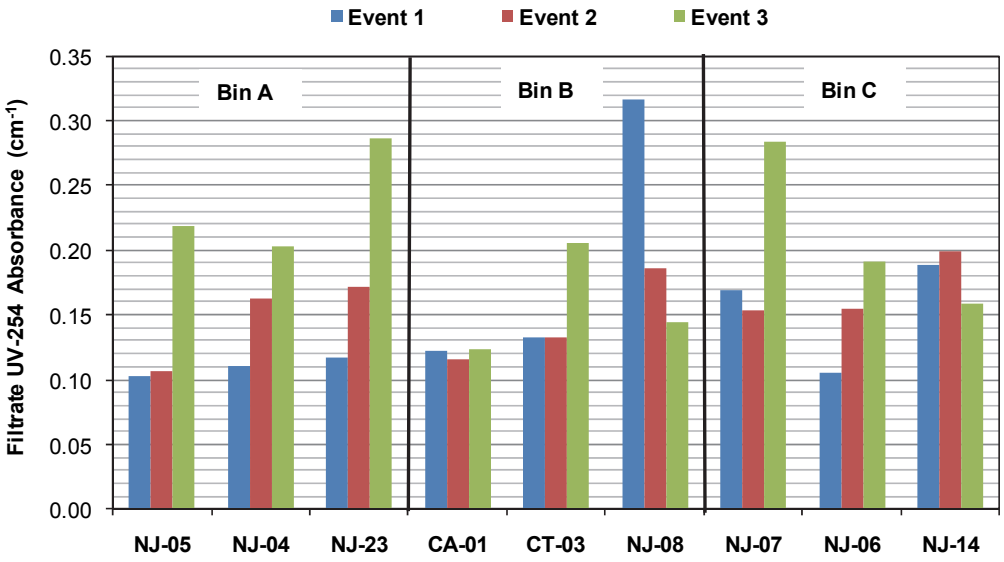


Figure 5.3. Filtrate UV-254 for the selected satellite facilities.

5.4 Physical Parameters

5.4.1 Turbidity

Figure 5.4 presents the filtrate turbidity for the selected satellite facilities. Data from NJ-07, NJ-08, and NJ-14 were different from expected on the basis of the results obtained from the reconnaissance survey. The NJ-08 facility from Bin B produced effluent with consistently high turbidity (2.7–14.6 NTU), although it was expected to produce effluent with low turbidity (<0.2 NTU). Contrary to this result, the NJ-06 and NJ-07 facilities, which were expected to produce effluents with high turbidity, reported much better effluent water qualities with turbidities of less than 0.4 NTU. The reconnaissance survey was based on a single grab sample; therefore, any changes in plant conditions or sample collection procedure would result in differences in the effluent water quality for subsequent samples. It is also possible that the membrane system for the NJ-08 facility had either a membrane breach after the reconnaissance survey was completed or post-membrane regrowth. As shown, the filtrate turbidities varied from 0.1 to 14.6 NTU, although the majority of these facilities produced effluents with turbidities of less than 0.2 NTU. The filtrate turbidity for NJ-06 decreased substantially during the detailed water quality evaluations. Improper flushing of the sampling ports during collection of samples from the NJ-06 and NJ-07 facilities during the reconnaissance survey may have contributed towards high filtrate turbidities. The NJ-14 facility was selected from Bin C for the disinfection study on the basis of the results from the reconnaissance survey and the detailed water quality evaluations, which confirmed that this facility had high turbidity levels, particle counts, and total coliform levels in the filtrate. However, the absence of bacteriophage in the effluent of NJ-14 raises the possibility that the elevated turbidities and coliform levels were due to regrowth.

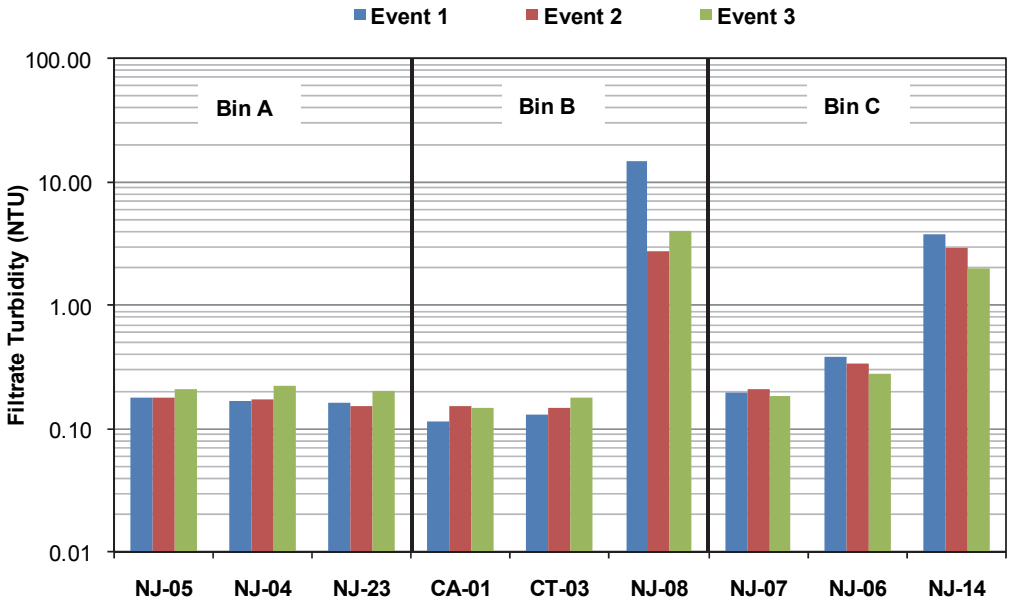


Figure 5.4. Filtrate turbidities for the selected satellite facilities.

5.4.2 Particle Counts

The particle counts in the filtrate samples ranged from 2900 to 1,481,000 per 100 mL of sample (Figure 5.5). Samples collected from the CT-03 and NJ-14 facilities showed consistently high particle counts during all three sampling events. Figure 5.6 presents the size distribution of particles amongst the filtrate samples collected from selected satellite facilities. About 40% of the total particle counts (for >2 µm particles) were in the size range of 3 to 7 µm for most of these facilities, whereas the 7 to 15 µm size range was found to contribute the least to the total particle counts. The exceptions were the CT-03 and NJ-14 facilities, which had much higher percentages of large particles contributing toward their higher overall particle counts. The NJ-14 facility had high filtrate turbidity, whereas the CT-03 facility did not, indicating that particle counts do not relate with turbidity.

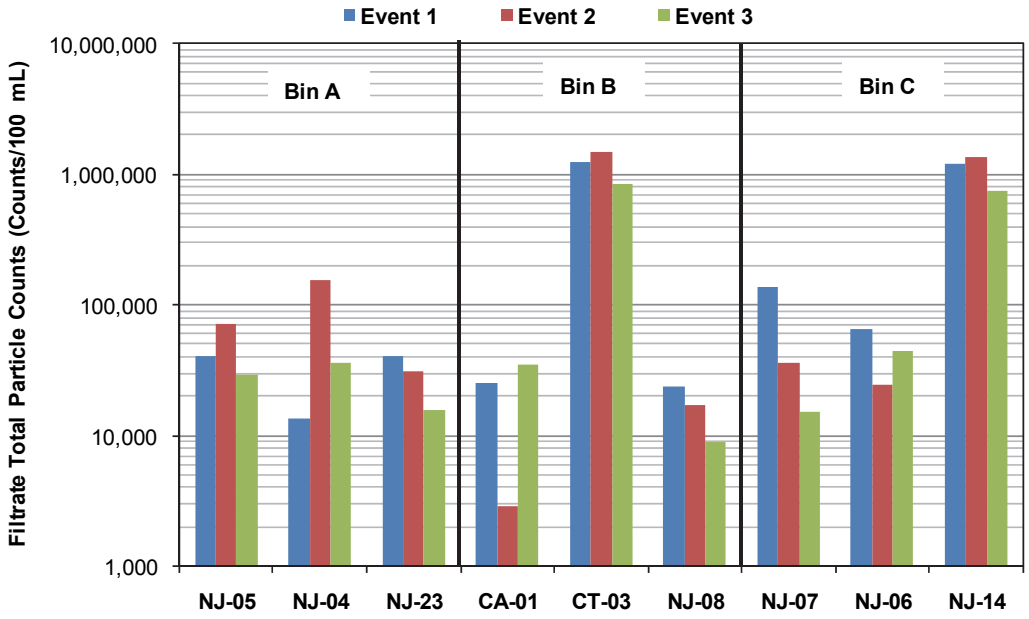


Figure 5.5. Filtrate total particle counts (>2 µm) for the selected satellite facilities.

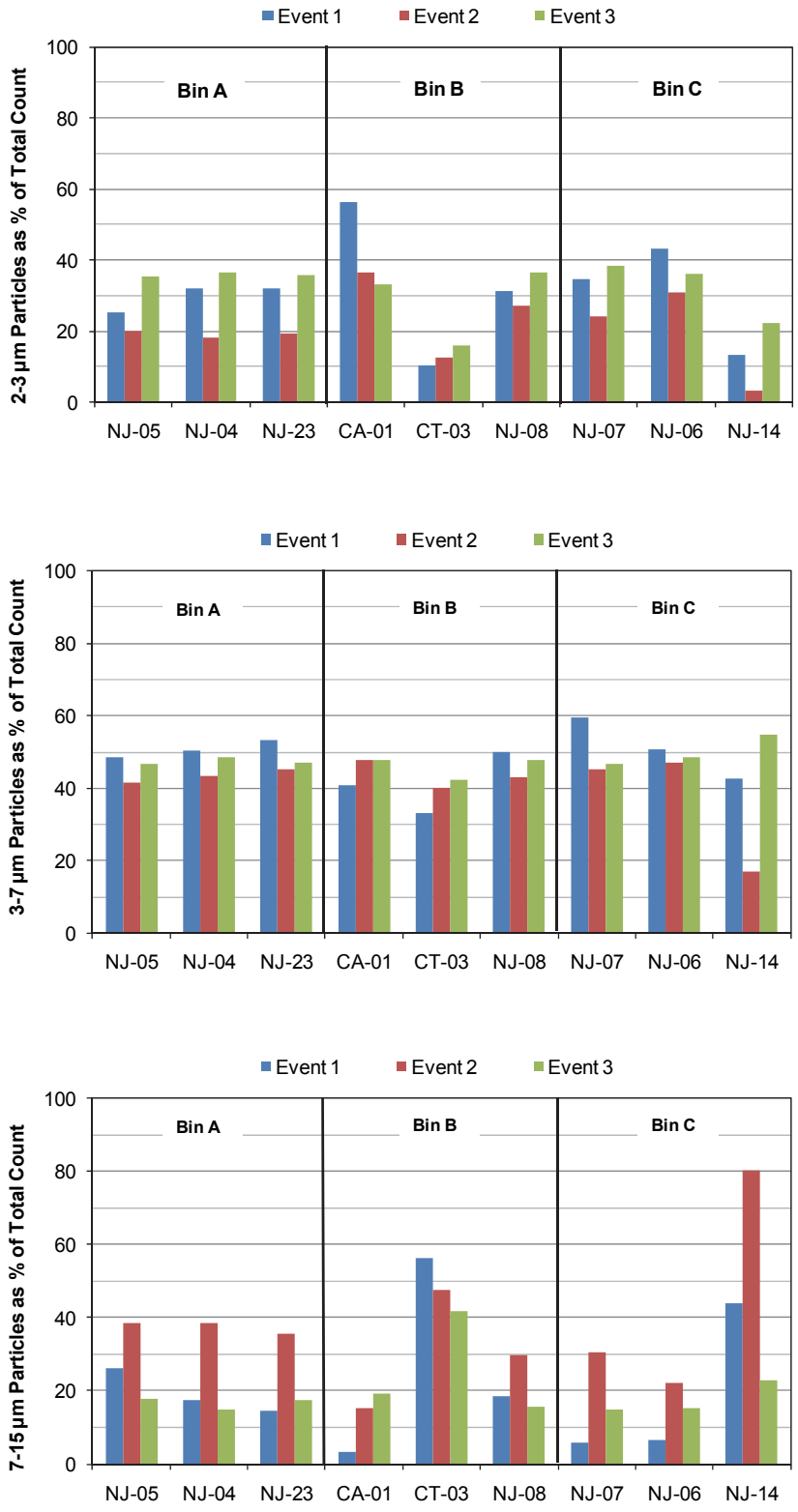


Figure 5.6. Size distribution of particles found in filtrates of selected satellite facilities.

5.5 Microbial Parameters

5.5.1 Total Coliform Bacteria

Figure 5.7 presents the total coliform bacterial concentrations in the bioreactor and filtrate samples and corresponding log removal values (LRVs). The bacterial concentrations in the bioreactor varied from 5 to 9 logs, whereas the filtrate concentrations varied from less than 1 to 90,000 CFU/100 mL. The difference in bacterial concentrations in the bioreactor samples of the satellite facilities was mostly less than 2 logs amongst the three different sampling events. On the basis of bioreactor and filtrate concentrations, the LRVs for total coliform bacteria varied from 2.0 to 7.5 logs. The bacterial counts in the filtrate samples collected from the CT-03 and NJ-14 facilities were exceptionally high. The filtrate samples from the NJ-14 facility were collected from the clear well (filtrate reservoir) because of the absence of a sampling port on the filtrate line, so coliform regrowth in the reservoir probably contributed to these high counts. Similarly, high counts in the filtrate samples from the CT-03 facility were probably due to coliform regrowth at the sampling port.

5.5.2 Indigenous Male-Specific Bacteriophage

The indigenous male-specific bacteriophage concentrations in the bioreactor and filtrate samples and corresponding LRVs are presented in Figure 5.8. The bioreactor concentrations varied from 200 to 570,000 PFU/100 mL, whereas the filtrate concentrations varied from less than 1 to 24 PFU/100 mL. The LRVs for male-specific bacteriophage varied from 2.3 to 5.8 logs. The male-specific bacteriophage were measured at the detection limit (1 PFU/100 mL) in the filtrate samples collected from the NJ-14 facility, although high concentrations of coliform bacteria were found in these samples, indicating the possibility of regrowth of bacteria in the clear well at this facility.

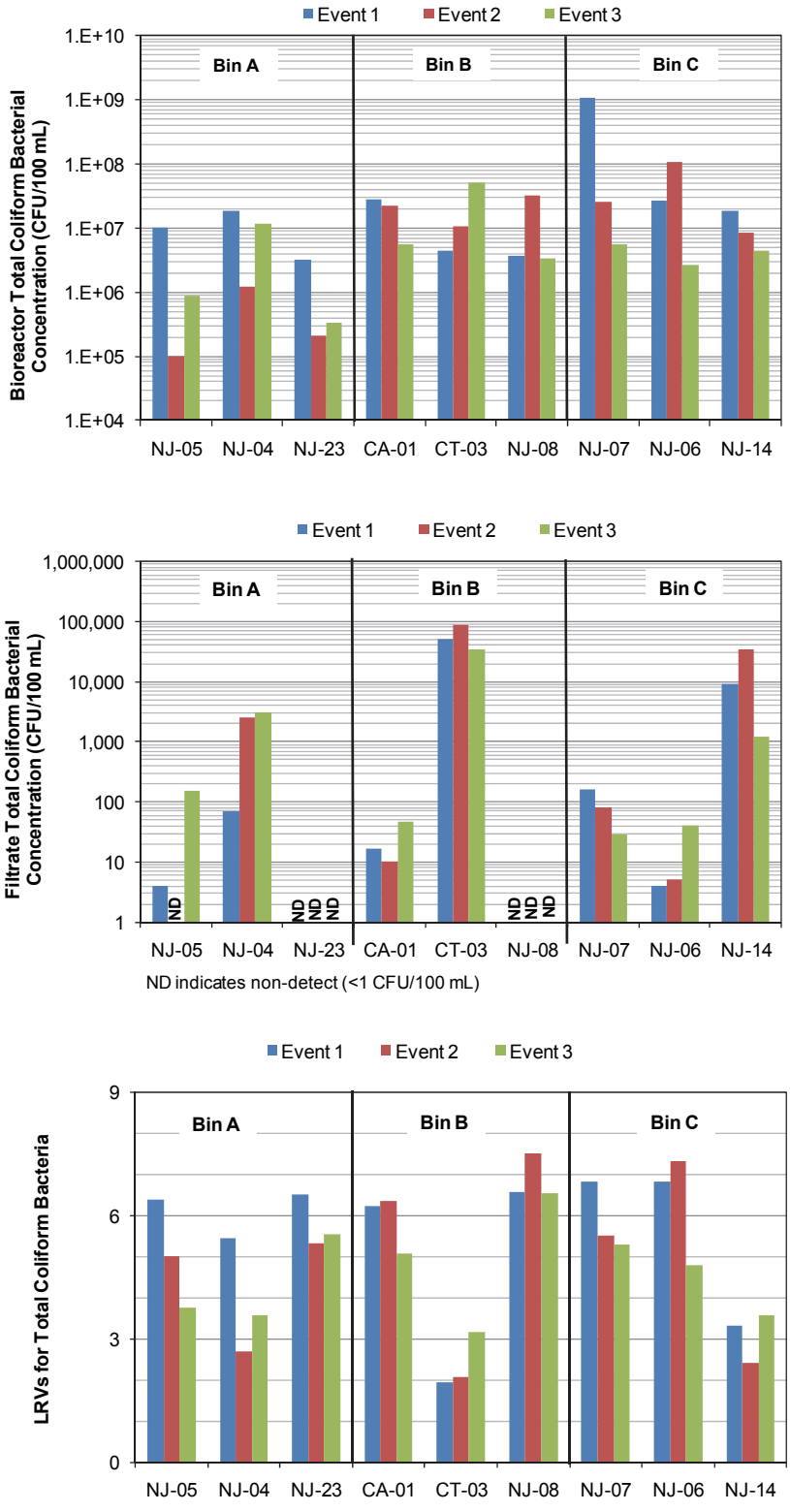


Figure 5.7. Total coliform bacterial concentrations in the bioreactors and filtrates and corresponding LRVs for the selected satellite facilities.

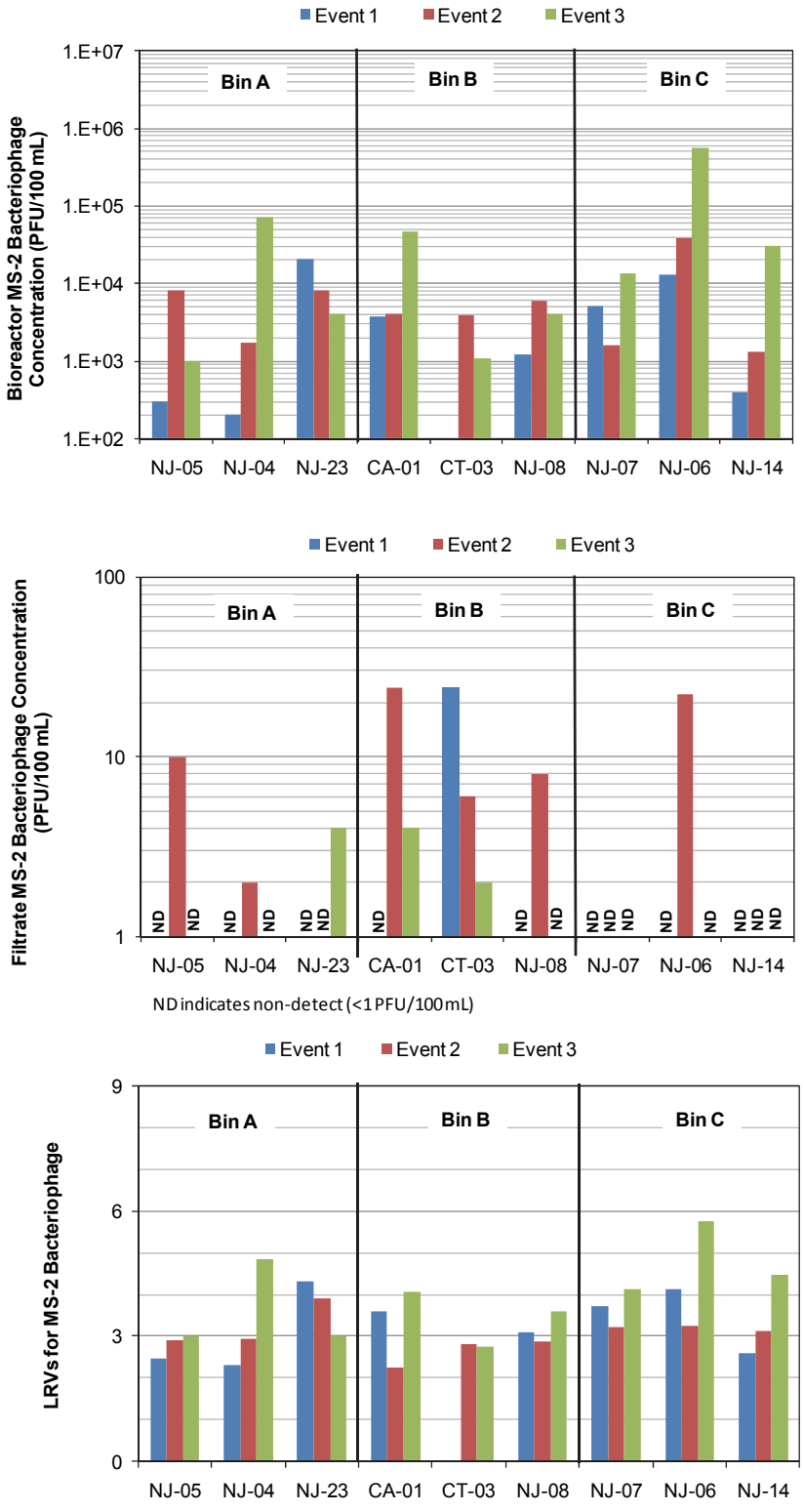


Figure 5.8. Indigenous male-specific bacteriophage concentrations in the bioreactors and filtrates and corresponding LRVs for the selected satellite facilities.

5.5.3 Enterovirus, Rotavirus, Hepatitis A Virus, Adenovirus

Table 5.1 presents the results for different viruses in the filtrate samples collected from the nine satellite facilities during three different sampling events for each facility. All analyses were performed by using quantitative PCR (qPCR). Enterovirus, rotavirus, and hepatitis A virus were not detected in any of the filtrate samples. Adenoviruses were detected in filtrate samples from all nine facilities sampled. Kuo et al. (2010) investigated removal of adenovirus in a full-scale MBR facility and found 10^3 viral particles/L in the MBR effluent. Several possible explanations for these observations still need to be substantiated. Because high concentration of adenoviruses are present in wastewater (Bofill-Mas et al., 2006; Kuo et al., 2010), they are likelier to be present in the MBR filtrate. qPCR cannot determine if these organisms were infectious.

Table 5.1. Presence of Enterovirus, Rotavirus, Hepatitis A Virus, and Adenovirus in Filtrates from Selected Satellite Facilities

Bin	Plant Identifier	Sampling Event	Presence of:			
			Enterovirus	Rotavirus	Hepatitis A Virus	Adenovirus
A	NJ-05	1	Negative	Negative	Negative	Negative
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Positive
	NJ-04	1	Negative	Negative	Negative	Positive
		2	Negative	Negative	Negative	Positive
	NJ-23	1	Negative	Negative	Negative	Negative
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Positive
B	CA-01	1	Negative	Negative	Negative	Positive
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Positive
	CT-03	1	Negative	Negative	Negative	Positive
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Negative
	NJ-08	1	Negative	Negative	Negative	Positive
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Positive
C	NJ-07	1	Negative	Negative	Negative	Negative
		2	Negative	Negative	Negative	Negative
		3	Negative	Negative	Negative	Positive
	NJ-06	1	Negative	Negative	Negative	Positive
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Positive
	NJ-14	1	Negative	Negative	Negative	Positive
		2	Negative	Negative	Negative	Positive
		3	Negative	Negative	Negative	Positive

5.5.4 Giardia and Cryptosporidium

Amongst the nine facilities sampled, *Giardia* cysts were detected in filtrate samples from two satellite facilities (CT-03 and NJ-14), whereas *Cryptosporidium* oocysts were not detected in any filtrate samples (Table 5.2). Samples from both CT-03 and NJ-14 also had much higher particle counts than the other facilities, and the percent contribution of 7 to 15 µm particles to the total particle count was almost double compared to that of the other facilities, indicating that these facilities could have breached membranes. The presence of *Giardia* cysts in MBR effluents has been reported in another study (Bukhari, 2012).

Table 5.2. Presence of *Giardia* and *Cryptosporidium* in Filtrates from Selected Satellite Facilities

Bin	Plant Identifier	Sampling Event	Count for: *Giardia* (Cysts/10 L)	Count for: *Cryptosporidium* (Oocysts/10 L)
A	NJ-05	1	<1	<1
		2	<1	<1
		3	<1	<1
	NJ-04	1	<1	<1
		2	<1	<1
		3	<1	<1
	NJ-23	1	<1	<1
		2	<1	<1
		3	<1	<1
B	CA-01	1	<1	<1
		2	<1	<1
		3	<1	<1
	CT-03	1	**3**	<1
		2	**3**	<1
		3	**3**	<1
	NJ-08	1	<1	<1
		2	<1	<1
		3	<1	<1
C	NJ-07	1	<1	<1
		2	<1	<1
		3	<1	<1
	NJ-06	1	<1	<1
		2	<1	<1
		3	<1	<1
	NJ-14	1	**18**	<1
		2	**3**	<1
		3	**17**	<1

5.6 Summary of Results from Detailed Water Quality Evaluations

Table 5.3 summarizes the results obtained from detailed water quality evaluations. All nine satellite facilities demonstrated high nitrification efficiency during the repeat sampling events, with filtrate ammonia concentrations below 0.1 mg of N/L for most facilities and below 1 mg of N/L for all facilities. Ammonia concentrations were consistently lower for all three samples collected from these facilities, which indicates that, when properly designed and operated, satellite MBR facilities can achieve complete nitrification. Satellite facilities consistently produced oxidized effluent with filtrate TOC concentrations mostly below 6 mg/L (ranging from 3.3 to 10.5 mg/L), and values were mostly consistent during the three sampling events for each facility. Transmittance values (based on UV-254) in the filtrate samples ranged from 48 to 79% and were found to vary substantially amongst different sampling events from the same facility.

Filtrate turbidities during the repeat sampling were below 0.2 NTU for the majority of satellite facilities sampled and were consistent during the three sampling events, although turbidities for some facilities were different from those observed during the reconnaissance survey. The particle counts in the filtrate samples ranged from 2900 to 1,481,000 per 100 mL of sample and were found to be consistently high in samples collected from the CT-03 and NJ-14 facilities during all three sampling events.

The satellite MBR facilities demonstrated 2.0 to 7.5 log removal for total coliform bacteria (median, 5.3 logs), whereas the filtrate concentrations varied from less than 1 to 90,000 CFU/100 mL. The LRVs for indigenous male-specific bacteriophage varied from 2.3 to 5.8 logs (median, 3.2 logs), whereas the filtrate concentrations varied from less than 1 to 24 PFU/100 mL. Enterovirus, rotavirus, and hepatitis A viruses were not detected in any of the filtrate samples. Adenoviruses were detected in filtrate samples from all nine facilities. *Giardia* cysts were detected in filtrate samples from two satellite facilities (CT-03 and NJ-14), whereas *Cryptosporidium* oocysts were not detected in any filtrate samples. Samples from both CT-03 and NJ-14 facilities also had much higher particle and bacterial counts.

Results from the detailed water quality evaluation demonstrated that the satellite facilities consistently produced effluents with low concentrations of ammonia, TOC, and turbidity. This finding suggests that these effluents would be effectively disinfected at free chlorine CTs much lower than those indicated in Title 22. The UV-254 varied significantly during the three sampling events, indicating that the UV disinfection process, if applied to these effluents, should be designed carefully to account for changes in characteristics of residual organics present in these effluents.

Table 5.3. Summary of Results from Detailed Water Quality Evaluations

Plant Identifier	Sampling Event	TOC (mg/L)	Ammonia (mg/L-N)	Turbidity (NTU)	UV-254 (cm^{-1})	Total Particle Counts (Count/100 mL)	Total Coliform Bacteria (CFU/100 mL)	Indigenous Male-Specific Bacteriophage (PFU/100mL)
NJ-05	1	4.2	0.02	0.2	0.10	40,542	4	1
	2	6.0	0.02	0.2	0.11	71,344	1	10
	3	3.8	0.03	0.2	0.22	29,692	151	1
NJ-04	1	4.6	0.02	0.2	0.11	13,677	68	1
	2	6.5	0.02	0.2	0.16	154,435	2,500	2
	3	6.0	0.02	0.2	0.20	36,126	3,100	1
NJ-23	1	5.6	0.02	0.2	0.12	41,051	1	1
	2	7.5	0.02	0.2	0.17	31,157	1	1
	3	8.1	0.02	0.2	0.29	15,730	1	4
CA-01	1	4.9	0.50	0.1	0.12	25,130	17	1
	2	4.9	0.02	0.2	0.12	2,884	10	24
	3	5.3	0.02	0.1	0.12	35,283	47	4
CT-03	1	10.5	0.50	0.1	0.13	1,227,325	50,000	24
	2	4.6	0.45	0.2	0.13	1,480,723	90,000	6
	3	4.8	0.61	0.2	0.21	831,558	35,000	2
NJ-08	1	5.3	0.04	14.6	0.32	23,542	1	1
	2	5.3	0.02	2.7	0.19	17,135	1	8
	3	5.3	0.02	4.0	0.14	9,013	1	1
NJ-07	1	5.8	0.02	0.2	0.17	135,526	160	1
	2	5.8	0.02	0.2	0.15	36,481	79	1
	3	6.9	0.05	0.2	0.28	15,174	29	1
NJ-06	1	4.1	0.09	0.4	0.11	65,117	4	1
	2	3.8	0.12	0.3	0.16	24,181	5	22
	3	4.4	0.27	0.3	0.19	44,668	41	1
NJ-14	1	3.3	0.02	3.8	0.19	1,208,739	9,300	1
	2	4.1	0.02	2.9	0.20	1,348,011	34,000	1
	3	4.0	0.02	2.0	0.16	741,504	1,200	1

Chapter 6

Impact of Cleaned and Breached Membranes on Effluent Water Quality

6.1 Introduction and Objective

Data generated from the reconnaissance survey and detailed water quality evaluations provide insight on effluent water qualities produced by a wide range of satellite facilities operating under routine conditions. Although this information is critical for characterization of effluents from satellite facilities, assessing the impact of membrane system failure on effluent water quality and subsequent disinfection requirements is also important. Because of regulatory requirements, simulating worst-case scenarios such as membrane failure in a full-scale water recycling facility is not feasible. In order to achieve this objective, two different pilot systems were utilized during the study period and membrane cleaning and breaching events were performed and monitored in order to assess their impact on effluent quality and subsequent disinfection requirements.

6.2 Baseline Concentrations of Water Quality Parameters for Intact System

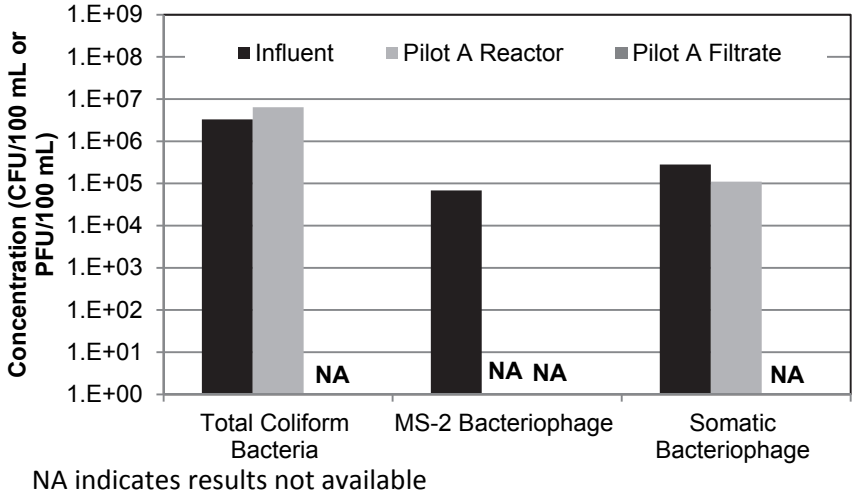
Water quality sampling of two pilot MBR systems was conducted to determine baseline concentrations of microbial indicators present in the filtrates of these two pilot systems and to ensure that the membranes for these pilot systems were intact before the membrane cleaning and breaching experiments occurred. Samples were collected from the influent, bioreactor, and filtrate of both pilot systems and were analyzed for total coliform bacteria, indigenous male-specific bacteriophage, and somatic bacteriophage.

As shown in Figure 6.1, the concentrations of total coliform bacteria, male-specific bacteriophage, and somatic bacteriophage in the influent wastewater were 6–7, 4–5, and 5–6 logs, respectively. The concentrations of these organisms in the bioreactor were similar to those in the influent wastewater, although the results for the male-specific bacteriophage concentration in the reactor of system B were inconclusive. The total coliform bacterial concentration in the filtrate sample for MBR pilot system B was measured at 5 CFU/100 mL, whereas the male-specific and somatic bacteriophage concentrations were measured at 17 and 2 PFU/100 mL, respectively. Because pilot system B utilized backwash after each filtration cycle, it is possible that contamination of the backwash tank could have resulted in the presence of coliform bacteria in the filtrate line and subsequently in the filtrate samples. Other studies have reported such a phenomenon with other MBR systems that utilized backwashing as a membrane fouling control strategy (Adham and DeCarolis, 2004; Hirani et al., 2010). Results from the baseline sampling demonstrated that MBR pilot system B achieved 5.8 log, 3.6 log, and 5.1 log removal of total coliform bacteria, male-specific bacteriophage, and somatic bacteriophage, respectively, while operating with intact membranes. When analyses were conducted for *Cryptosporidium* and *Giardia*, none of these protozoa was detected in the filtrate samples for MBR system B.

The filtrate sample from MBR pilot system A was not collected during this sampling event because of a filtrate pump failure on the day of the sampling event, but previous sampling events for this pilot system had shown the absence of total coliform bacteria and male-specific

bacteriophage in the filtrate samples. A later sampling event for MBR pilot system A demonstrated the absence of protozoa in the filtrate samples.

Results from the baseline sampling event confirmed that both MBR pilot systems were operating with intact membranes and that either one of these pilot systems could be utilized for membrane cleaning and membrane breaching experiments. Pilot system A was selected for further experiments because the pilot setup was more convenient for sampling for *Giardia*, *Cryptosporidium*, and viruses.



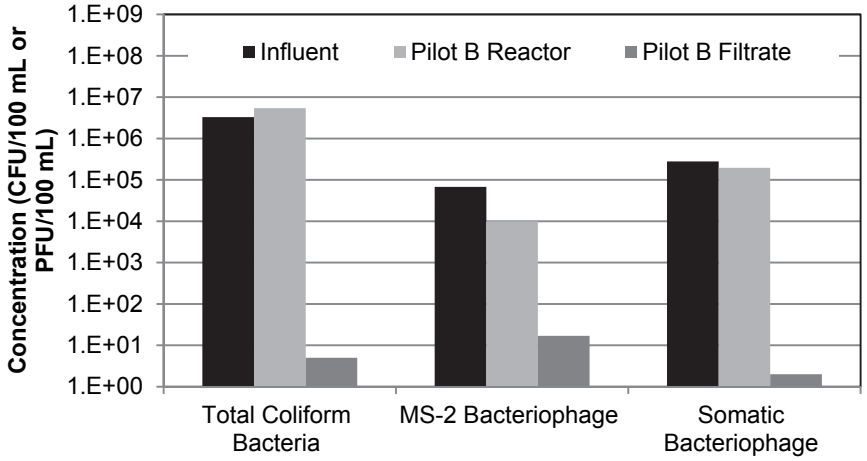


Figure 6.1. Concentration of organisms in the influent wastewater, reactor, and filtrate of the MBR pilot systems.

6.3 Impact of Cleaned Membranes on Effluent Water Quality

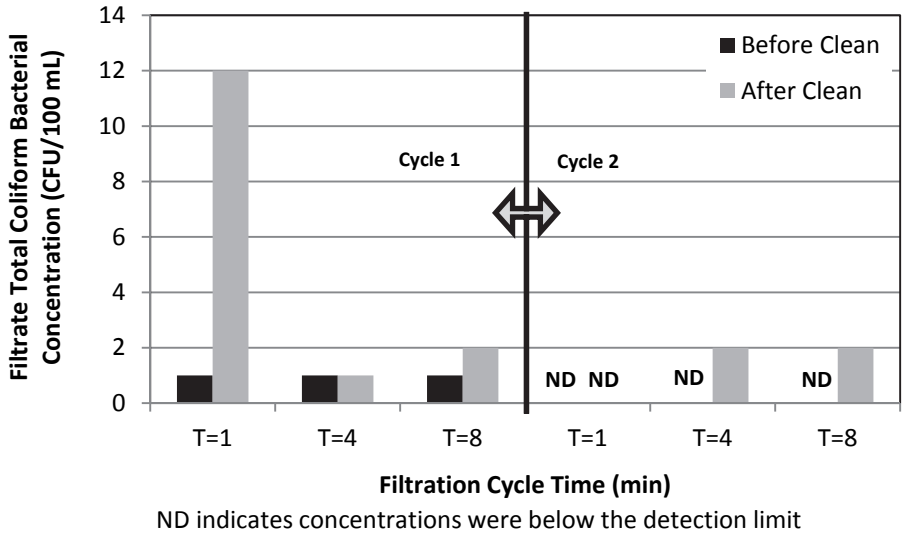
To assess the impact of chemical cleaning on microbial rejection by the MBR process and subsequent disinfection requirements, MBR influent and effluent samples were collected immediately before and after chemical cleaning. Samples spanning the entire filtration cycle were collected over two consecutive filtration cycles to determine the log removal of coliform bacteria and indigenous male-specific bacteriophage. A sample also was analyzed for enteric viruses and protozoa.

After completion of baseline sampling for pilot system A, influent and filtrate samples were collected after the system was in operation for several weeks. The intent of this sampling event was to determine the rejection of microbial indicators by a fouled membrane. After completion of the fouled membrane sampling, the membranes were cleaned as specified by the manufacturer. The permeability of the membranes increased by about 25% after cleaning of the membranes. A second set of samples was collected immediately after cleaning of the membranes. Influent and filtrate samples were analyzed for the same set of parameters as they were for the fouled membranes. Water quality samples were collected at 1, 4, and 8 min in the 9-min filtration cycle for two consecutive cycles. The objective of collecting multiple samples during the filtration cycle was to observe the impact of a fouling control strategy (relaxation) on rejection of indigenous organisms by the MBR system. For the pilot system utilized for the study, the filtration cycle was 9 min long followed by a 1-min relaxation period.

6.3.1 Total Coliform Bacteria

Figure 6.2 presents the filtrate coliform bacterial concentrations before and after cleaning of the membranes. Among the six samples collected over two consecutive filtration cycles, the total coliform bacterial concentrations in the filtrate samples collected after cleaning of the membranes were similar to or higher than those for samples collected before cleaning of the membranes, although these concentrations were mostly equal to or less than 2 CFU/100 mL. Other than the first sample collected during the first filtration cycle (Cycle 1, $T = 1$ min) for the cleaned membrane, filtrate coliform bacterial concentrations were usually low, indicating that membrane cleaning did not pose a substantial risk with respect to the passage of total coliform bacteria.

Figure 6.3 presents the LRVs for total coliform bacteria before and after cleaning of the membranes. The MBR system achieved about a 7 log removal of total coliform bacteria before the membranes were cleaned. After cleaning of the membranes, the LRVs for the coliform bacteria decreased from 7 logs to 4 logs for the first sample collected at the start of the filtration cycle but the LRVs increased during the filtration cycle to levels normal for the middle of the cycle. It is unclear if the lower LRV or greater passage of coliform bacteria observed for the first sample was due to experimental or analytical error or if it was an actual impact of membrane cleaning. Given the pore size of the membrane (0.1 μm), the coliform bacteria should be removed to a great extent through the intact membranes because of size exclusion even when the membranes are clean, but this hypothesis could not be confirmed on the basis of the results from the study. The samples collected during the second filtration cycle after cleaning the membranes showed a minimal difference in LRVs for the total coliform bacteria compared to the samples collected before the membranes were cleaned.



ND indicates concentrations were below the detection limit

Figure 6.2. Filtrate total coliform bacterial concentrations before and after cleaning the MBR membranes.

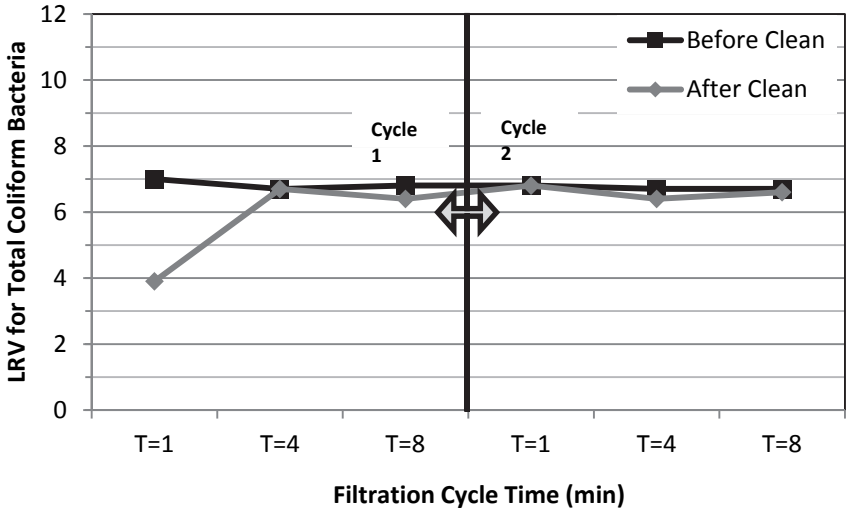


Figure 6.3. LRVs for total coliform bacteria before and after cleaning the MBR membranes.

6.3.2 Indigenous Male-Specific Bacteriophage

Figure 6.4 presents the filtrate indigenous male-specific bacteriophage concentrations before and after cleaning of the membranes. Filtrate male-specific bacteriophage concentrations were observed to be higher for cleaned membranes than for fouled membranes for four out of six samples collected over two consecutive filtration cycles. Because male-specific bacteriophage are smaller (0.025 μm) than the nominal membrane pore size (0.1 μm), they are expected to pass through the clean membranes to a greater extent than through the fouled membranes if the bacteriophage are not particle associated. Pore blocking and pore constriction would typically enhance the rejection of viruses through membranes, so membrane cleaning would be expected to increase the passage of viruses. Although results from this experiment may support this

hypothesis, the viral concentrations in the filtrate samples were still relatively low for most of the samples collected after cleaning the membranes. The LRVs calculated on the basis of influent and filtrate concentrations are shown in Figure 6.5.

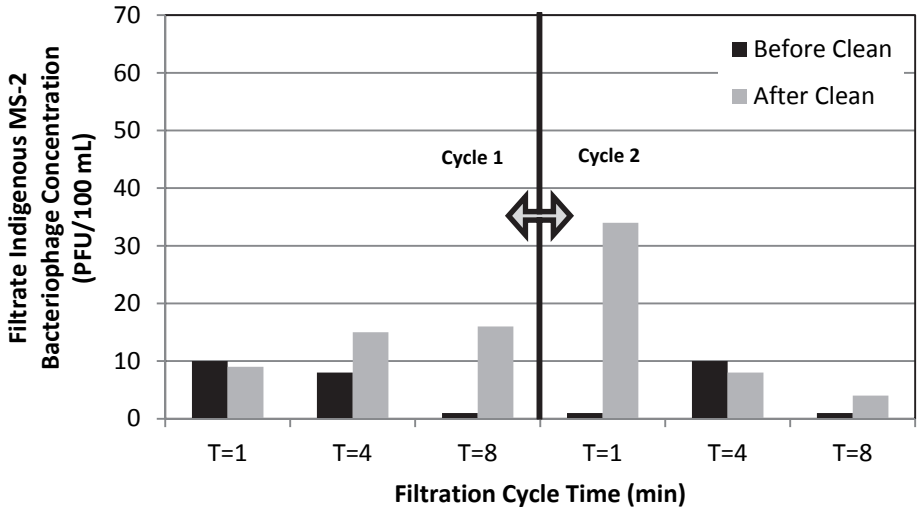


Figure 6.4. Filtrate indigenous male-specific bacteriophage concentrations before and after cleaning the MBR membranes.

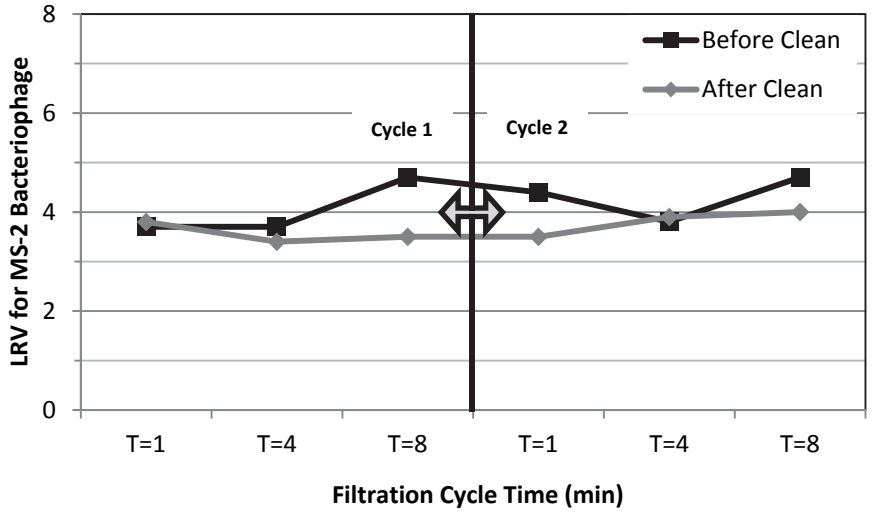


Figure 6.5. LRVs for male-specific bacteriophage before and after cleaning the MBR membranes.

6.3.3 Enterovirus, Rotavirus, Hepatitis A Virus, Adenovirus

Any impact from cleaning could not be deduced because enteroviruses, rotaviruses, and hepatitis A viruses were not detected in the filtrate samples collected before and after membrane cleaning, whereas adenoviruses were detected in both samples.

6.3.4 Giardia and Cryptosporidium

Giardia and *Cryptosporidium* were not detected in the 10 L filtrate samples collected before and after chemical cleaning. *Giardia* cysts (8–16 μm) and *Cryptosporidium* oocysts (4–6 μm) are larger than the membrane pore size (0.1 μm), so one could expect their complete removal through size exclusion by an intact membrane.

6.4 Impact of Breached Membranes on Effluent Water Quality

Loss of membrane integrity in an MBR can result in the passage of particles and microorganisms in the filtrate. The current regulations in California (CDPH Title 22 regulations) stipulate monitoring of filtrate turbidity to safeguard against membrane breach. The regulations require that the filtrate turbidity of MBR systems should be below 0.2 NTU for 95% of the time within a 24-hour period and should never exceed 0.5 NTU. In order to determine the impact of membrane breach on the passage of indigenous microorganisms and subsequent disinfection requirements, a membrane breach experiment was conducted on one of the MBR pilot systems. The intent of the experiment was to breach the membrane in a way that could cause the filtrate turbidity to exceed CDPH Title 22 requirements.

The membrane breach experiment was conducted on pilot system A. The mixed liquor from the membrane tank was drained, and the membrane module was pulled out from the membrane tank by using a crane (Figure 6.6). One of the 18 membrane sheets was then compromised by slitting it to cause a significant spike in the filtrate turbidity. The slit was 3 cm long and 2–4 mm wide. Figure 6.7 shows the picture of the membrane sheet that was intentionally compromised. The membrane module was then reinstalled in the membrane tank, and the MBR system was brought back. Samples spanning the entire filtration cycle were collected over two consecutive filtration cycles to determine the log removal of coliform bacteria and indigenous male-specific bacteriophage. A sample was also analyzed for enteric viruses and protozoa.

Figure 6.6. Uninstalling the membrane module to breach the membrane.

Figure 6.7. Photograph of the breached membrane.

Filtrate turbidity of the MBR system was recorded continuously at 1-min intervals before and after breaching of the membranes. Figure 6.8 presents the filtrate turbidity observed before and after breaching of the membranes. As expected, the filtrate turbidity for the MBR system was consistently below 0.1 NTU before the membrane was breached. The filtrate turbidity varied from 0.05 to 1.0 NTU for the first 8 h after breaching of the membrane and degraded progressively after the membrane system was operated with the breached membrane for several hours. Figure 6.9 shows the variation in filtrate turbidity over three consecutive filtration cycles of 10 min each (9 min of filtration followed by 1 min of relaxation). As shown, the filtrate turbidity spiked intermittently in the filtration cycle but gradually decreased to normal levels once the membrane breach was plugged with mixed liquor solids. The filtrate turbidity became progressively worse after several hours of operation (Figure 6.10), probably because the membrane breach (slit) gradually widened with time.

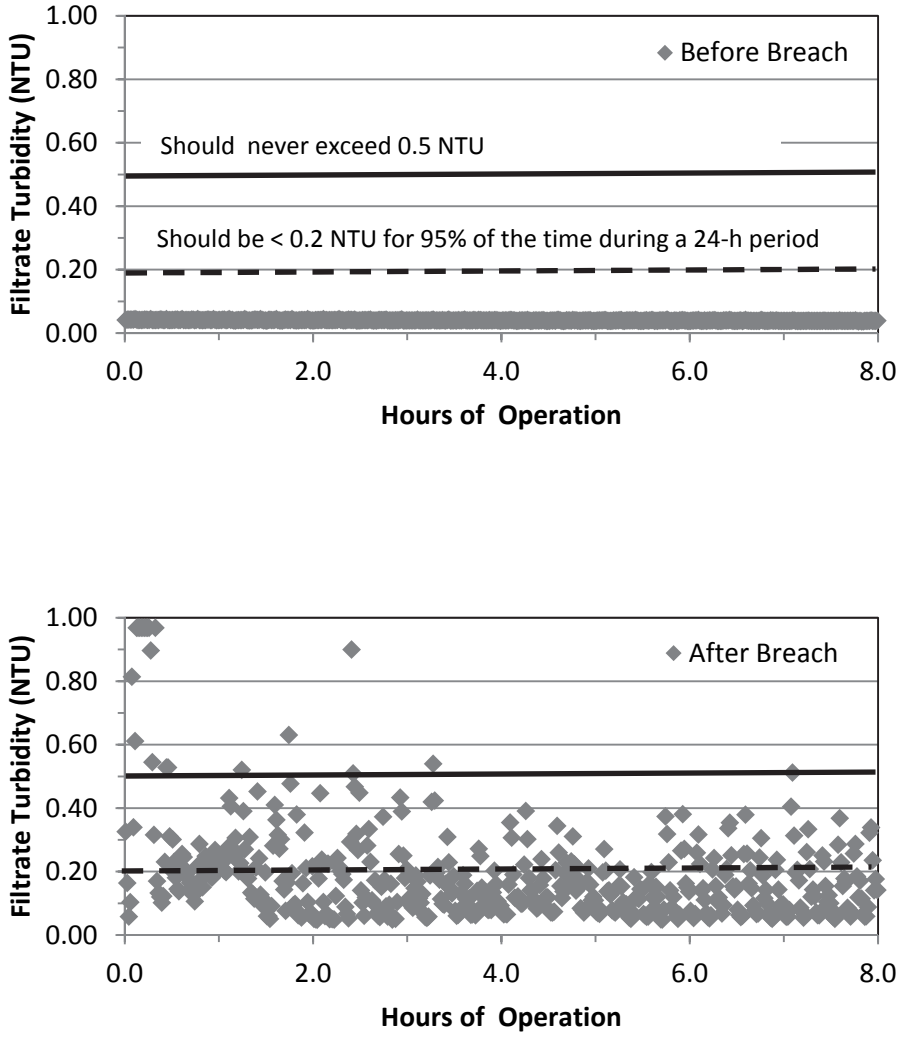


Figure 6.8. Filtrate turbidity before and after membrane breach.

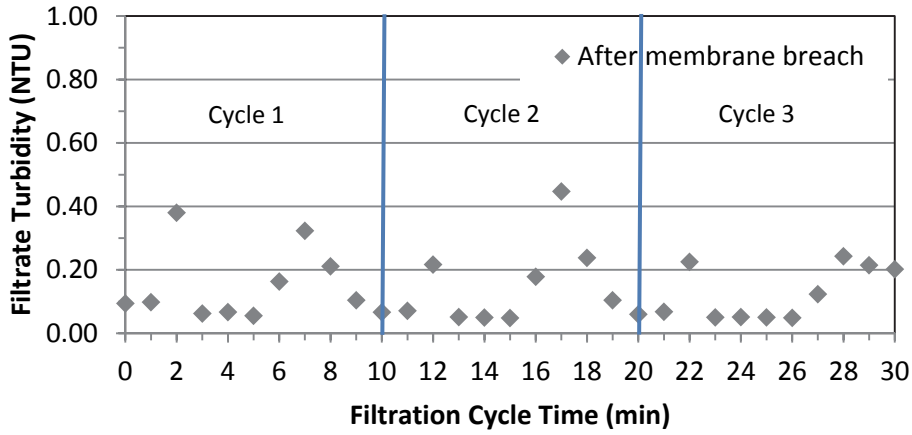


Figure 6.9. Variation in filtrate turbidity within the filtration cycle 30 min after membrane breach.

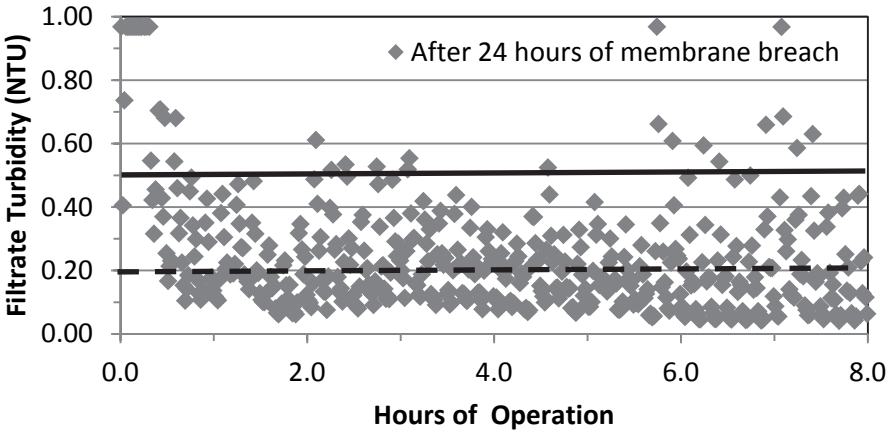


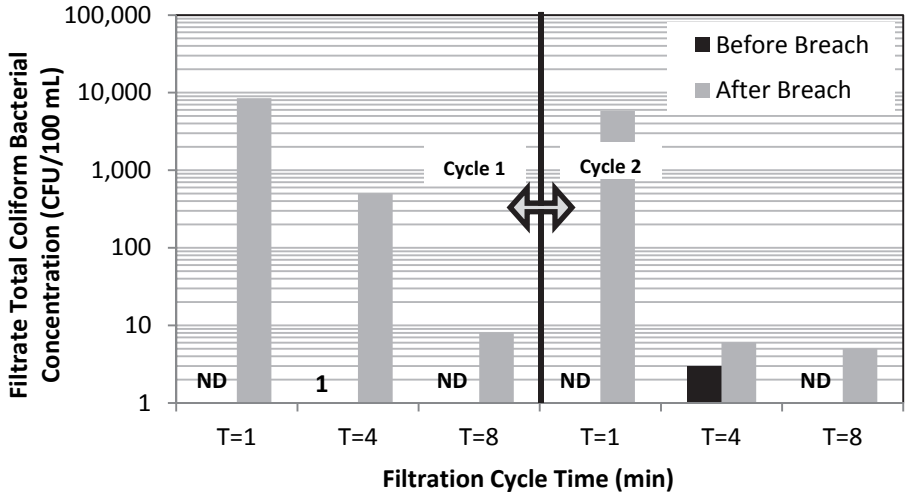
Figure 6.10. Filtrate turbidity 24 h after membrane breach.

6.4.1 Total Coliform Bacteria

The filtrate total coliform bacterial concentrations before and after breaching of the membranes are shown in Figure 6.11. For the samples collected when the membranes were intact, the filtrate concentrations were always at or below 3 CFU/100 mL. Membrane breach caused the filtrate coliform bacterial concentrations to increase substantially for most of the samples. The highest concentration (8500 CFU/100 mL) was observed for the first filtrate sample (Cycle 1, $T = 1$ min), and it gradually declined as the filtration cycle progressed. Following the relaxation period and at the beginning of the second filtration cycle, the coliform bacterial concentration increased from 8 to 5800 CFU/100 mL, indicating that air scour coupled with relaxation may have helped remove the cake layer from the membrane surface and unplugged the membrane breach, which could have enhanced the removal of the coliform bacteria as the filtration cycle progressed. A similar

phenomenon was observed during the second filtration cycle; rejection of coliform bacteria increased as the filtration cycle progressed.

MBRs are typically operated at a high mixed MLSS concentration (8000–10,000 mg/L). As the membrane filtration begins, the solid loading on the membrane surface increases, resulting in cake layer formation. Although air scour applied on the membrane surface mitigates the cake layer formation, it is essential to relax or backwash the membranes every few minutes (typically every 8–10 min) to remove the solids from the membrane surface. When the membranes are in relaxation mode (filtration process is stopped), air scour is more effective in removing the solids from the membrane surface because the influx of solids towards the membrane surface does not occur during the relaxation mode. Although this phenomenon can assist in mitigating membrane fouling, it can also unplug the membrane breach and can potentially increase the passage of microorganisms at the onset of the filtration cycle. The LRVs observed for the coliform bacteria over two consecutive filtration cycles are shown in Figure 6.12.



ND indicates concentrations were below the detection limit

Figure 6.11. Filtrate total coliform bacterial concentrations before and after breaching the MBR membranes.

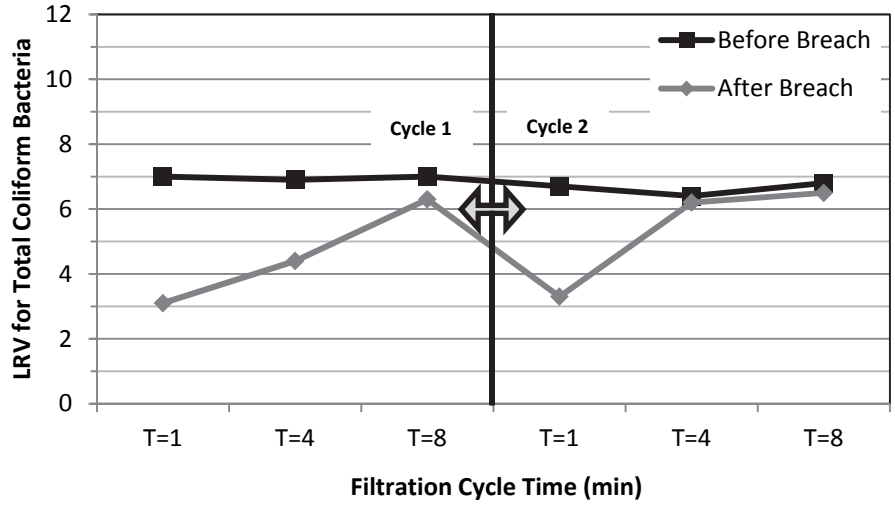


Figure 6.12. LRVs for total coliform bacteria before and after membrane breach.

6.4.2 Indigenous Male-Specific Bacteriophage

Figure 6.13 presents the filtrate indigenous male-specific bacteriophage concentrations before and after membrane breach. Although male-specific bacteriophage were detected in all the samples collected before and after membrane breach, their concentrations after membrane breach were higher than before the breach in five of six samples. Because the differences in concentrations were not substantial, the LRVs for male-specific bacteriophage did not change substantially before and after membrane breach (Figure 6.14). Because there were always acceptable numbers of indigenous male-specific bacteriophage detected in the bioreactor and filtrate samples (before and after breach), assay sensitivity was not an issue.

There was a definite difference in rejection of coliform bacteria and indigenous male-specific bacteriophage by the breached membrane. The rejection of coliform bacteria increased as the filtration cycle progressed and as the membrane breach was plugged with mixed liquor, resulting in reduction of the effective size of the breach. On the contrary, the rejection of the indigenous male-specific bacteriophage did not change as the membrane breach was plugged, even though the male-specific bacteriophage are smaller than the coliform bacteria. The higher densities of coliform bacteria may therefore include free-floating, non-particle-associated coliform bacteria that can pass through the breached membrane.

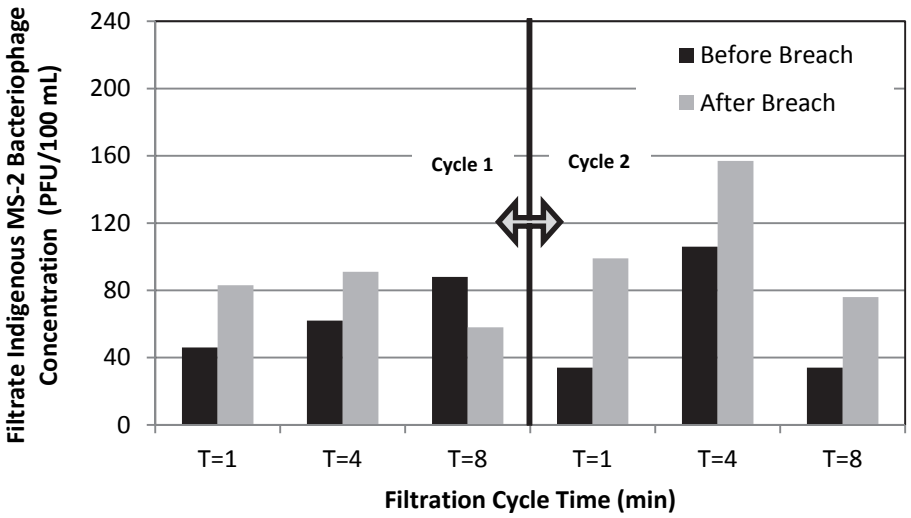


Figure 6.13. Filtrate indigenous male-specific bacteriophage concentrations before and after breaching the MBR membranes.

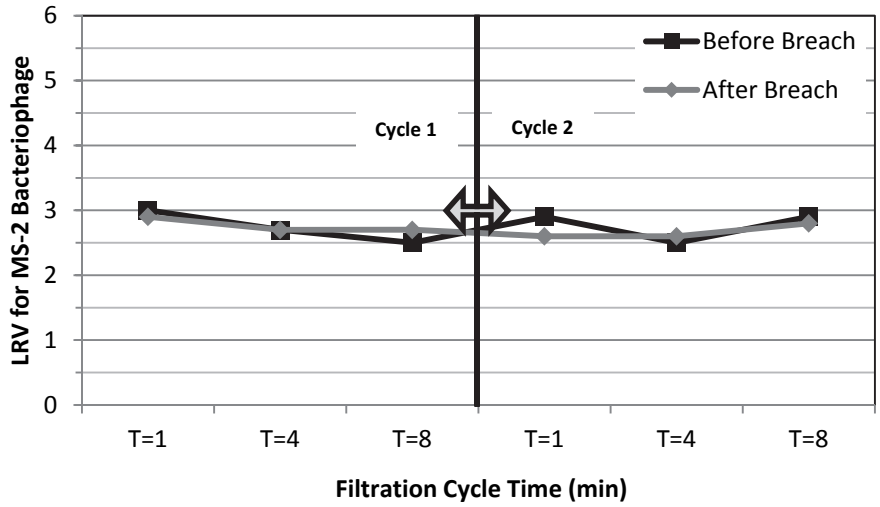


Figure 6.14. LRVs for male-specific bacteriophage before and after membrane breach.

6.4.3 Enterovirus, Rotavirus, Hepatitis A Virus, Adenovirus

Any impact from membrane breaching could not be deduced because enteroviruses, rotaviruses, and hepatitis A viruses were not detected in the filtrate samples collected before and after membrane breach, whereas adenoviruses were detected in both samples.

6.4.4 Giardia and Cryptosporidium

Giardia cysts and *Cryptosporidium* oocysts were not detected in the 10 L filtrate samples collected before membrane breach. After the membrane was breached, *Giardia* cysts were detected in the filtrate sample, though at a low concentration (1/10 L). *Cryptosporidium* oocysts were not detected in the filtrate sample collected after membrane breach.

Chapter 7

Free Chlorine CT Values for MBR Effluents from Routine and Compromised Conditions

7.1 Introduction and Objective

To assess the disinfection requirements for MBR effluents during operation under routine and stressed conditions, bench-scale microbial inactivation experiments were conducted on effluents from satellite facilities and MBR pilot systems. Effluents from three different satellite facilities (from different performance bins) were collected during three separate sampling events (three events per each facility), and these effluents were subjected to free chlorine CTs ranging from 1 to 59 mg-min/L to assess microbial inactivation. Effluents from an MBR pilot system were collected immediately after the membranes were cleaned, and the effluents were subjected to free chlorine CTs ranging from 4 to 46 mg-min/L to assess inactivation of total coliform bacteria and male-specific bacteriophage. In order to assess the impact of membrane breach on disinfection requirements of MBR effluents, several filtrate samples were collected from an MBR pilot system with a breached membrane (filtrate turbidity ranging from 1.0 to 6.9 NTU), and microbial inactivation experiments were conducted on these samples as well.

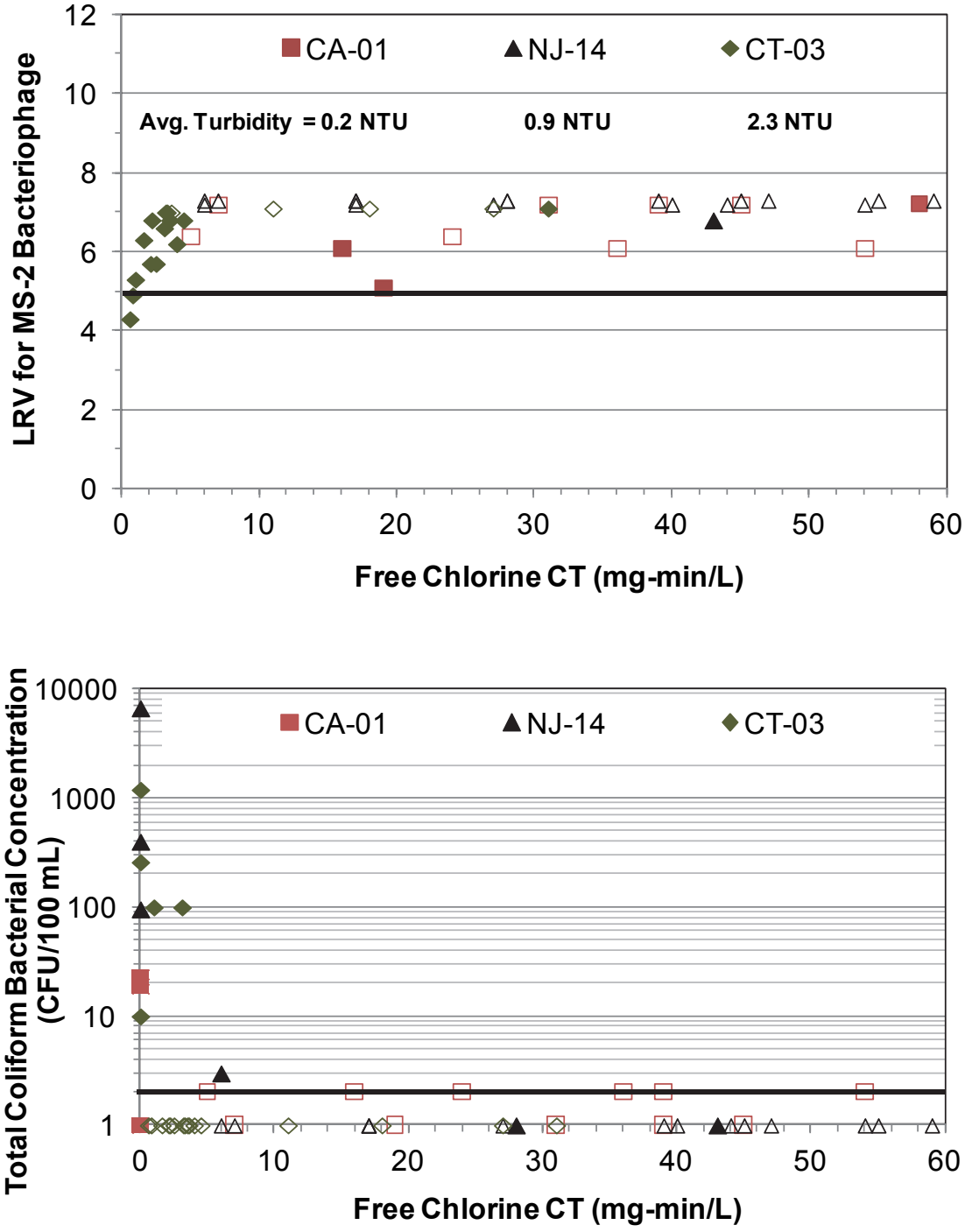
7.2 CT Values for Effluents from Satellite MBR Facilities

Microbial inactivation experiments on the effluents from the three selected satellite facilities from different performance bins were conducted to ensure proper representation of a wide range of effluent water qualities produced by satellite facilities. Two satellite facilities from Bin B and one satellite facility from Bin C were selected for these experiments. Because Bin A consisted of satellite facilities that produced the best water qualities, microbial inactivation experiments on effluents from Bin A facilities would hypothetically demonstrate much lower disinfection requirements than would Bin B and C facilities. Therefore, only bins B and C were selected for microbial inactivation experiments because they would represent worst-case scenarios and would more likely be utilized by regulators to develop disinfection requirements.

Results from the microbial inactivation experiments conducted on filtrate samples from the CA-01, NJ-14, and CT-03 facilities are presented in Figure 7.1. On the basis of the results obtained, a free chlorine CT value of 10 mg-min/L was sufficient to provide a 5 log removal of seeded male-specific bacteriophage and removal of total coliform bacteria to the method detection limit (1 CFU/100 mL). Because facilities NJ-14 and CT-03 belonged to Bin C (worst effluent water qualities), free chlorine CT requirements for these facilities would represent the most conservative scenarios for disinfection of effluents from the satellite facilities evaluated. The effluent water qualities for the satellite facilities at the time of inactivation studies are presented in Table 7.1.

Table 7.1. Effluent Water Quality for the Satellite Facilities at Time of Microbial Inactivation Studies

Plant Identifier	Inactivation Experiment/Run	Ammonia (mg/L-N)	Turbidity (NTU)
CA-01	1	0.4	0.2
	2	0.2	0.3
	3	0.2	0.1
NJ-14	1	0.3	0.2
	2	0.2	2.3
	3	0.1	0.1
CT-03	1	0.2	3.3
	2	0.2	2.9
	3	0.1	0.7



Open symbols indicate concentrations less than the method detection limit.

Figure 7.1. Inactivation of total coliform bacteria and seeded male-specific bacteriophage in MBR filtrate from satellite facilities.

7.3 CT Values for Effluents from MBR Systems with Cleaned Membranes

To determine the impact of membrane cleaning on microbial inactivation in MBR effluent, two sets of bench-scale experiments were conducted on filtrate samples collected immediately after cleaning of the membranes. During these experiments, the filtrate samples were subjected to 12 different free chlorine CTs ranging from 4 to 46 mg-min/L. As shown in Figure 7.2, a CT of 5 mg-min/L was sufficient to achieve 5 log removal of seeded male-specific bacteriophage. Because the total coliform bacteria were not present in the filtrate samples collected immediately after cleaning of the membranes, they were measured below the detection limit for all disinfected samples. Results from these experiments show that membrane cleaning did not cause any significant deterioration in the effluent water quality with respect to the disinfection efficacy.

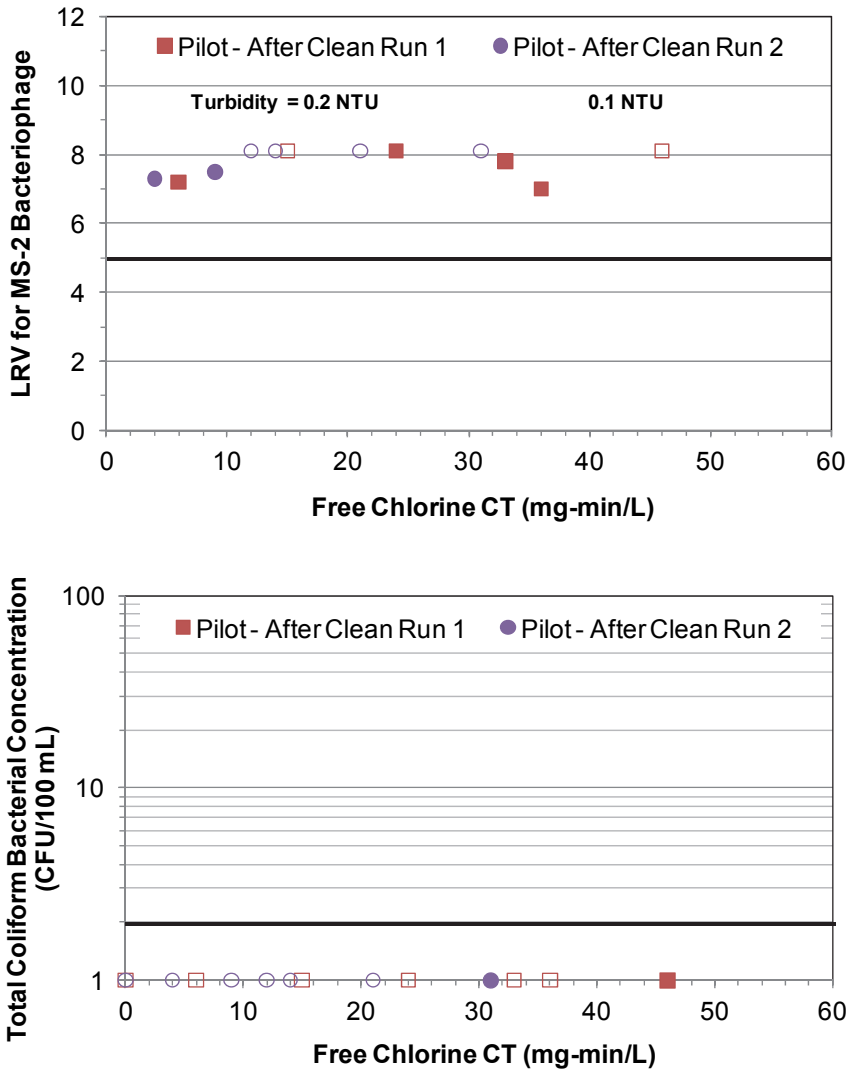


Figure 7.2. Inactivation of total coliform bacteria and seeded male-specific bacteriophage in MBR filtrate collected immediately after cleaning the membranes.

7.4 CT Values for Effluents from MBR Systems with a Breached Membrane

Bench-scale microbial inactivation experiments were conducted on the filtrate samples collected from the MBR system operating with a breached membrane to develop the residual−response curves for total coliform bacteria and seeded male-specific bacteriophage. The objective of these experiments was to determine the free chlorine CTs necessary to achieve a desired level of microbial inactivation in MBR effluents produced from breached membranes. In these experiments, multiple filtrate samples were collected from the MBR system operating with breached membranes. The turbidity of these samples ranged from 2.8 to 6.9 NTU. To achieve the desired filtrate turbidity of 1.0 NTU, filtrate samples collected while the MBR system was operating with intact membranes were blended with those from the breached membrane. Two sets of experiments were conducted on those samples with a turbidity of 1.0 NTU, whereas four sets of experiments were conducted on samples with turbidities ranging from 2.8 to 6.9 NTU. The results from the experiments were divided into three groups on the basis of filtrate turbidity: (1) 1.0 NTU, (2) 2.8 to 4.1 NTU, and (3) 6.9 NTU.

As shown in Figure 7.3, a CT of 30 mg-min/L was required to achieve greater than 5 log removal of seeded male-specific bacteriophage and removal of total coliform bacteria at or below the method detection limit (2 CFU/100 mL) for samples with a filtrate turbidity of 1.0 NTU. These CT values were also sufficient to reduce the concentration of total coliform bacteria and male-specific bacteriophage to below the method detection limit for the majority of the samples. Regulations in the state of California require MBR systems to shut down or divert the filtrate flow if the turbidity exceeds 0.5 NTU. As such, these experiments, being conducted on filtrate samples with a turbidity of 1.0 NTU, represent a worst-case MBR effluent scenario.

Figure 7.4 presents the residual−response curves and concentration of total coliform and male-specific bacteriophage in the filtrate at different CTs for samples with turbidity ranging from 2.8 to 4.1 NTU. Results from the experiments show that a CT of 14 mg min/L was still sufficient to achieve greater than 5 log removal of seeded male-specific bacteriophage, although greater CT values may be required to reduce the concentration of total coliform bacteria to less than 2 CFU/100 mL.

Figure 7.5 presents the results obtained from the microbial inactivation experiments conducted on filtrate samples with a high turbidity (6.9 NTU). Although such high levels of turbidity are not likely to be observed in MBR filtrate, the objective of this experiment was to determine the impact of high filtrate turbidity on microbial inactivation. Results from the experiment showed that CTs of 36 mg-min/L or higher were sufficient to achieve greater than 5 log removal of seeded male-specific bacteriophage. However, high filtrate turbidity reduced the disinfection efficacy of free chlorine in inactivating total coliform bacteria and male-specific bacteriophage to the extent that even a CT of 88 mg-min/L was not sufficient to reduce the concentration of these organisms to below the method detection limit.

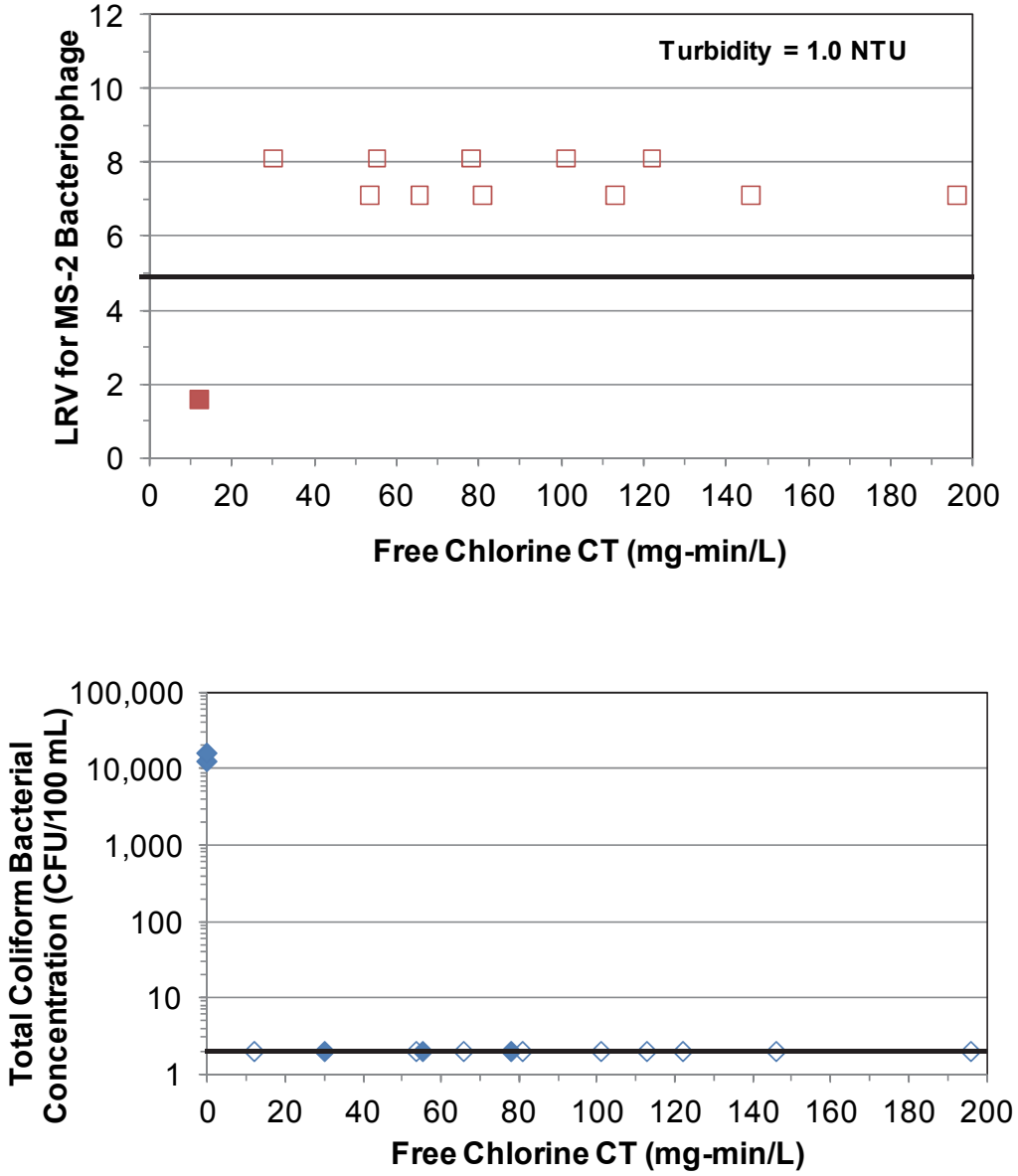


Figure 7.3. Inactivation of total coliform bacteria and seeded male-specific bacteriophage in MBR filtrate at a turbidity of 1.0 NTU.

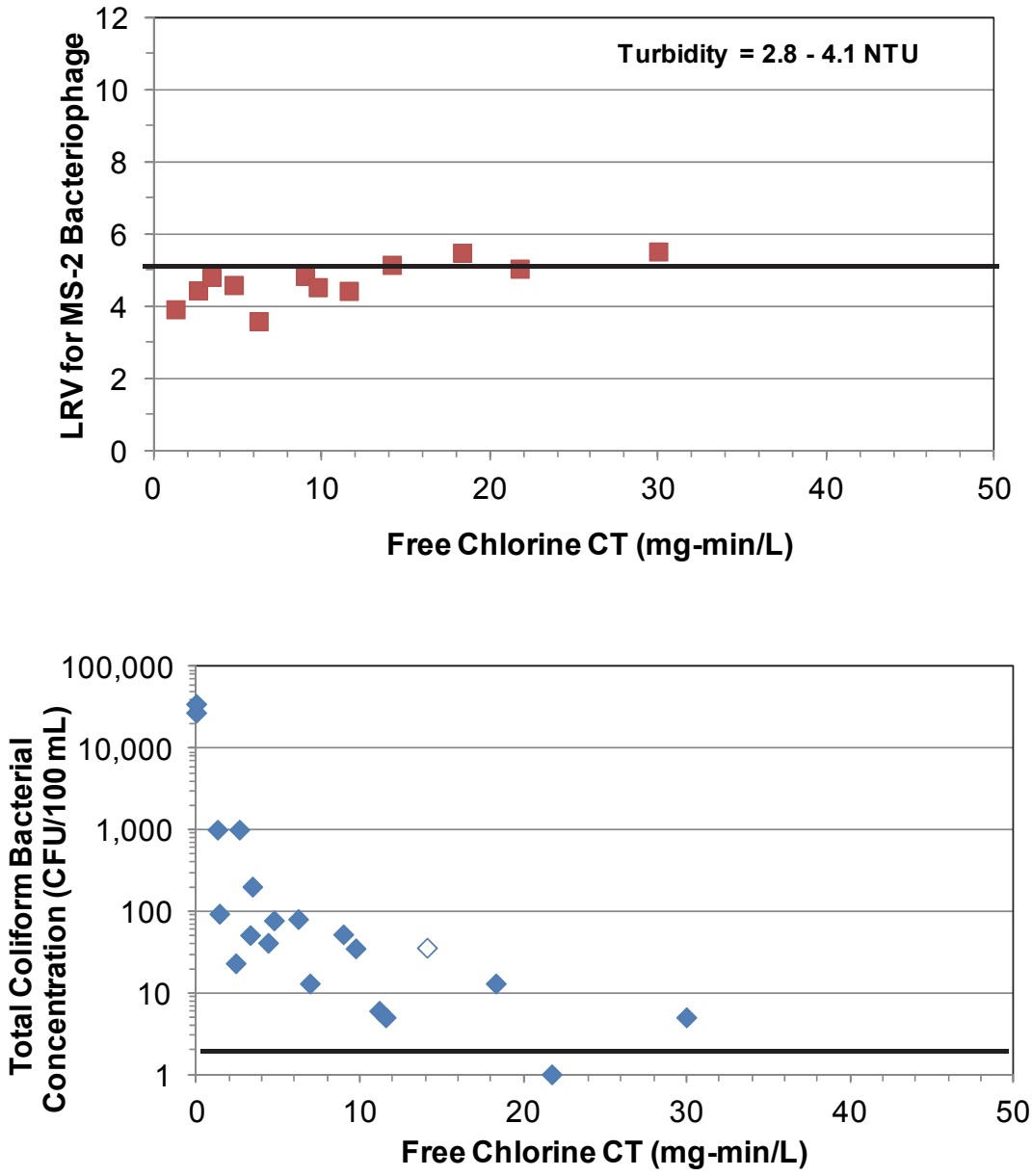


Figure 7.4. Inactivation of total coliform bacteria and seeded male-specific bacteriophage in MBR filtrate at a turbidity of 2.8 to 4.1 NTU.

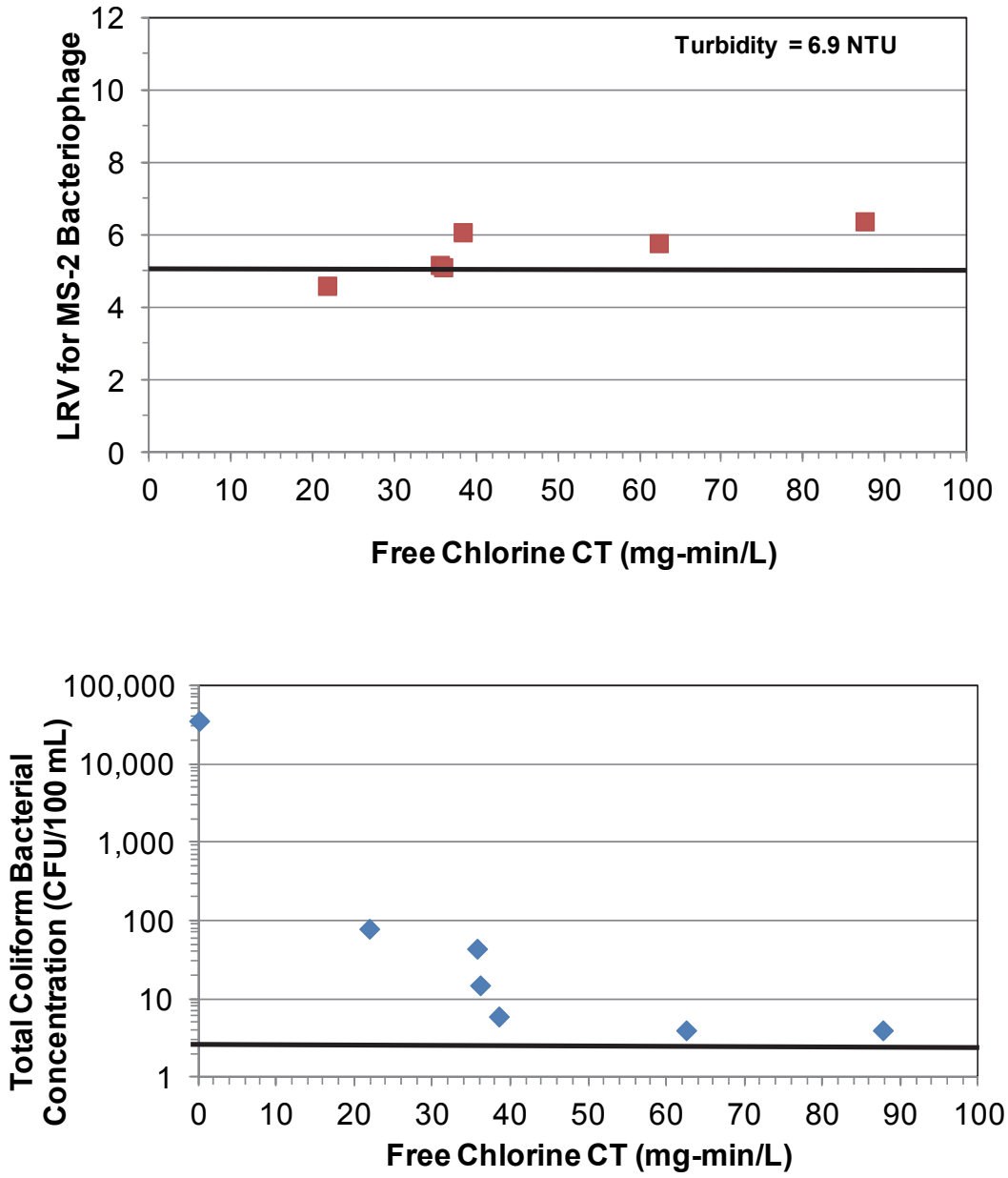


Figure 7.5. Inactivation of total coliform bacteria and seeded male-specific bacteriophage in MBR filtrate at a turbidity of 6.9 NTU.

Chapter 8

Variability in Effluent Ammonia Concentration at a Water Recycling Facility

8.1 Introduction and Objective

Use of free chlorine as a disinfectant will require ammonia concentration in the effluents of satellite facilities to be low. Although it is expected that the satellite MBR facilities will produce fully nitrified effluents because they are typically operated at a long SRT, understanding the impact of operating conditions, upsets in bioreactor basins, and operational issues on effluent ammonia concentration is critical. Therefore, the objective of this task was to monitor the variability in effluent ammonia concentration at a full-scale water recycling facility along with operational data to assess the consistency in nitrification efficiency of the facility and to correlate any possible failures with operational parameters. In order to achieve this objective, an online ammonia analyzer was installed at the CA-01 water recycling facility, and operational parameters that can impact nitrification, such as dissolved oxygen concentrations in the aeration basins and SRT, were monitored and recorded.

8.2 Effluent Ammonia Concentration at an MBR Water Recycling Facility

Figure 8.1 presents the MBR effluent ammonia concentrations at the CA-01 facility over 2500 h. Although the CA-01 facility was able to produce fully nitrified effluent for most of the test period, the effluent ammonia concentrations occasionally reached up to 3.4 mg of N/L. Details on potential causes for these spikes are discussed in the following sections.

To provide a keener understanding of diurnal variations in effluent ammonia concentration, effluent concentrations for two different selected weeks are presented in Figures 8.2 and 8.3. During the week of March 18, 2011 (Figure 8.2, 25–192 h of operation), the effluent ammonia concentrations were usually below 0.4 mg of N/L, but spikes in concentration were observed on March 20, 21, and 23. During the week of June 16, 2011 (Figure 8.3, 2185–2352 h of operation), the effluent ammonia concentrations were typically below 0.4 mg of N/L, but spikes in concentration were observed at about 6 p.m. for 5 out of 7 days during that week.

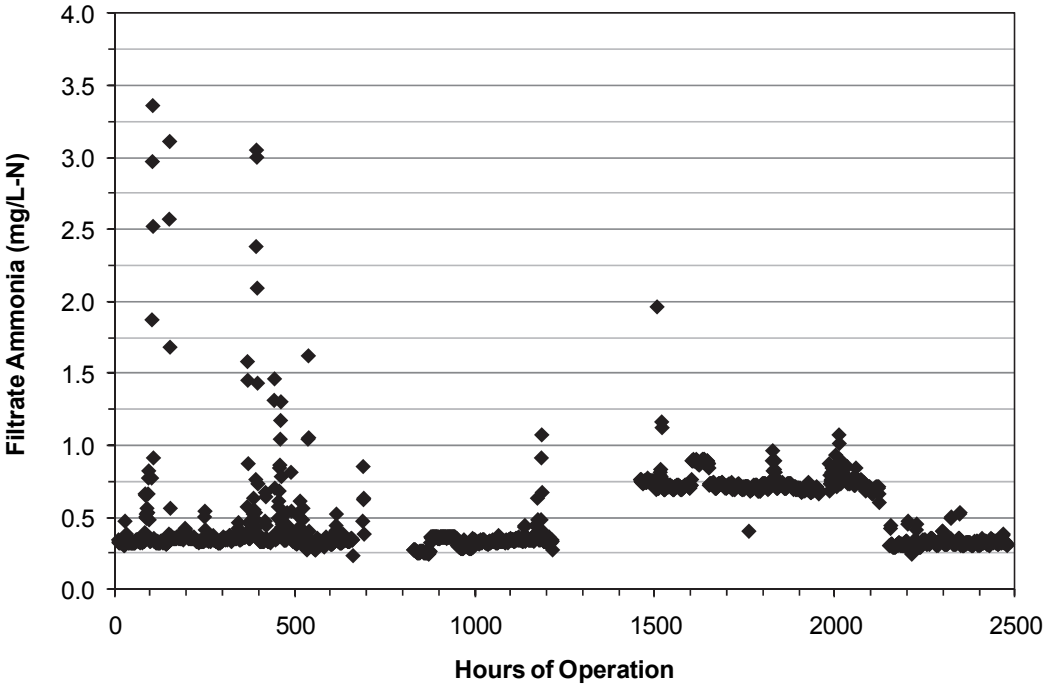


Figure 8.1. Ammonia concentrations measured in the MBR filtrate produced at the CA-01 facility.

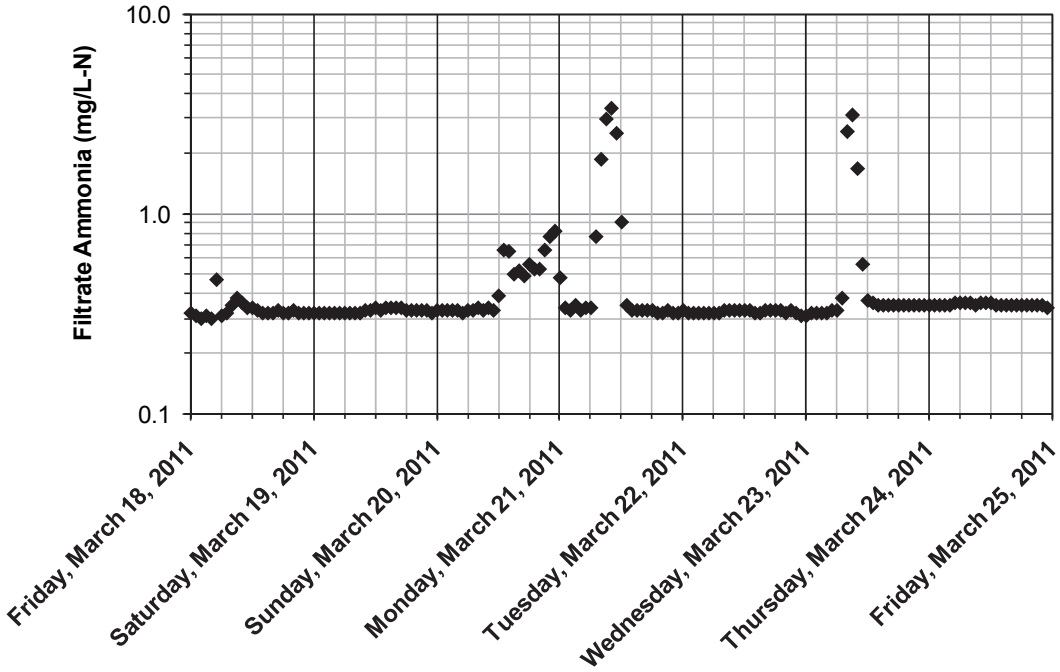


Figure 8.2. Diurnal variations in ammonia concentration in the MBR filtrate at the CA-01 facility measured using an online ammonia analyzer (week of March 18, 2011).

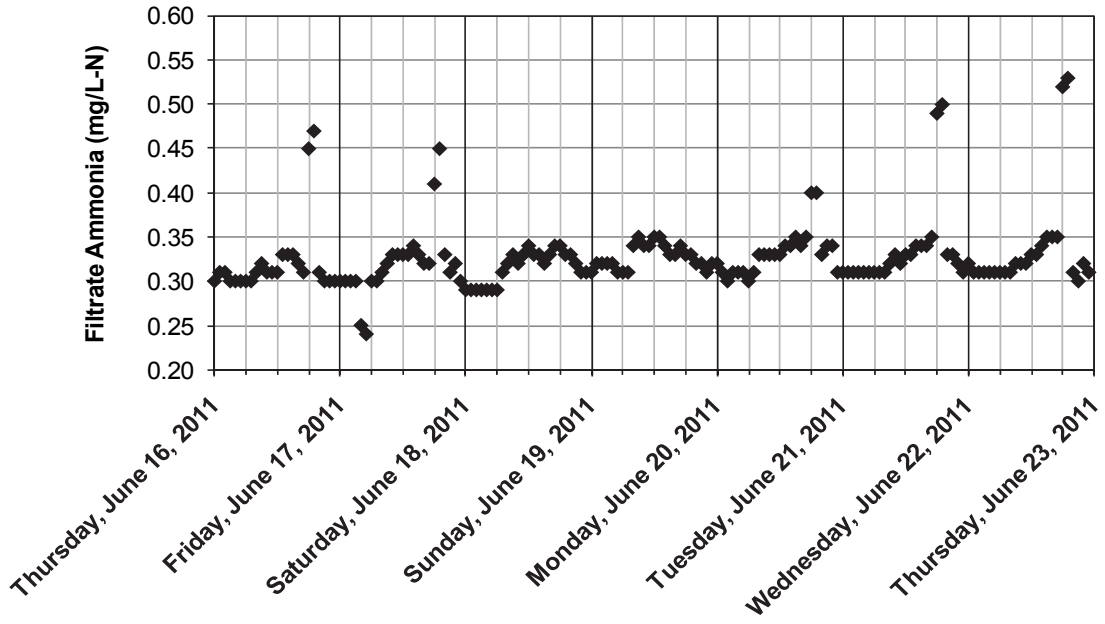


Figure 8.3. Diurnal variations in ammonia concentration in the MBR filtrate at the CA-01 facility measured using an online ammonia analyzer (week of June 16, 2011).

8.3 Potential Causes for Spike in Effluent Ammonia Concentration

Operational information such as the dissolved oxygen concentration in the aeration basins and sludge wasting rate (to calculate the SRT) were obtained to determine the potential causes for occasional spikes in effluent ammonia concentration at the CA-01 water recycling facility. The aeration basins are typically designed to operate at a dissolved oxygen concentration of 2 mg/L or higher. Typically, an SRT of 12 days or longer is desired to ensure complete nitrification for facilities such as CA-01 that operate in a warmer climate. Additional details on factors that can impact nitrification efficiency are discussed in the literature review (Appendix A).

8.3.1 Dissolved Oxygen Concentration

Figure 8.4 presents the dissolved oxygen concentrations measured in the aeration basin by using an online dissolved oxygen analyzer and corresponding effluent ammonia concentrations measured by using an online ammonia analyzer at the CA-01 water recycling facility during the week of March 18, 2011. As shown, elevated ammonia concentrations were observed when dissolved oxygen concentrations were measured below 1 mg/L in the aeration basin. The CA-01 facility does not have an ammonia discharge limit, so the facility does not have to meet a low effluent ammonia concentration continuously. On the contrary, to reduce operational costs by cutting power consumption by the process air blowers, the dissolved oxygen set points in the aeration basins were lowered. Once the plant staffers were made aware of the filtrate ammonia concentrations recorded by the online ammonia analyzer, dissolved oxygen set points were adjusted to achieve better nitrification; effluent ammonia concentrations after 700 h of operation show improvement (fewer excursions) after this adjustment (Figure 8.1). Data obtained during

1500–2500 h of operation show that properly designed and operated satellite facilities can consistently achieve low effluent ammonia concentrations.

The dissolved oxygen concentrations measured in the aeration basin and corresponding effluent ammonia concentrations during the week of June 16, 2011, at the CA-01 facility are shown in Figure 8.5. As stated earlier, excursions observed in effluent ammonia concentrations were minimized after the dissolved oxygen set points in the aeration basins were adjusted to higher values. Although excursions in the effluent ammonia concentrations were minimized, the effluent ammonia concentrations increased slightly at around 6 p.m. for 5 out of 7 days during the week of June 16, 2011. During communications with the plant supervisor, it was found that the process control loop for the process air blower was slow to respond to the changes in the dissolved oxygen concentration in the aeration basin, which caused the dissolved oxygen concentration to decrease during certain times of the day when high organic or ammonia loading occurred. This factor could have caused the observed increase in effluent ammonia concentrations during this time of day.

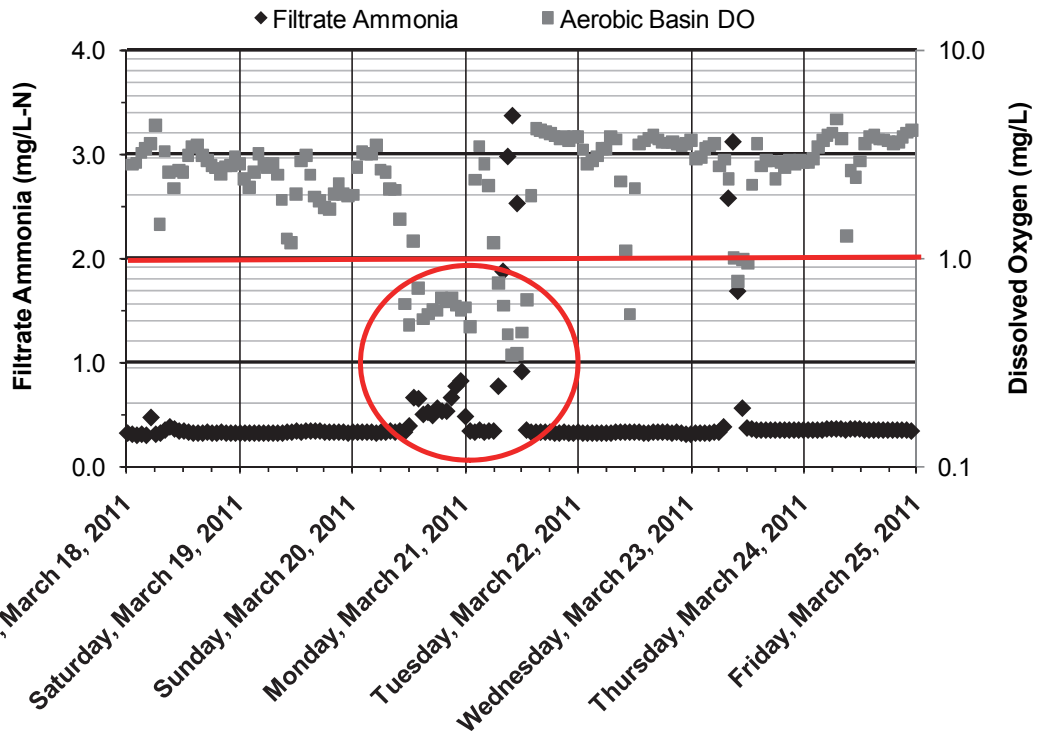


Figure 8.4. Dissolved oxygen concentrations in the aeration basin and corresponding effluent ammonia concentrations at the CA-01 facility (week of March 18, 2011).

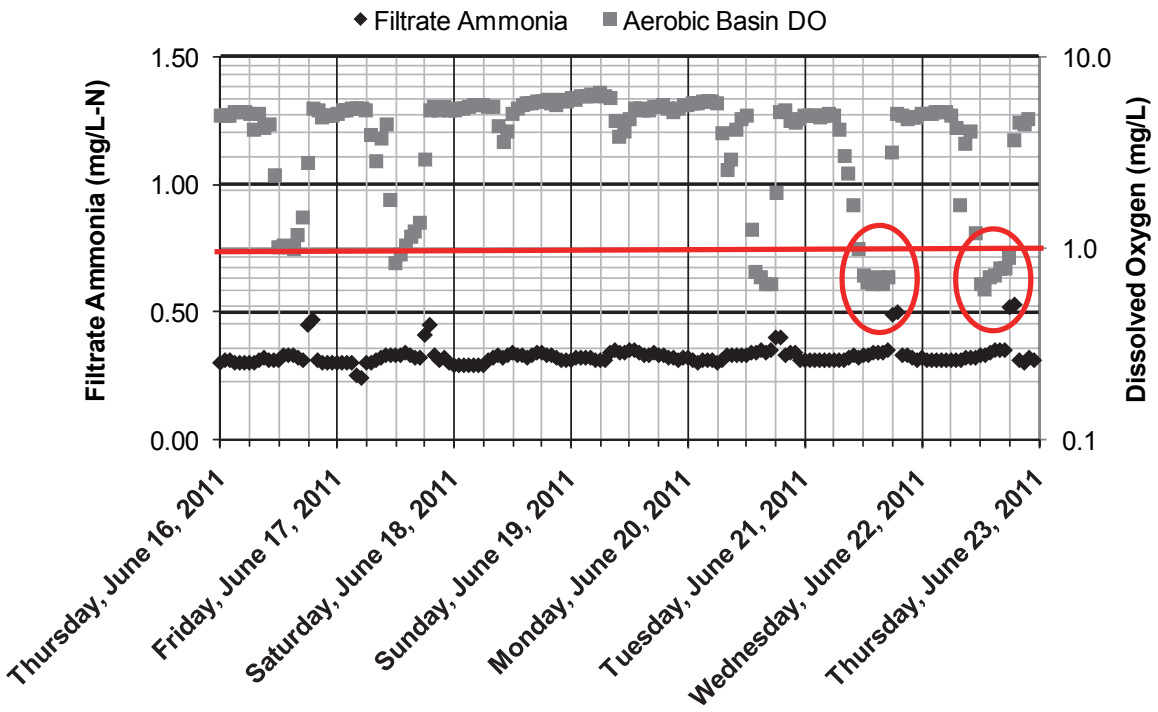


Figure 8.5. Dissolved oxygen concentrations in the aeration basin and corresponding effluent ammonia concentrations at the CA-01 facility (week of June 16, 2011).

8.3.2 SRT

Figure 8.6 presents the 7-day average SRT for the CA-01 water recycling facility calculated on the basis of the sludge wasting rate. On an average, 40,000 gal of sludge per day was wasted from the 750,000 gal reactor basins (total volume), which corresponds to an average SRT of 19 days. Because the 7-day average SRT was above 12 days for most of the study period, sufficient to retain nitrifiers in the bioreactor basins, it is unlikely that the SRT played a role in the excursions observed in the effluent ammonia concentrations.

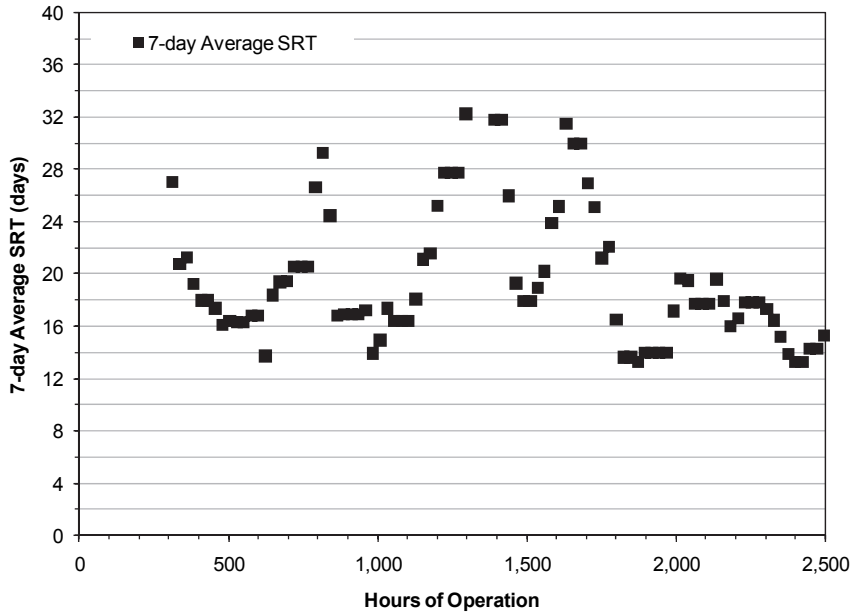


Figure 8.6. Seven-day average SRT at the CA-01 water recycling facility.

Chapter 9

Summary: White Paper on Disinfection Guidelines for Satellite Water Recycling Facilities

9.1 Introduction and Objective

Use of recycled water to augment surface and groundwater supplies has increased substantially in arid and semi-arid states in the United States. Recycled water is typically obtained from large centralized water recycling facilities and is conveyed to end users through recycled water conveyance lines. This approach requires large investments in conveyance infrastructure and is feasible only for nearby end users with high water demands. In order to increase the use of recycled water by scattered end users with smaller water demands, it is often prudent to consider satellite water recycling facilities situated near the end users to minimize the cost of conveyance infrastructure.

Water recycling applications such as landscape irrigation, toilet flushing, cooling water, etc., require use of disinfected tertiary-treated water in California (California Department of Water Resources, 2004). In Florida, low-rate land applications for irrigation of public access areas, residential irrigation, or irrigation of edible crops require tertiary treatment that can provide a TSS level at or below 5 mg/L prior to disinfectant application. In Washington, reclaimed water used for spray irrigation of food crops, irrigation of public access areas, and fire hydrants and sprinkler systems must be coagulated and filtered prior to disinfection. When satellite recycling facilities are to be utilized for such applications, a high level of treatment (disinfected tertiary water) is necessary and has to be achieved with a small footprint; MBRs are often the treatment of choice. Use of membranes for solid separation allows MBRs to produce effluents with low concentrations of microorganisms and particles. Further, operation at a longer SRT allows MBRs to produce fully nitrified effluents.

Disinfection guidelines published by the NWRI/AWWARF for the UV disinfection of wastewater for reuse applications recommend a lower UV dose for low pressure membrane-filtered effluent (80 mJ/cm^2) than for medium-filtered effluent (100 mJ/cm^2) to account for better effluent water quality produced by the latter (NWRI/AWWARF, 2003). Such reduced disinfectant requirements have not been developed for free chlorine, and the MBRs are still subject to the same chlorine disinfection requirements as conventional treatment processes. In order to increase use of recycled water through satellite treatment, it is necessary to develop disinfection guidelines for satellite MBR systems that are commensurate to the water quality produced by these systems. Therefore, the objective of this study was to develop disinfection guidelines for MBR effluents when free chlorine is used as a disinfectant. This white paper summarizes the findings of this study with respect to effluent water qualities produced by satellite MBR systems, as well as summarizing disinfection requirements for these effluents. The white paper also summarizes the recommended process and effluent water quality monitoring requirements along with the process control strategies necessary to implement lower free chlorine CT values at satellite MBR facilities.

9.2 Effluent Water Qualities Produced from Satellite Facilities

Research to date has demonstrated the ability of the MBR process to produce superior effluent water quality with respect to ammonia, organics, particles, and microorganisms (Judd, 2011), but the lack of data on real-world performance of MBR facilities has precluded the ability to lower the disinfection requirements for MBR effluents. The objective of this aspect of the study was to collect effluent water quality data from a wide range of satellite facilities (38 facilities) to allow proper characterization of MBR effluents with respect to inorganic, organic, physical, and microbial parameters. The MBR facilities sampled during the study used different process configurations (submerged and external), membrane geometries (hollow-fiber, flat-sheet, and tubular), fouling control strategies (relaxation and backwash), and membranes of various ages. The MBR facilities sampled were spread across six different states and four different USEPA regions; flow rates at these facilities ranged from 0.001 to 1.8 MGD.

Table 9.1 summarizes the effluent water qualities produced by these facilities. Results from the survey showed that 90% of the satellite facilities sampled produced effluents with TOC concentrations of less than 8.1 mg/L, ammonia concentrations of less than 0.44 mg of N/L, turbidities of less than 0.7 NTU, UV-254 values of less than 0.22 cm^{-1}, total particle counts of less than 145,840/100 mL, total coliform bacterial concentrations of less than 100 CFU/100 mL, and indigenous male-specific bacteriophage concentrations of less than 21 PFU/100 mL. Results from the reconnaissance survey demonstrated that satellite MBR facilities are capable of producing oxidized, nitrified effluent that has a lower concentration of particles and microbial indicators. However, they also showed that a lack of regulatory requirements means that the facilities are not always operated or maintained to ensure high performance. This study also focused on understanding the operational variables and online monitoring tools needed to maintain operation within a stated level of performance. Sustainability of this performance level would then support reduction of subsequent disinfection CT requirements.

Table 9.1. Summary of Effluent Water Qualities Produced by 38 Satellite MBR Facilities

	Concentrations			
Parameter	**50th Percentile**	**90th Percentile**	**Min.**	**Max.**
Turbidity (NTU)	0.21	0.71	0.09	8.58
Ammonia (mg of N/L)	<0.02	0.44	<0.02	3.41
TOC (mg/L)	4	8	2	27
Total coliform bacteria (CFU/100 mL)	1	100	<1	293
Indigenous MS-2 bacteriophage (PFU/100 mL)	<1	21	<1	848
Particle counts > 2 µm (counts/100 mL)	26,715	145,840	2648	2,044,564
UV-254 (cm^{-1})/corresponding UVT (%)	0.12/76	0.22/60	0.06/88	0.35/45

9.3 Variability in Effluent Water Qualities Produced from Selected Satellite Facilities

Detailed water quality evaluations on selected satellite facilities were conducted to assess the filtrate water qualities with respect to a much broader range of water quality parameters as well as to assess the variability in water qualities during multiple sampling events.

Results from the detailed water quality evaluations showed that all nine satellite facilities demonstrated consistently high nitrification efficiency with filtrate ammonia concentrations mostly below 0.1 mg of N/L for most facilities and below 1 mg of N/L for all facilities. Ammonia concentrations were consistently lower for all the three samples collected from these facilities, which indicates that, when properly designed and operated, satellite MBR facilities can achieve complete nitrification. Satellite facilities produced oxidized effluent with filtrate TOC concentrations below, for the most part, 6 mg/L (ranging from 3.3 to 10.5 mg/L), and these levels were consistent during the three sampling events for each facility. Filtrate transmittance (based on UV-254) in the filtrate samples ranged from 48 to 79% and was found to vary substantially during different sampling events for the same facility, suggesting that characterizing UV demand is an important design consideration in sizing for effective UV disinfection.

Filtrate turbidities were below 0.2 NTU for the majority of satellite facilities sampled and were consistent during the three sampling events, although turbidities for some facilities were different from those observed during the reconnaissance survey. The particle counts in the filtrate samples ranged from 2900 to 1,481,000 per 100 mL of sample and were found to be consistently high in samples from two (CT-03 and NJ-14) out of the nine facilities sampled.

The satellite MBR facilities demonstrated 2.0 to 7.5 log removal for total coliform bacteria (median, 5.3 logs), whereas the filtrate concentrations varied from less than 1 to 90,000 CFU/100 mL. The LRVs for indigenous male-specific bacteriophage varied from 2.3 to 5.8 logs (median, 3.2 logs) while the filtrate concentrations varied from less than 1 PFU/100 mL to 24 PFU/100 mL. Enterovirus, rotavirus, and hepatitis A virus were not detected in any of the filtrate samples. Adenoviruses were detected in filtrate samples from all nine facilities sampled; the presence of these organisms suggests a need to carefully evaluate UV disinfection requirements for MBR effluents. *Giardia* cysts were detected in filtrate samples from two satellite facilities (CT-03 and NJ-14), whereas *Cryptosporidium* oocysts were not detected in any samples. Both CT-03 and NJ-14 facilities also had much higher particle and bacterial counts.

9.4 Impact of Membrane Cleaning and Breach on Effluent Water Qualities

Influent and filtrate samples were collected before and after membrane cleaning to assess the impact of cleaning on effluent water quality and subsequent disinfection CT values. Results from the cleaning experiment showed an increased passage of total coliform bacteria for the sample collected at the beginning of the first filtration cycle, but the LRVs increased to normal levels by the middle of the filtration cycle. Because the filtrate coliform bacterial concentrations after cleaning were mostly equal to or less than 2 CFU/100 mL, membrane cleaning did not seem to pose a substantial risk with respect to passage of total coliform bacteria. Filtrate male-specific bacteriophage concentrations were observed to be higher for cleaned membranes than for fouled membranes in four out of six samples collected over two consecutive filtration cycles, but these concentrations were not high enough (<34 PFU/100 mL) to pose any challenge to the subsequent disinfection process. Enterovirus, rotavirus, and hepatitis A virus were not detected by using

qPCR in the filtrate samples collected before and after membrane cleaning, whereas the detection of adenoviruses occurred regardless of cleaning status. *Giardia* and *Cryptosporidium* were not detected in the filtrate samples collected before and after chemical cleaning.

To assess the impact of loss of membrane integrity on effluent water quality, a membrane sheet of a pilot MBR system was purposely breached to an extent that filtrate turbidity was higher than 0.5 NTU. Before membrane breach, the filtrate coliform bacterial concentrations were always at or below 3 CFU/100 mL. Membrane breach caused the filtrate coliform bacterial concentrations to increase substantially for most of the samples. The highest concentration (8500 CFU/100 mL) was observed for the first filtrate sample (Cycle 1, T = 1 min), and it gradually declined as the filtration cycle progressed, probably because of plugging of the breach by mixed liquor solids. Although male-specific bacteriophage were detected in all the samples collected before and after membrane breach, their concentrations were higher after the breach than before the breach in five of six samples. Differences in rejection between total coliform bacteria and indigenous male-specific bacteriophage suggest that indigenous male-specific bacteriophage are likelier to be particle associated than are coliform bacteria and thereby are consistently rejected by the membrane even after a loss of membrane integrity. Further, the higher densities of coliform bacteria may include free-floating coliform bacteria that can pass through the breached membrane. *Giardia* cysts and *Cryptosporidium* oocysts were not detected in the filtrate samples collected before membrane breach. Following membrane breach, *Cryptosporidium* oocysts were not detected in the filtrate, but *Giardia* cysts were detected at a low concentration (1/10 L). Enterovirus, rotavirus, and hepatitis A virus were not detected in the filtrate before and after the breach, whereas adenoviruses were detected in both samples.

9.5 Effluent Ammonia Concentrations at a Water Recycling Facility

In order to understand the impact of operating conditions and upsets in bioreactor basins on effluent ammonia, an online ammonia analyzer was installed at the CA-01 water recycling facility. Dissolved oxygen concentrations in the aeration basins and the SRT of the facility were monitored to understand the impact of these parameters. Results from online ammonia monitoring showed that the CA-01 facility was able to consistently produce fully nitrified effluent for most of the test period, although the effluent ammonia concentrations occasionally reached up to 3.4 mg of N/L during the first 700 h of operation. Upon investigation, the dissolved oxygen concentrations in the aeration basins appeared to impact the ammonia concentration. Because the facility was not required to meet effluent ammonia limits, the dissolved oxygen set points for the aeration basins were set to a lower-than-desired value to reduce costs by cutting the process air blowers' power consumption. After modification of the dissolved oxygen set point, the facility was able to consistently achieve low effluent ammonia concentrations. Because the SRT for the facility was always long enough (above 12 days) to retain the nitrifiers in the bioreactor basins, it is unlikely that the SRT had any impact on effluent ammonia excursions.

9.6 Recommended Free Chlorine CT Values for Satellite MBR Facilities

Reduced UV disinfectant requirements have been established for low-pressure membrane treatment of wastewater for reuse application (NWRI/AWWARF, 2003). In order to assess the appropriate reduction in chlorine CT requirements for MBR effluents, bench-scale free chlorine microbial inactivation studies were conducted on effluents from satellite facilities and MBR pilot systems operating under routine and stressed conditions. On the basis of the results, to achieve a

5-log removal of seeded male-specific bacteriophage and a total coliform bacterial concentration at or below 2.0 CFU/100 mL:

- a free available chlorine CT of 10 mg-min/L was sufficient for effluents from selected satellite water recycling facilities;
- a free available chlorine CT of 5 mg-min/L was sufficient for effluents collected from MBR pilot systems after chemical cleaning of the membranes; and
- a free available chlorine CT of 30 mg-min/L was sufficient for effluents collected from MBR pilot systems with breached membranes when filtrate turbidity was ≤ 1.0 NTU. Greater CTs were necessary as turbidities from breaches increased.

Similar results have been reported in other studies. Hoff and Akin (1986) assessed free chlorine CT values required by different types of waterborne pathogens at pH 6.0 and 5 ºC and demonstrated the wide range in pathogen resistance to a single disinfectant, with *E. coli* requiring a CT of 0.04 mg-min/L and poliovirus type I requiring a CT of 1.7 mg-min/L. Mansell et al. (2008) showed that a free chlorine CT of 40 mg-min/L was sufficient to achieve 5 log removal of seeded MS-2 bacteriophage and total coliform bacterial concentration below 2.2 CFU/100 mL for MBR effluents when filtrate turbidity varied from 1.8 to 2.6 NTU.

9.7 Recommended Process and Effluent Water Quality Monitoring Requirements to Allow Use of Lower Free Chlorine CT Values

Results from the study demonstrated the ability of the MBR process to produce oxidized, nitrified effluent that has a very low concentration of particles and pathogens. Microbial inactivation studies conducted on effluents from satellite MBR facilities and pilot MBR systems showed that a free available chlorine CT of 30 mg-min/L and turbidity of ≤ 1.0 NTU were sufficient to achieve a 5 log removal of seeded male-specific bacteriophage and total coliform bacterial concentrations at or below 2.0 CFU/100 mL. In order to employ these low CT values at satellite facilities, implementing a process control strategy that will ensure production of high-quality effluent by the MBR process with respect to particles and ammonia is critical. Figure 9.1 presents a process control strategy to implement lower free chlorine CT values to achieve a desired level of disinfection at satellite water recycling facilities. Additional studies are needed to determine the CT requirements for alternative disinfectants such as ozone or chlorine dioxide. This study was intended to develop disinfection guidelines for satellite MBR facilities using the existing approach of meeting effluent water quality requirements with respect to total coliform bacteria and male-specific bacteriophage. Because future disinfection regulations may incorporate additional organisms such as *Cryptosporidium* and *Giardia*, the presence of these organisms in MBR effluents was also assessed as part of this study.

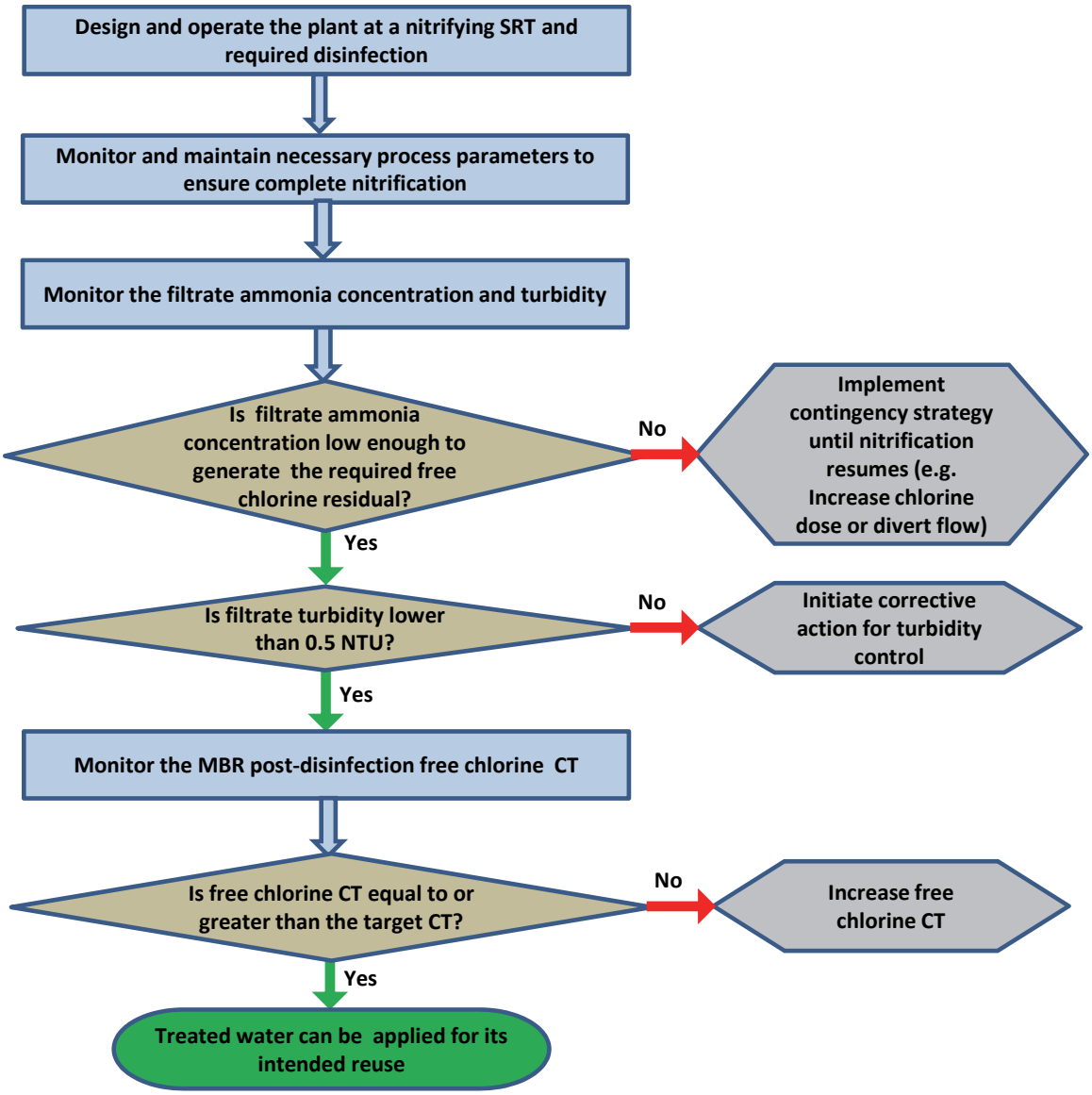


Figure 9.1. Process control strategy for the satellite water recycling facilities to implement lower free chlorine CT values.

9.7.1 Process Design and Monitoring Requirements

9.7.1.1 SRT

Satellite MBR facilities are typically designed to operate at a long SRT (>12 days) to take advantage of a smaller footprint through use of higher MLSS concentrations. Although most satellite facilities produced fully nitrified effluents, designing these facilities at or above a nitrifying SRT to ensure retention of nitrifiers in the bioreactor basins is critical. Such design would ensure production of effluents with low ammonia concentration and availability of free chlorine as disinfectant. The design SRT should also account for the site-specific changes in temperature because the temperature affects the nitrification kinetics.

9.7.1.2 Process Aeration Design and Dissolved Oxygen Monitoring

Dissolved oxygen concentrations in the aeration basins play a critical role in maintaining a low effluent ammonia concentration. Therefore, sizing the process air blowers to maintain a sufficient dissolved oxygen concentration in the aeration basins is important. Dissolved oxygen concentrations above 2 mg/L or higher are desired to achieve complete nitrification, and process modeling based on influent wastewater quality and on bioreactor configuration should be utilized to ensure complete nitrification. Dissolved oxygen monitoring in the aeration basins is also critical in controlling the biological process aeration and subsequently achieving complete nitrification.

9.7.2 Effluent Water Quality Monitoring Requirements and Response to Process Failure

9.7.2.1 Ammonia

Implementation of lower CT values will require continuous monitoring of effluent ammonia. Online ammonia analyzers should be installed to continuously monitor ammonia in MBR effluent at satellite facilities. If the effluent concentration is higher than 3 mg/L, then contingency plans should be implemented until complete nitrification resumes. Such contingency design measures would allow the presence of sufficient free chlorine residual in the disinfected effluent to achieve target CTs and limit oversizing of chlorine dosing pumps to account for failure of the nitrification process.

9.7.2.2 Turbidity

Filtrate turbidities for satellite MBR facilities serve as an indicator to ensure membrane integrity. Results from this study showed that a breached membrane would allow passage of particles and microorganisms at a much higher level than an intact membrane would. Although the proposed CT values account for filtrate turbidity of up to 1.0 NTU, online monitoring of filtrate turbidity should be implemented at the satellite facilities to ensure production of effluent with low turbidity. Because the CDPH's Title 22 regulations require membrane-filtered effluent turbidity not to exceed 0.5 NTU, corrective actions for turbidity control should be implemented if filtrate turbidity exceeds 0.5 NTU. Monitoring filtrate turbidity indicates that the micro- or ultrafiltration membranes utilized in the MBR process are intact and are not allowing passage of protozoa, because chlorine is not effective in inactivation or destruction of protozoa.

9.7.2.3 Postdisinfection Free Chlorine Residual

Monitoring of postdisinfection free chlorine residual would ensure that sufficient free chlorine is available to achieve the desired level of microbial inactivation after minor excursions observed for filtrate turbidity and ammonia. If the free chlorine residual is lower than the target residual, then the chlorine dose should be increased accordingly; this step will ensure that the treated water is disinfected sufficiently and can be reused.

9.8 Future Research Needs

Results from the study allowed characterization of effluents produced from satellite MBR facilities and determination of free chlorine disinfection requirements for these effluents. Data obtained from the study demonstrated the ability of the satellite MBR facilities to produce

oxidized, nitrified effluents with very low concentrations of particles and microorganisms. Although it can be concluded that lower free chlorine CT values (30 mg-min/L) can be employed at satellite facilities to achieve total coliform bacterial concentrations at or below 2 CFU/100 mL and 5 log removal of male-specific bacteriophage, further research should be conducted to allow widespread implementation of this lowered disinfectant requirement. Specifically, research should focus on

- demonstrating the effectiveness of proposed CT values and monitoring requirements at a full-scale water recycling facility in meeting current disinfection regulations;
- studying the occurrence and removal of adenoviruses by the MBR process during the treatment of municipal wastewater; and
- identifying surrogates for detecting the presence of microbial indicators in the MBR filtrate and evaluating online sensors for the detection of pathogens.

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Appendix A

Literature Review

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Chapter 1

Satellite Water Recycling Facilities

Satellite wastewater treatment facilities treat wastewater obtained prior to entering or withdrawn from a sewer collection system and reuse the treated effluent for local recycling applications while returning the treatment residuals to the collection system for processing at a centralized treated facility. Satellite facilities can obtain the wastewater for local treatment and recycling in three specific ways: (1) interception type, where the wastewater is intercepted in a high-rise building prior to the collection system, (2) extraction type, where the water is pumped from the centralized collection system in a process referred to as "sewer mining" or "sewer scalping," and (3) upstream type, where the water is obtained from developments at the extremities of a centralized collection system (Metcalf and Eddy, 2007). Satellite facilities differ from decentralized systems in that decentralized facilities are not connected to a centralized collection facility (Crites and Tchobanoglous, 1998). Because of this operational distinction, decentralized facilities have greater design demands in addressing solid-handling issues and can have greater considerations related to flow equalization.

1.1 Benefits of Satellite and Decentralized Facilities

Installation of satellite and decentralized facilities has been increasing as a viable water recycling approach because of their demonstrated reliability, minimal footprint, elimination of the need for new recycled water distribution pipelines, and postponement of central treatment capital improvement projects. Because of their distance (namely, satellite) or independence (namely, decentralized) from large centralized facilities, these systems are typically designed for unattended operation through use of automated monitoring and control systems or the need for minimal assessment and maintenance.

From the broader vantage point of sustainable watershed management, there is some advocacy for wastewater infrastructure to rely more upon a decentralized ecological model that employs local water reuse better integrated with local ecosystem needs through the creation of a smaller water-recycling loop within the hydrologic cycle (Kirksey, 2009). Satellite systems represent a good compromise between utilization of existing centralized systems and achievement of more-cost-effective localized reuse of treated water.

1.2 Effluent Quality Requirements for Reuse

Water reuse is defined as utilization of wastewater following treatment to achieve effluent quality standards appropriate to the water's designated beneficial use. The United States does not have federal effluent quality or treatment standards for reclaimed water, but the USEPA issued updated guideline recommendations (USEPA, 2004). Each state has adopted regulations and guidelines differently, with California (under Title 22) recognized as one of the states with a comprehensive set of high-effluent-water-quality treatment process requirements (O'Connor et al., 2008). Evaluating satellite treatment technology in terms of California regulations and evaluating treatment performance findings against requirements from other states with unrestricted-human-contact recycled water regulations are important. A summary of the treatment requirements and effluent water quality requirements for microbes and solids on a state-by-state basis is provided in Appendix A.

Title 22 defines categories of reclaimed water through designated effluent criteria for total coliform bacteria and turbidity. Title 22 relies on media or membrane filtration to condition the water for effective disinfection. Filtration performance is monitored by using turbidity, whereas the disinfection performance is monitored by using total coliform bacterium concentration in the disinfected effluent. Treatment requirements deemed necessary to meet the most stringent disinfected tertiary recycling criteria include media or membrane filtration to reduce turbidity to less than 2 or 0.2 NTU, respectively, followed by chlorine disinfection to ensure a minimum CT of 450 mg-min/L at all times. This treatment scheme is expected to achieve a 5-log reduction of virus. If an alternative disinfectant is to be used, then a 5-log inactivation or removal of virus should be demonstrated by using the disinfection process when combined with the filtration process.

The goal of the most stringent disinfection tertiary recycling criteria, shown in Table 1.1, is the production of essentially enteric-virus-free water for applications with unrestricted access.

Table 1.1. California Recycling Criteria

Total Coliform Criteria (MPN/100 mL)	**Turbidity Criteria (NTU)**
<2.2 for median of 7 days of consecutive samples; 23 allowed once in any 30-day period.	≤2 for daily average; AND ≤5 for 95% of the time in a 24 h period; AND ≤10 at any time for granular media filtration OR ≤0.2 more than 95% of time in a 24 h period AND ≤0.5 NTU at any time for membrane filtration

Although there have not been sufficient data generated to demonstrate virus-free water from a risk-based analysis, the criteria in Table 1.1 rely upon the findings of the Pomona Virus Study (Sanitation Districts of Los Angeles County, 1977). This study demonstrated through pilot evaluations of media filtration systems that the Title 22-required treatment, when performed to successfully meet the required turbidity and total coliform bacteria effluent criteria, also reduced the concentration of seeded poliovirus by 5 logs. This study established the chlorine disinfection standard at a CT of 450 mg-min/L with a modal contact time of not less than 90 min based on peak dry weather flow. UV light irradiation is also allowed if the process can be demonstrated to comply with the stipulations of the Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse (NWRI/AWWARF, 2003).

Section 60320.5 of Title 22 allows acceptance of other oxidation, filtration, and disinfection process trains by the regulatory agency if the applicant can demonstrate performance equivalent to that of the Title 22-cited process. As a result of the data generated from the Pomona Virus Study, equivalency is defined as 5-log reduction of seeded virus as well as demonstration of the coliform effluent criteria cited in Table 1.1. The demonstration must challenge operation of the alternative filter and disinfection process by evaluating the most challenging water quality and vulnerable system operating conditions in replicate and demonstrating at least 5-log reduction of viable viruses from the concentration to the filter influent through the combined process.

The California Title 22 equivalency performance requirements and other relevant state programs provide baseline performance criteria against which alternative satellite treatment technologies should be evaluated. Technology performance demonstrations for a designated beneficial reuse application should verify that (a) the proposed technology can meet the required effluent quality specifications under a defined set of operating conditions, (b) deviation from these conditions can be prevented either through continuous monitoring of appropriate indicators or surrogates, and (c) if deviation occurs, the ability to automatically activate chemical addition or divert the wastewater to the sewer exists.

Satellite treatment processes utilize technologies designed to produce high-quality effluents suitable for unrestricted access water reuse within a limited footprint. These high-effluent-quality processes produce a fully nitrified particle-free effluent that should require much lower disinfection requirements to achieve the combined process 5-log virus reduction. Since the Title 22 requirements were developed, new infectious disease agents have surfaced. These new organisms of concern include bacteria (for example, *E. coli* O157:H7, *Listeria*, and *Heliocobacter*), viruses (for example, poliovirus, coxsackievirus, echovirus, hepatitis A virus, rotavirus, and norovirus), and parasites (for example, *Cryptosporidium*, *Cyclospora*, *Toxoplasma*, *Microsporidia*, and *Giardia*) (Gerba and Smith, 2005). Therefore, considering these new risk drivers in updated disinfection requirements is prudent.

1.3 Satellite Facility Treatment Technologies

Selection of a satellite facility treatment technology depends primarily upon the effluent water quality requirements and site-specific constraints. These systems all rely upon an attached, suspended, or hybrid aerated activated sludge secondary process for carbonaceous BOD removal, TSS removal, microbial removal, and nitrification. This process can be modified to include an anoxic zone or tank for denitrification and an anaerobic zone or tank for phosphorus removal. Solid separation is then achieved by using filtration. Footprint minimization and higher effluent quality are usually key drivers for these facilities because these systems are often constructed on small or constrained sites and because the effluent is often utilized for irrigation of green space with nonrestricted public access. High removal efficiency for microbes, solids, and nutrients is therefore usually compulsory.

The two most viable activated sludge technologies for satellite water recycling facilities are sequencing batch reactors (SBRs) and membrane bioreactors (MBRs). Although both SBRs and MBRs are suspended growth processes, they rely upon different solid separation processes that result in different volumetric loading rate tolerances. Use of membrane filtration for solid separation in the MBR process allows it to operate at a high MLSS concentration in the range of 8000–12,000 mg/L. On the other hand, reliance on gravity settling for solid separation in SBRs requires the process to operate at a lower MLSS concentration of 2000–5000 mg/L, because the ability of the sludge to settle within the SBR decreases drastically at a high MLSS concentration. Operation at a lower MLSS concentration requires a longer hydraulic retention time (HRT) and subsequently results in a larger footprint for SBRs than for MBRs. The SBR uses a single tank for aeration and clarification as a fill-and-draw type system, with the mixed liquor remaining in the reactor during these cycles. This arrangement allows only one process to occur at a time and results in a longer HRT time for the treatment. The SBR systems typically require a HRT of 15–40 h (Metcalf and Eddy, 2007), whereas MBR systems require an HRT of 4–11 h for municipal wastewater treatment (Hirani et al., 2007).

Membrane filtration in MBRs also replaces the media filtration process typically used in conventional activated sludge plants that have to provide tertiary treatment to achieve better effluent water quality. Use of SBRs for satellite facilities also requires media filtration after secondary treatment to produce water that has a low concentration of microbial contaminants and suspended solids. Although media filtration technologies such as cloth filters, sand filters, and dual media filters can achieve better solid removal than clarification, the water quality produced by media filtration is still inferior to that produced by membrane filtration. This observation is clearly evident in the current filtrate turbidity performance standards specified by the California Department of Public Health (CDPH) for media filters and membrane filters. The current Title 22 regulations of CDPH require media filters and membrane filters to produce effluent with turbidity of less than 2 NTU and 0.2 NTU respectively for 95% of the time during a 24-h period.

MBR systems are also highly automated and require little or no supervision. This feature makes them a more attractive option for satellite facilities because most of these facilities are not manned for 24 h a day. Because the MBR process can achieve higher effluent water quality with a much smaller footprint than do conventional treatment processes and requires little or no supervision, it is the most widely used process for satellite facilities.

1.3.1 Nutrient Removal

The nutrient reduction in wastewater treatment consists of nitrogen and phosphorus removal through biological treatment, chemical treatment, or a combination of both. Nitrogen removal is typically accomplished by a biological nitrification process for ammonia removal and a biological denitrification process for nitrate removal. Phosphorus removal is accomplished by biological treatment using anaerobic zones in activated sludge processes, chemical treatment by addition of a coagulant, or a combination of both. Although the level of nutrient removal (ammonia, nitrate, and phosphorus) required by a satellite treatment facility site is typically governed by site-specific water reuse needs, ammonia removal is critical for the facilities that employ chlorination for disinfection, because this compound combines with free chlorine to form chloramine, which is a less efficacious disinfectant than is free chlorine. In order to achieve complete ammonia removal, satellite facilities should be designed for complete nitrification.

The growth rate of nitrifying organisms is much lower than that of heterotrophic organisms, and operation at a longer SRT is required for retaining these organisms in the bioreactor basins for complete nitrification. The reported specific growth rates for nitrifiers at 20 ºC range from 0.25 to 0.77 g of new VSS/g of VSS per day (Metcalf and Eddy, 2003), and the SRT for stable nitrification ranges from 4 to 20 days, depending on the temperature of the water. Complete nitrification ensures the reduction of effluent ammonia to levels typically below 1 mg/L. Figure 1.1 shows data collected from six full-scale activated sludge facilities situated in the southwestern United States and demonstrates a minimum SRT requirement of at least 5 days for almost complete nitrification, resulting in low effluent ammonia concentrations in a warm climate.

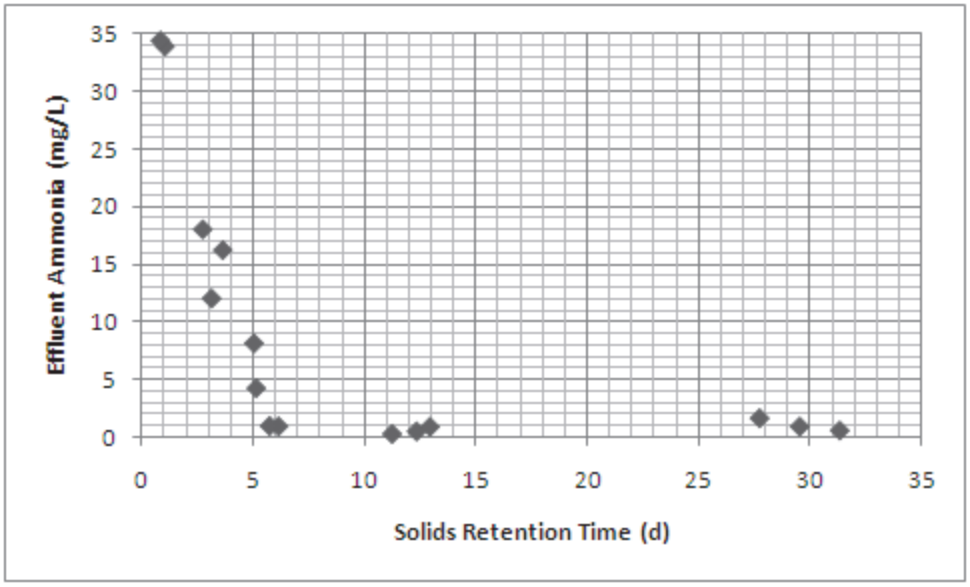

Figure 1.1. Impact of activated sludge solid retention time on effluent ammonia concentrations at six full-scale facilities in southwestern United States.
Adopted from Stephenson and Oppenheimer, 2007.

The MBR process reliance upon membranes for solid separation allows the biological process to operate at a higher MLSS concentration (8000–12,000 mg/L), which is typically associated with a longer SRT that results in production of a fully nitrified effluent. Operation at a higher MLSS concentration also results in a smaller bioreactor volume due to a higher volumetric loading rate. These features allow the MBR process to produce a high-quality, fully nitrified effluent with a small footprint.

The SBR process can also produce fully nitrified effluent but may require longer retention time than does the MBR process. This result is primarily because of two reasons: (1) lower MLSS concentration in the bioreactor, resulting in a lower volumetric loading rate, and (2) sequencing of treatment processes (fill, react, settle, draw, and idle) in a single tank, thereby allowing only one process to occur at any given time. Libralato et al. (2009) assessed the performance of an activated sludge SBR and MBR for treatment of hotel wastewater and found that the SBR required an HRT of 2 h to treat 120 m^3 of wastewater/day, whereas MBR required an HRT of only 16 h to treat 150 m^3 of wastewater/day. Even though the influent COD concentration for the MBR plant (324 mg/L) was actually higher than that for the SBR plant (225 mg/L), the MBR plant demonstrated a higher COD and TSS removal efficiency. Figure 1.2 shows the ammonia removal observed in a submerged MBR system over 3200 h. While operating at an SRT of 41 days, the MBR plant was able to achieve effluent ammonia concentrations of less than 0.1 mg of N/L with influent ammonia concentration varying from 21 to 35 mg of N/L.

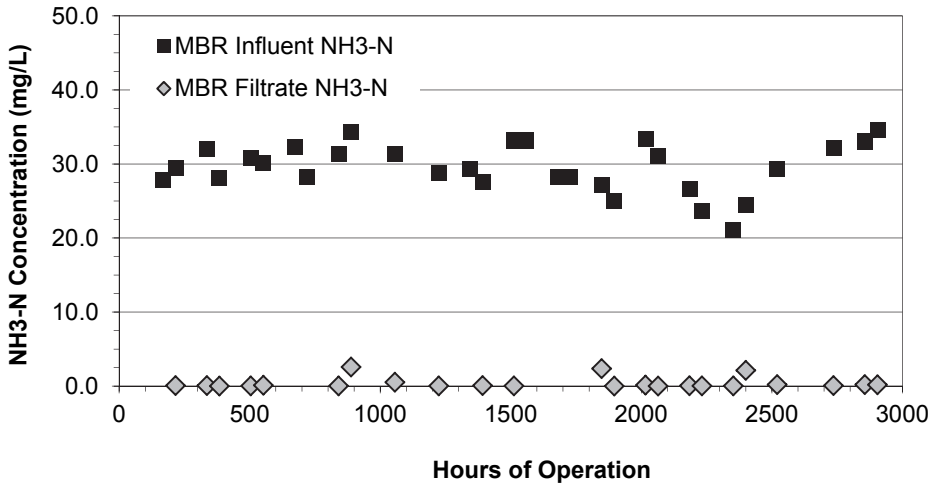

Figure 1.2. Ammonia removal observed in a submerged MBR system.
Source: Hirani et al., 2010b.

For any treatment process that utilizes biological nitrification for ammonia removal, maintaining adequate dissolved oxygen concentrations (typically > 1.0 mg/L) to prevent sluggish growth of nitrifying organisms or cessation of nitrification, which can occur if dissolved oxygen falls below approximately 0.5 mg/L, is critical. Because the MBR process operates at a higher MLSS concentration, the oxygen transfer efficiency of fine bubble diffusion for MBR systems is lower than that in the conventional activated sludge processes that operate at lower MLSS concentrations; this situation results in a slightly higher process air requirement for the MBR in order to maintain the same dissolved oxygen concentration in the reactor. An improperly designed process aeration system for the MBR system can result in a lower dissolved oxygen concentration in the aerobic zones and incomplete nitrification in the bioreactors. This condition would result in the presence of nitrite in the effluent, which may reduce the effective chlorine disinfection dose because nitrite is readily oxidized by chlorine requiring 4 g of chlorine/g of NO_2-N (Metcalf and Eddy, 2003). Incomplete nitrification will also result in the presence of ammonia in the effluent, which can react with free chlorine to form the weaker disinfectant, chloramine.

1.3.2 Solid Removal

The MBR process incorporates surface filters consisting of low-pressure microfiltration (MF) or ultrafiltration (UF) membranes for solid separation. These membranes can be installed externally to or within the biological reactor. External membrane systems usually consist of a tubular configuration and are pressure driven. Submerged membrane systems consist of hollow-fiber or flat-sheet configurations, are usually vacuum driven, and can be integrated within the aeration tank or placed in a separate membrane tank.

A satellite SBR system is usually combined with membrane filtration or staged surface cloth and membrane filtration. Surface filters (for example, cloth media filters, disc filters, and diamond cloth media filters) were developed in the 1990s and used in place of depth filters in satellite applications because of their superior solid removal capabilities (Figure 1.3, adapted from Olivier et al., 2003), compactness, and ease of use.

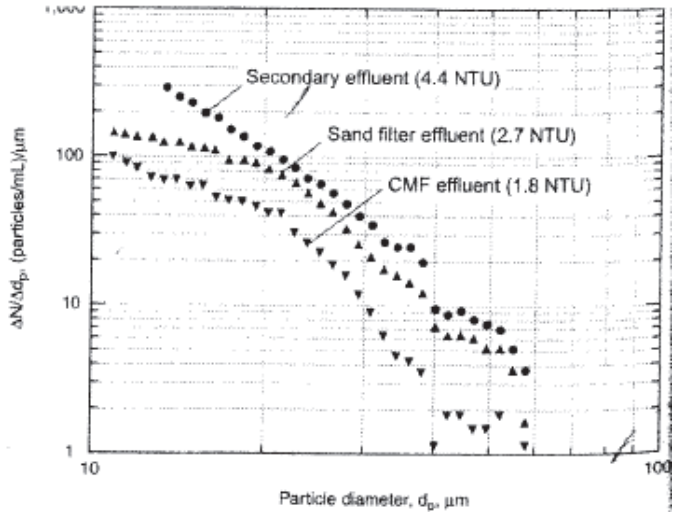

Figure 1.3. Solid removal by sand filters and cloth media filters.
From Olivier et al., 2003.

The effluent quality from cloth surface filters, however, is inferior to that produced by a membrane filtration process (namely, MBR). The superior solid removal performance of an MBR, compared to other filter technologies, is attributable to the smallness of the membrane pores, which ranges from 0.08 to 2.0 µm for MF membranes and 0.005 to 0.1 µm for UF membranes. Cloth media surface filters, in comparison, have openings in the 10- to 30-µm range. Depth filters rely on many removal mechanisms in addition to pore size straining (for example, sedimentation, impaction, interception, adhesion, flocculation, adsorption, and biological growth), but they cannot come close to the low turbidity levels (typically <0.1 NTU) achievable with the membrane filters utilized in an MBR or integrated with an SBR system. Figure 1.4 shows the filtrate turbidity observed for five different MBR systems evaluated over 3500 h (Hirani et al., 2007). As shown, filtrate turbidity for these systems was measured below 0.2 NTU for 95% of the time.

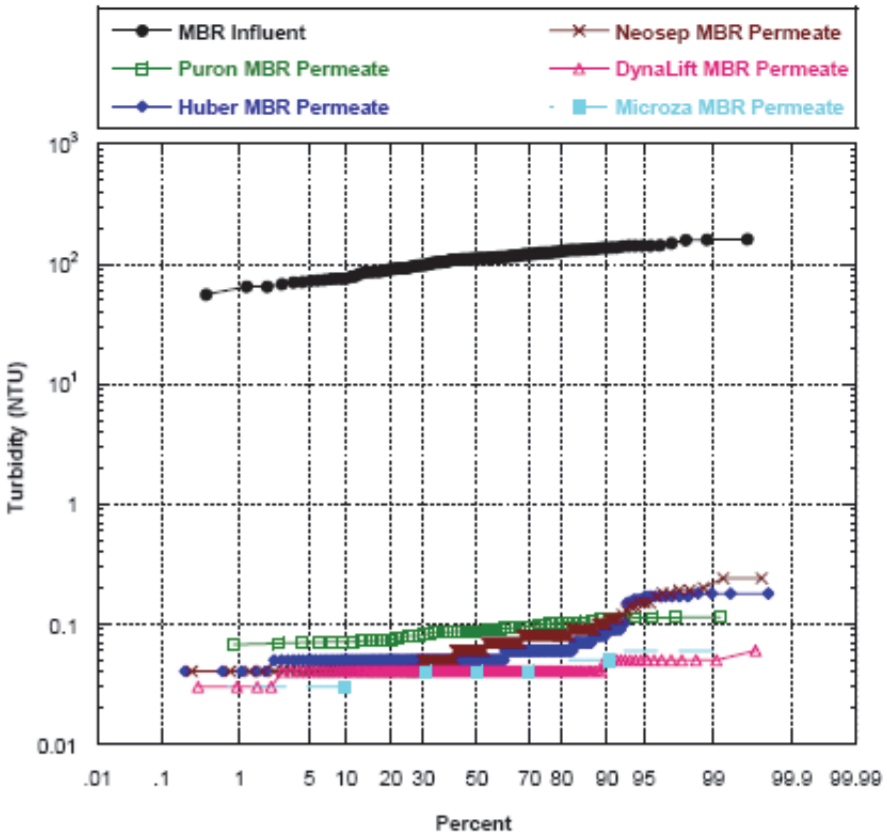

Figure 1.4. Filtrate turbidity for various MBR systems.
From Hirani et al., 2007.

Table 1.2 provides a summary of the SBR−cloth−membrane and MBR satellite systems commercially available with dissolved documented performance for solid removal.

Table 1.2. Summary of SBR and MBR Satellite Systems

Major Vendor	Performance (Metcalf and Eddy, 2007)
Aqua-Aerobic Systems, Inc. Submerged rotating or fixed disk US Filter/Kruger Products Hydrotech PET monofilament fabric	1–4 mg/L TSS 0.5–2 NTU Turbidity
GE/Zenon Kubota/Enviroquip Siemens Koch/Puron Huber Kruger/Toray Norit/Parkson Asahi Kasei/Pall	<1–5 mg/L TSS 0.1–0.5 NTU Turbidity

1.3.3 Microbial Removal

The major wastewater pathogen groups are bacteria, viruses, protozoan cysts, and helminths. The approximate size range of representative species within these groups, the approximate numbers found in raw sewage, and the approximate effluent quality achieved through different treatment processes are summarized in Table 1.3.

Table 1.3. Summary of Microbial Content of Wastewater

GROUP	PATHOGEN	SIZE (DIAMETER)	CONCENTRATION				
			Raw Sewage (#/100 mL)	Conventional Activated Sludge (CAS) Effluent	CAS + Depth Filter Effluent	CAS + Cloth Surface Filter Effluent	MBR Effluent
Bacteria		0.3 - 2 µm					
	Bacteroides		10^{7}-10^{10}				
	Coliforms, total		10^{6}-10^{9}	10^{3} - 10^{7}	10^{3} - 10^{6}		<100
	Coliforms, fecal		10^{4}-10^{8}	10^{2}-10^{6}	10^{2}-10^{6}		<100
	Clostridium perfringens		10^{3}-10^{5}				
	Enterococci		10^{4}-10^{5}				
	Fecal Streptococci		10^{4}-10^{7}				
	Pseudomonas aeruginosa		10^{3}-10^{6}				
	Shigella		10^{0}-10^{3}				
	Salmonella		10^{2}-10^{4}				
Protozoa							
	Crypsosporidium parvum oocysts	3 - 6 µm	10^{1}-10^{4}	10^{1} - 10^{3}	0 -13		0 - 1
	Giardia lamblia cysts	6 -8 µm	10^{2}-10^{4}	10^{1} - 10^{3}	0 -18		0 - 1
Helminth							
	Ova		<2 -10^{3}	<17	<2		
Virus							
	Enteric virus	0.02-0.08 µm	10^{2}-10^{4}	<1 - 10^{3}	0.7-9.5		10^{0}-10^{3}
	Coliphage	0.02-0.03 µm	10^{2}-10^{7}	10-10^{7}	<1-10^{3}		
Adapted in part from Metcalf&Eddy/AECOM (2003), Rose et al. (1996), and Adham and DeCarolis (2004)							

Total coliform bacteria, fecal coliform bacteria, or *E. coli* is usually employed as an indicator organism for other bacterial organisms, and coliphage is typically used as an indicator organism for enteric viruses because of the size similarities of these organisms. Reduction of coliform bacteria and coliphage to nondetectable levels may indicate complete removal of helminthes and protozoan cysts because of the greater size of these organisms. This is not unequivocally the case, however, because indigenous bacteria and viruses might exist in aggregates or associate with solids to a greater degree than do protozoan organisms. Indirect evidence of aggregates and particulate association is seen in in the log reductions observed for seeded coliphage, typically smaller than for indigenous coliphage (Hirani et al., 2010a).

The average log removal values (LRVs) observed for total and fecal coliform bacteria, male specific coliphage and somatic coliphage, and seeded phage during various MBR studies are shown in Figures 1.5, 1.6, and 1.7. For indigenous coliform bacteria and coliphage (Figure 1.5 and Figure 1.6), the variation in LRVs usually reflects the differences in the influent concentrations because organisms are rarely detected in the effluent. There have been sporadic exceptions, where some of the authors (Adham and DeCarolis [2004]; Zhang and Farahbakhsh [2007]) have reported substantial numbers of effluent total coliform bacteria in the permeate line at concentrations as high as 5000 MPN/100 mL and 250 CFU/100 mL. These incidences of high total coliform bacterial effluent concentrations were attributed to permeate line contamination issues because the fecal coliform bacteria and coliphage concentrations remained below detection, thereby ruling out evidence of a membrane breach. Adham and DeCarolis (2004) also postulated that removal might not be as high immediately after backwash because of removal of the dynamic cake layer on the membranes. A facility survey of average effluent total coliform bacterial concentrations of MBR systems ranged from <1 to 53 PFU/100 mL, as shown in Figure 1.8.

Figure 1.6 demonstrates that the indigenous coliphage average LRV is always above 2 and that no organisms were reported in the effluent for these studies. Figure 1.7 demonstrates a lower performance for seeded coliphage. This result is expected because, unlike the native coliphage, the seeded coliphage are initially not particle associated and, therefore, are better able to pass through the membrane (Hirani et al., 2010a).

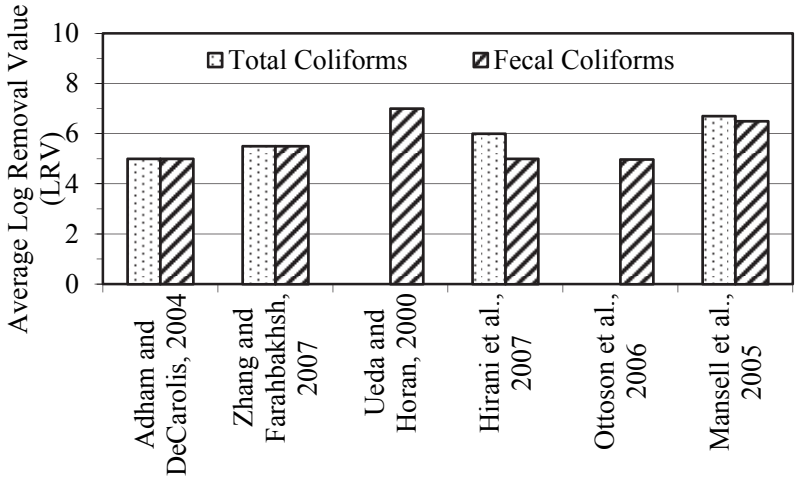

Figure 1.5. Coliform removal reported in different studies.

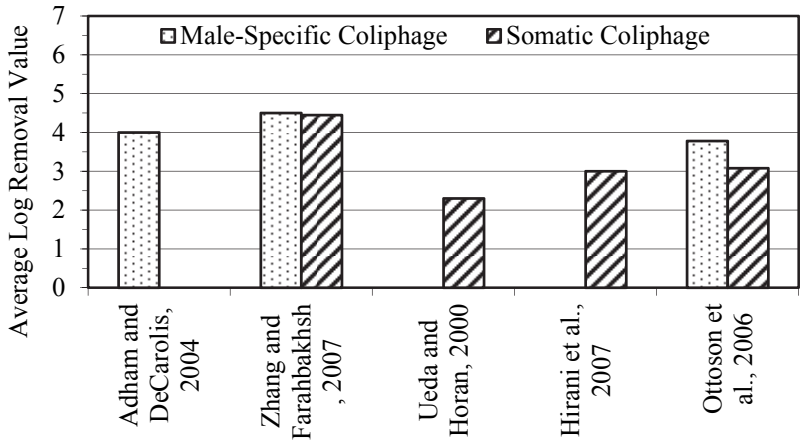

Figure 1.6. Indigenous coliphage removal reported in different studies.

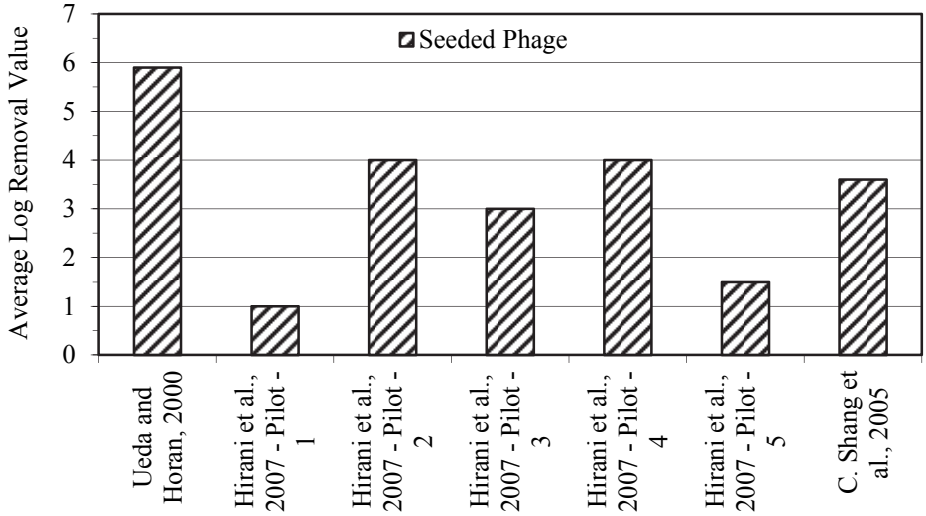

Figure 1.7. Seeded coliphage removal reported in different studies.

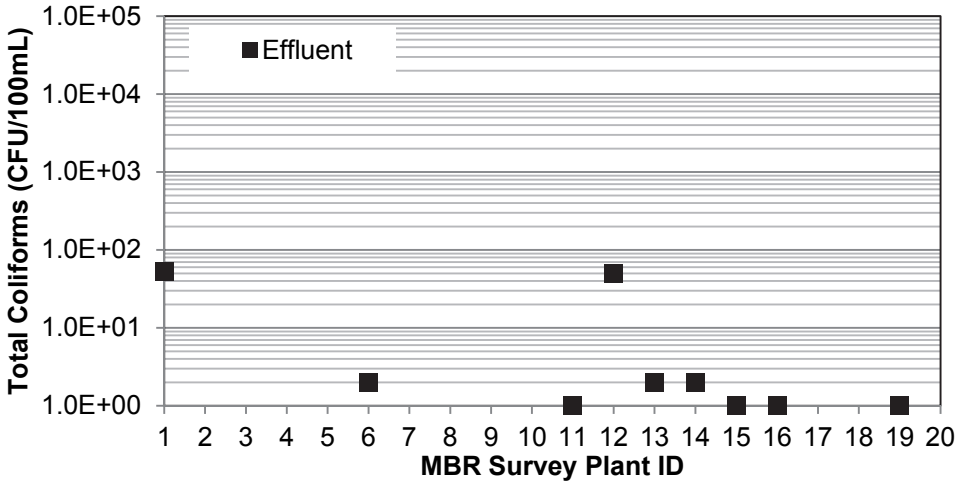

Figure 1.8. Average effluent total coliform values reported from facility survey. Adopted from Oppenheimer and Rittmann, in Press.

1.4 Satellite Facility Performance

Effluent water quality goals for wastewater treatment plants are typically met by using biological treatment, filtration, and disinfection. Water quality problems such as BOD, COD, nitrogen, and phosphorus are removed through biological treatment, whereas particles and microbes are removed through filtration and disinfection. Any upset in the biological nitrification process may result in higher effluent ammonia concentrations that can then impact the downstream disinfection process. Passage of particles and microbes may be affected by the performance of the filtration system and can also influence the downstream disinfection process performance. Some of the key operation- and maintenance-related issues that may impact effluent water quality for the MBR systems are discussed in this section.

1.4.1 Chemical Cleaning

During the filtration process, deposition of particles and bacterial cells occurs on the membrane surface, forming a slimy gel layer that can be removed by physical means of cleaning such as backwashing and air scour. This layer of biofilm reduces the effective pore size of the membrane and increases the filtration resistance. Several studies have shown the role of membrane biofilms and high-molecular-weight organic matter as a secondary barrier to microbial contaminants (Madaeni et al., 1995; Ueda and Horan, 2000; Farahbakhsh and Smith, 2004; Shang et al., 2005; Jacangelo et al., 2006; Kang et al., 2007). Shang et al. (2005) showed that membrane biofilms formed after 21 days of filtration contributed up to a 2.1-log removal of seeded MS-2 phage, whereas the membrane itself (0.4-um pore size) removed only 0.4 log of seeded MS-2 phage.

Although pore blocking, pore constriction, and biofilm formation on the membrane surface by organic foulants enhance the removal of microbes, they also reduce the permeability of the membranes. In order to remove these organic foulants and restore the permeability of membranes, periodic chemical cleanings are conducted on MBR systems. Chemical cleaning

removes a portion of these foulants from the membrane pores and surfaces and reduces the effectiveness of the MBR process in rejecting microbes. Figure 1.9 presents the LRVs observed for seeded MS-2 bacteriophage when membranes either were slightly or heavily fouled for an MBR system utilizing a 0.2-µm-pore-size membrane. The lower LRVs for seeded MS-2 bacteriophage were observed when the membranes were slightly fouled after being chemically cleaned. The LRVs increased significantly once the membrane's permeability dropped by 28% under highly fouled conditions (Hirani et al., 2008).

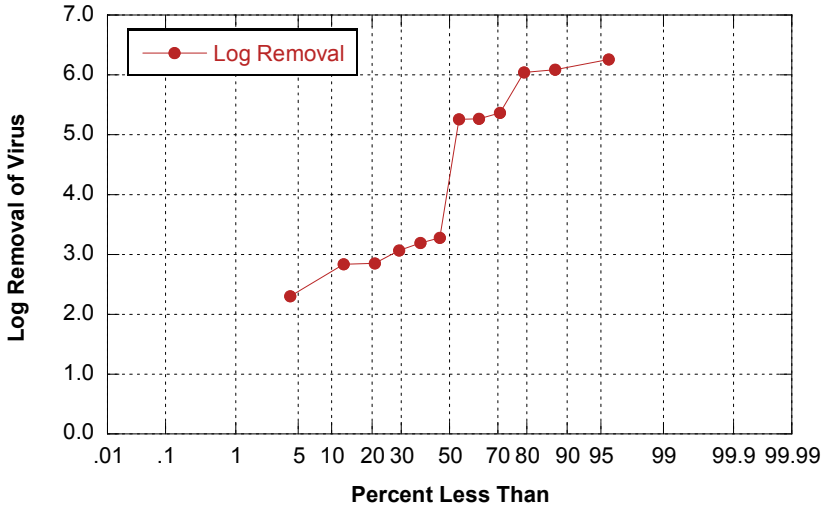

Figure 1.9. Log removal of seeded MS-2 bacteriophage by an MBR system under different membrane fouling conditions (Hirani et al., 2008).

1.4.2 Membrane Breach

Passage of particles through a membrane can occur during a membrane breach. This loss of integrity can result in a spike in both filtrate turbidity and microorganisms in the MBR filtrate. Typically, the filtrate turbidity increases immediately after relaxation or backwash and gradually decreases to a previously observed value once the membrane plugs with activated sludge after a few minutes of filtration. This phenomenon occurs during each filtration cycle. Figure 1.10 shows the spike in turbidity observed during the length of the filtration cycle for an MBR system operating with breached membranes. The data were obtained by the project team while evaluating a flat-sheet MBR system, which utilized relaxation as a fouling control strategy and operated at a 9-min filtration cycle followed by 1 min of relaxation. As shown in the figure, the filtrate turbidity increased immediately after relaxation and decreased gradually to normal value after a few minutes of filtration. Similar results have been observed for a hollow-fiber MBR system that utilized relaxation or backwashing as a fouling control strategy (Kippax et al., 2007).

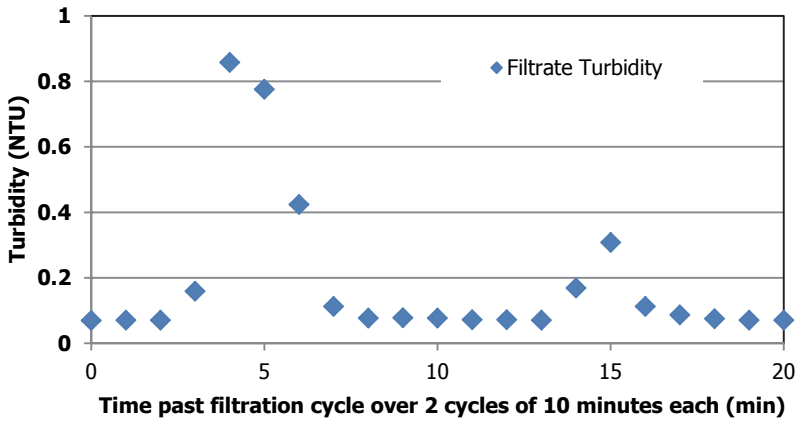

Figure 1.10. **Change in filtrate turbidity during membrane breach in MBR.**

1.4.3 Nitrification

The degree of nitrification affects the disinfection efficacy of chlorine because ammonia present in wastewater reacts with chlorine to form chloramine, which is a weaker disinfectant. Den-Blanken (1985) studied the effect of nitrification on chlorine disinfection and found that inactivation of bacterial viruses improved with better nitrification when he compared the effect of chlorination on moderately nitrified water (mean NH_4-N concentration of 15 mg/L) to that on well-nitrified water (mean NH_4-N concentration of 0.5 mg/L). MBR systems are typically designed to operate at a high MLSS concentration, which is typically achieved by operating at SRT of 10 days or more. Operation at such SRTs allows retention of slow-growing nitrifiers in the bioreactors and production of fully nitrified effluent. Although most MBR systems produce fully nitrified effluents, improper process design and/or operation can result in loss of nitrification and subsequent increases in effluent ammonia concentration. Because MBR systems operate at a higher MLSS concentration than do conventional activated sludge (CAS) systems, the design value of the α-factor for MBR is less than that for CAS. If an incorrect α-factor is employed during the process design, it can result in an undersized process aeration system. Insufficient process air supply can result in a low dissolved oxygen concentration (<0.5 mg/L) in the aeration tank, and such conditions can hinder growth of nitrifiers and result in a high effluent ammonia concentration. Operation at a higher-than-design MLSS concentration can also result in low dissolved oxygen concentration in the bioreactors, and such operation for an extended period can result in loss of nitrification.

Chapter 2

Disinfection of Treated Wastewater

Disinfection is required as a final barrier in order to prevent the passage of any viable pathogens remaining in a filtered activated sludge effluent from being discharged to the environment. This requirement applies to both direct point source discharges to a water body as well as to indirect non-point source discharges through reclamation activities such as irrigation. The adequacy of the disinfection process is dependent on a number of variables: (1) the types and concentrations of pathogenic organisms present in the wastewater being treated, (2) the efficacy of the treatment process in inactivating the pathogens, (3) the efficacy of the treatment process in removing suspended solids, thereby preparing the water for the subsequent disinfection process, (4) the efficacy of the treatment process in removing constituents contributing toward disinfectant demand, (5) pH, (f) temperature, (6) the concentration of disinfectant-demanding substances, and (7) the type and concentration of the disinfectant used.

The chemical and physical disinfectants described in Table 2.1 can be applied either alone or in combination. For all disinfectants, the presence of particles that can shield pathogenic organisms is a key concern and one of the reasons that MBR treatment is likely to yield an effluent quality better suited to disinfection at lower doses and shorter contact times. Chlorine is the most commonly utilized chemical disinfectant, and UV light is the most commonly utilized physical disinfectant (Blatchley et al., 2007). Detailed performance data for chlorine and UV light are provided in the following sections.

Table 2.1. Pros and Cons of Chemical and Physical Disinfectants Following MBR

Disinfectant (Type)	Pros	Cons
Chlorine (chemical)	Well-established technology Good wide-spectrum disinfectant Benefits of carrying a residual Onsite generation possible	Forms trihalomethanes Ineffective toward protozoan cysts Hazardous to store and ship Adds chloride and TDS to effluent Long contact time Mixing considerations
Chloramines (chemical)	Little by-product formation	Weak disinfectant Ineffective for inactivation of protozoan cysts and oocysts Adds nitrogen back into treated effluent Longest contact time Mixing considerations
Ozone (chemical)	Stronger biocide than chlorine Short contact time required Rapidly decomposing residual Onsite generation Adds oxygen to effluent	High dose needed for protozoan cysts Contactor design is critical Very corrosive Usually costlier
Chlorine dioxide (chemical)	Stronger biocide than chlorine	Forms chlorite High dose needed for protozoan cysts Requires more onsite monitoring Usually costlier
UV light (physical)	Effective toward protozoan cysts Eliminates use of toxic chemicals Short contact time and no residual	Less effective for some viruses (adenovirus) Photo repair can occur Requires more energy input Greater system maintenance needs

2.1 Chlorine

2.1.1 Microbial Sensitivity in Matrix-Free Water to Free and Combined Chlorine

Evaluation of chlorine disinfection kinetic data obtained under demand-free conditions (Haas and Karra, 1984) demonstrated the adequacy of the Chick-Watson Law (Equation 1) in describing the collected data with

$$ln(N/No) = -kC"t \quad (1)$$

where *N/No* is the ratio of microorganism concentration at time *t* to that at time zero; *C* is the disinfectant concentration, which must be constant; and *k* and *n* are empirical constants. Comparison of the empirical constants obtained by one researcher performing independent inactivation experiments using free or combined chlorine for the same microorganism (Table 2.2) clearly demonstrated the superior inactivation capabilities of free chlorine compared to those of combined chlorine.

Table 2.2. Superior Inactivation Kinetics of Free Compared with Combined Chlorine

Chlorine Type	Organism	pH	Temp (°C)	k ($l \bullet mg^{-1}min^{-1}$)	n
Free	*E. coli*	8.5	2–5	10.9	1.2
Combined	*E. coli*	8.5	3–5	0.0109	1.52
Free	*Enterobacter aerogenes*	7	20–25	1.39×10^4	3.78
Combined	*E. aerogenes*	7	20–25	0.241	1.35
Free	*Shigella dysenteriae*	7	20–25	9.07×10^7	4.92
Combined	*S. dysenteriae*	7	20–25	0.55	1.15

Comparison of free chlorine CT values required by different types of waterborne pathogens at pH 6.0 and 5 ºC (Hoff and Akin, 1986) demonstrates the wide range in pathogen resistance to a single disinfectant, with *E. coli* requiring a CT of 0.04 mg-min/L, poliovirus type I requiring a CT of 1.7 mg-min/L, and protozoan cysts (for example, *G. lamblia*, *G. muris*, and *E. histolytica*) requiring CT values ranging from 50 to 250 mg-min/L. Variations in sensitivity of a single genus to a disinfectant have also been observed because of the development of genetically based alterations in survivors of prior disinfectant exposures or because of differences in bacterial growth environments (Hoff and Akin, 1986). Variations between pathogen groups are still much larger than differences amongst a particular species and type and generally adhere to the following sequence of resistance towards chemical disinfectants (McDonnell and Russell, 1999):

Prions (CJD, BSE) > coccidia (*Cryptosporidium*) > spores (*Bacillus*, *Clostridium difficile*) > mycobacteria (*M. tuberculosis*, *M. avium*) > cysts (*Giardia*) > small nonenveloped viruses (polio) > trophozoites (*Acanthamoeba*) > gram-negative bacteria (nonsporulating)

(*Pseudomonas*, *Providencia*) > fungi (*Candida*, *Aspergillus*) > large nonenveloped viruses (enterovirus, adenovirus) > gram-positive bacteria (*S. aureus*, *Enterococcus*) > lipid-enveloped viruses (HIV).

2.1.2 Water Quality Impacts on Chlorine Demand

Key effluent quality constituents that will impact chlorine performance are summarized in Table 2.3. These constituents consume chlorine in competing reactions, so it is no longer available as free chlorine. It is either converted to less efficacious chloramines or consumed in oxidation or substitution and addition reactions. In wastewater effluents, residual ammonia will convert free chlorine to less effective chloramines, so complete nitrification is an important factor in reducing chlorine dose requirements.

Table 2.3. Wastewater Constituents That Interfere with Chlorine as a Disinfectant

Constituent	Impact
Aggregate organics (BOD, COD, TOC, etc.)	Certain functional groups and chemical structures will react with chlorine
Humic materials	React with chlorine to form chlorinated organic compounds
Oil and grease	May react with chlorine
TSS	Shield embedded microorganisms
Ammonia	Converts chlorine to weaker chloramines
Nitrite	Oxidized by chlorine, leads to NDMA formation
Iron	Oxidized by chlorine
Manganese	Oxidized by chlorine
pH	Affects distribution between hypochlorous acid (stronger disinfectant) and hypochlorite ion

Source: Metcalf & Eddy, Inc., 2003, p. 1246.

2.1.3 Recommended Dose Requirements

There are no federal regulations for recycled water, and guidelines for recommended chlorine dose and disinfected effluent monitoring requirements vary by state and effluent applications. States with well-developed recycled water requirements include California, Florida, Washington, Arizona, and Texas. Their requirements are summarized in the following.

In California, disinfected tertiary recycled water is required for surface irrigation of food crops, parks and playgrounds, schoolyards, residential landscaping, and unrestricted-access golf courses. The chlorine disinfection requirement for utilizing filtered effluent for this

application category is specified as a CT (the product of total chlorine residual and modal contact time measured at the same point) value of not less than 450 mg-min/L at all times with a modal contact time (time for highest concentration to pass through contact chamber) of at least 90 min, based on peak dry weather design flow. Approval of a lower disinfection CT requires a demonstration that the combined filtration and disinfection process will inactivate and/or remove 99.999% of F-specific bacteriophage MS-2 or poliovirus in the wastewater. This alternate process must still produce disinfected effluent for which the median concentration of total coliform bacterium does not exceed an MPN of 2.2 per 100 mL utilizing the bacteriological results of the last 7 days for which analyses have been completed. The number of total coliform bacteria must not exceed an MPN of 23 per 100 mL in more than one sample in any 30-day period, and no sample shall exceed an MPN of 240 total coliform bacteria per 100 mL.

In Florida, reclaimed water is defined as water receiving at least secondary treatment and basic disinfection that is reused after flowing out of a domestic wastewater treatment facility. Low-rate land applications for irrigation of public access areas, residential irrigation, or edible crops require tertiary treatment that can provide a TSS level at or below 5 mg/L prior to disinfectant application and high-level disinfection that result in fecal coliform concentrations (per 100 mL of sample) below detectable limits for 75% of the values acquired over a 30-day period with any one sample not to exceed 25 fecal coliform bacteria per 100 mL and with any one sample not to exceed 5.0 mg of TSS/L at the point of disinfectant application. The total chlorine CT requirement is based upon the fecal coliform bacterial concentrations before disinfection and is specified as 25 mg-min/L CT for fecal coliform bacteria of <1000 MPN/100 mL; 40 mg-min/L CT for fecal coliform bacteria of 1000 to <10,000 MPN/100 mL; and 120 mg-min/L CT for fecal coliform bacteria of 10,000 MPN/100 mL and higher.

In Washington, reclaimed water used for spray irrigation of food crops, irrigation of public access areas, and fire hydrants and sprinkler systems must be coagulated and filtered prior to disinfection. Washington is presently re-evaluating its guidelines, but existing chlorine disinfection requirements cite a minimum residual of 1 mg of free chlorine/L following a contact time of at least 30 min measured as t_{10} (time required for 10% of the disinfectant to pass through the contact chamber).

In Arizona, reclaimed water used for irrigation of food crops, recreational impoundments, public access landscape irrigation, toilet flushing, fire protection systems, spray irrigation of orchards and vineyards, closed-loop air conditioning systems, vehicle and equipment washing, and snow making must be Class A reclaimed water that has been subjected to secondary treatment, filtration, and disinfection. Class A reclaimed water just prior to disinfection achieves a 24 h average turbidity of 2 NTU and never exceeds 5 NTU. There must also not be any detectable fecal coliform organisms in four of the last seven monthly reclaimed water samples collected, and no single sample at or above 23 organisms per 100 mL is permissible.

In Texas, reclaimed water for irrigation or other uses where there is the potential for public contact (namely, residential and urban use irrigation, fire protection, irrigation of food crops with direct contact, irrigation of pastures for milking animals, maintenance of water bodies with possibility of recreational activities, and toilet flushing) must have a 30 day average quality of 5 mg/L for BOD_5 or $CBOD_5$, turbidity of 3 NTU, a fecal coliform or *E. coli* 30-day geometric mean of 20 CFU/100 mL and a maximum single grab sample value of 75 CFU/100 mL, and an *Enterococcus* 30 day geometric mean of 4 CFU/100 mL and a maximum single

grab sample value of 9 CFU/100 mL. There is also a recommendation to carry out periodic fecal coliform bacterial sampling in certain reclaimed water distribution piping systems.

2.2 UV Light

2.2.1 Microbial Sensitivity in Matrix-Free Water

Compiled experimental UV doses to achieve 4- and 5-log inactivation of specific bacteria, viruses, and protozoa (Chevrefils et al., 1999) were adapted for presentation in Table 2.4 as the range and mean of observed values by species. Interspecies variations are generally much larger than the intraspecies range, and resistance to disinfection does not follow the same trend observed for chemical disinfectants, likely because of differences in their inactivation mechanisms.

Table 2.4. UV Doses Required for Various Microorganisms

Pathogen	UV Dose (Fluence) (mJ/cm^2) for a Given Log Reduction without Photoreactivation			
	4-log		5-log	
	Range	Mean	Range	Mean
Spore				
Bacillus subtilis	78–81	79	-	-
Bacterium				
E. coli [1]	1.1–12.8	6.8	1.3–13	8.3
Legionella	6.4–9.4	7.8	8.0–9.6	8.8
Salmonella	7–210	38.8	8.5–250	90.8
Shigella	3–8.2	N/A	4	-
Streptococcus faecalis	9–11.2	12	-	-
Vibrio	2–130	N/A	3.6–150	-
Yersinia	4.6–5	N/A	-	-
Protozoan				
Cryptosporidium parvum	2.2–<16	<10	-	-
Virus[1]				
MS-2 (Phage)	61.9–120	87.1	80.1–133	108.7
PHI X 174 (Phage)	7–10.5	9	10.6–12.5	N/A
Calcivirus	30	N/A	36–39	N/A
Adenovirus	100–165	128.5	195–210	-
Poliovirus	21.5–40	30	32	
Coxsackievirus	32.5–36	-	-	-
Rotavirus	36–38	N/A	48	-
Hepatitis	16.4–29.6	N/A	-	-
Echovirus	28–33	N/A	-	-

[1] Different species or types were combined for range and average to elicit representative dose requirements because dose requirements were similar.

2.2.2 Impact of Water Quality

The UV dose needed to achieve target inactivation levels for specified pathogens may increase because of certain influent water quality parameters that will exert a UV demand by absorbing UV radiation at the germicidal wavelengths. The water quality parameters affecting UV disinfection of wastewater are presented in Table 2.5. Many of these constituents are similar to the ones that impact chlorine disinfection. In the case of TSS, it is the same shielding of the microorganism that interferes with the efficacy of the disinfectant. For natural organic matter, iron, and manganese, it is the same impact of disinfectant demand that leads to a higher delivered dose requirement. The key difference is that the presence of ammonia will have a much smaller impact on UV disinfection than chlorine does, because it results in only a small UV demand but converts free chlorine to much less effective chloramines.

Table 2.5. Effects of Water Quality on UV Disinfection of Wastewater

Constituent	Effect
BOD, COD, TOC	No major effect, unless BOD is primarily humic acids, which decrease UVT
NOM	Strongly absorbs UV
TSS	Absorbs and scatters UV, shields embedded bacteria
Alkalinity	Can impact scaling onto lamp sleeves
Ammonia	No major effect
Nitrite	No major effect
Nitrate	No major effect
$Fe^{2+/}Mg^{2+}$	Strongly absorbs UV
pH	Affects speciation of metals and carbonate

Source: Metcalf & Eddy, Inc., 2003, p. 1309.

2.2.3 Recommended Dose Requirements

California regulations provide the option to utilize an alternative disinfectant to chlorine, provided that it can be demonstrated to inactivate or remove 99.999% of F-specific bacteriophage MS-2 or poliovirus in the wastewater when combined with the filtration process. The CDPH relies upon the specifications in the Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse (NWRI/AWWARF, 2003) for evaluating new UV installations. These guidelines provide the detailed approach by which the installed equipment must be tested in order to ensure that the delivered dose falls within the

disinfection dose specifications. An installation's dose requirement is dependent upon the type of upstream filtration process installed in the process train and is specified as 100 mJ/cm^2 following sand or cloth filtration and 80 mJ/cm^2 following MF or UF.

Florida encourages the use of alternative disinfection methods due to the possible harmful effects of chlorine used in conjunction with wastewater. The Florida Department of Environmental Protection (FDEP) accepts UV designs that comply with the same guidelines and are supported with validation testing reports as a means for providing reasonable assurance that the dissolved-dose wastewater treatment facility can meet the high-level disinfection criteria. The differences between the 2000 and 2003 editions are minor, with one additional requirement being the need to perform velocity measurements when inlet and outlet conditions are not identical with respect to geometry, placement of diffusers, and/or flow conditioning devices. NWRI recently funded an update to the second edition to provide updates and revisions incorporating the knowledge gained during the past 7 years from an increasing number of UV installations.

The application of UV disinfection has grown tremendously in the last decade because it eliminates some of the negative environmental consequences associated with the use of chlorine. UV installations are typically permitted on a case-by-case basis. Most states rely upon the NWRI/AWWARF guidelines for site-specific commissioning requirements of water recycling facilities. Work is being done to create a test protocol that combines requirements of the NWRI/AWWARF guidelines with other resources developed by the USEPA and NSF International (Shen et al., 2009). All of these protocols rely upon the use of bioassay testing, in which a challenge microorganism with a well-characterized UV response is utilized to assess the full-scale reactor delivered dose performance under the anticipated envelope of treatment flows and water quality regimens.

2.3 Modifying Disinfectant Requirements for Satellite Treatment

Existing water reuse disinfection guidelines were established before development and implementation of newer technologies frequently employed at satellite installations. Therefore, understanding how new technologies improve effluent quality compared to more-traditional treatments, how this improved effluent quality can be monitored as real-time performance, and what type of verification data might be necessary for regulators to reduce subsequent disinfectant dose requirements is important. Being able to implement lower dose requirements that still protect human health is an important consideration in minimizing the release of potentially harmful disinfection by-products and energy use resulting in greenhouse gas emissions that contribute to climate change.

2.3.1 Satellite Improvements in Effluent Quality

Satellite treatment installations employing MBRs will produce effluent quality superior to the tertiary effluent quality obtained by using depth filters or cloth filters. The MBR effluent will have lower microbial concentrations, but more importantly, it will have a much lower probability of passing particle-embedded microbes and the suspended solids that impede a subsequent chemical or physical disinfection process. California requires an MBR system installed to meet the most restrictive Title 22 requirements to demonstrate continuous adherence to effluent turbidity requirements. Although performance within these turbidity standards does not indicate the absence of pathogens or pathogen indicator organisms, it

should produce an effluent quality that requires a much lower subsequent disinfectant dose and shorter contact time. Another important consideration is the extent to which the MBR is providing complete ammonia removal through its nitrification process, because the passage of residual ammonia will convert free chlorine to chloramines, which are less effective at disinfection.

2.3.2 Effluent Quality Monitoring Requirements

Monitoring the key performance processes that will impact the satellite process effluent water quality with respect to solid and ammonia content is important. Process performance characteristics that will impact the passage of solids relate to the integrity of the membranes and the potential impact of the cleaning cycle frequency at which time the sludge layer is temporarily removed from the membrane surface. Process performance characteristics that will impact the ammonia content relate to the performance of the biological reactor. A sufficient SRT appropriate to the effluent temperature must be maintained in order to ensure the maintenance of nitrifying organisms within the reactor. The level of nitrification can vary slightly from day to day, and the ability to continuously monitor the ammonia content of the effluent would provide a critical operation control tool that could allow reduction of subsequent chemical or physical disinfectant dose requirements.

2.3.3 Approach to Lower Dose Requirements

In order to allow regulators to lower subsequent chemical and physical dose requirements for satellite facilities employing technologies such as MBRs that produce higher-quality effluent, providing additional data on the following types of information is important:

1. Better characterization and more frequent monitoring of full-scale installed facility performance relative to solid removal and ammonia removal. Data sets that allow for discernment of assignable operational causes for poorer-effluent-quality performance will help to establish operational guidelines and routine monitoring requirements that will ensure minimal effluent quality performance.
2. Discernment of how differences in effluent quality assessed through turbidity and ammonia measurements will impact chemical and physical disinfectant dose requirements.

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Appendix B

Methods for Water Quality Analysis

Physicochemical Parameters

Male Specific Bacteriophage

All male specific bacteriophage analyses were performed by using the single agar layer method (USEPA Method 1602). Influent samples were typically diluted 10- to 1000-fold, and 10-mL volumes for each dilution were analyzed in duplicate. Undiluted predisinfection filtrate samples were analyzed in duplicate 50-mL aliquots. As specified under Method 1602, each 10-mL sample was mixed with 50 µL of magnesium chloride and was warmed to 37.5 °C, followed by the addition of 1 mL of *E. coli* Famp host. Samples were mixed by swirling and transferred to a 46.5 °C water bath. Once the temperature had reached 41 °C, a 10-mL volume of 2× tryptic soy agar (containing ampicillin-streptomyocin antibiotics) was added to each sample tube, mixed by gentle inversion, and poured onto a plate after 3 min. Once the agar solidified, the plate contents were incubated overnight at 37 °C. The following day, plaques were enumerated.

Total Coliforms

Influent and effluent grab samples from each location were analyzed for total coliforms by using the membrane filtration method (Standard Method 9222B; Eaton et al., 2005). Raw influent sample dilutions ranged from 100- to 10,000-fold. Occasionally dilutions of 100,000 to 1×10^6-fold were necessary. Predisinfection filtrate samples were usually analyzed at 100 mL volumes in duplicates. Each sample passed through through 0.45-µm-pore-size GN-6 Metricel Grid filters (PALL Life Sciences), and the filter was aseptically mounted onto m-Endo agar plates. The plate contents were incubated at 36 °C overnight (16–24 h), and the presumptive coliform colonies were distinguished with their green sheen and were enumerated.

Particle Counts

Predisinfection filtrate samples were analyzed for their particle characteristics by using the Met One WGS-267 Water Grab Sampler (HACH, Loveland, CO). The unit has a sample inlet port, which draws the test sample with the aid of a peristaltic pump, and the sample is analyzed with a laser particle analyzer. The sample is pushed through an outlet port and into a discard container. Before and between test samples, the instrument was cleaned by pumping a 300- to 400-mL volume of DI water through the instrument at a flow rate of approximately 100 mL per min. Test sample volumes of 200 mL were typically analyzed, and the particles were categorized into 2.0-, 3.0-, 5.0-, 7.0-, 10.0-, and 15.0-µm sizes.

Ammonia-Nitrogen

For predisinfection filtrate samples, ammonia-nitrogen was determined by following Salicylate Method 8155, which uses ammonia salicylate and ammonia cyanurate powder pillows. The assay detection range was 0.01 to 0.50 mg of NH_3-N/L. Each assay was conducted by adding 10 mL of the test sample to a vial followed by addition of a powder pillow of ammonia salicylate. The mixture was shaken vigorously and was allowed to react for 3 min. An ammonia cyanurate powder pillow was then added to each vial, shaken vigorously, and allowed to react for 15 min. Prior to performance of UV-Vis

Spectrophotometry (HACH DR 5000; HACH) on the test sample, a 10-mL aliquot of DI water was used as the method blank to zero the spectrophotometer. Ammonia content in the test sample was determined by measuring the greenness at 655 nm.

UV-254

UV-254 absorbance was determined on a DR 5000 UV-Vis Spectrophotometer (HACH). Prior to testing of each sample, the spectrophotometer was zeroed by using DI water. Following this the UV absorbance of 1- to 2-mL predisinfection filtrate samples was measured at 254 nm in duplicate.

Turbidity

Turbidity was determined by using the 2100N Turbidimeter (HACH). The instrument was zeroed by using 15 to 20 mL of DI water. Aliquots of 15 to 20 mL of predisinfection filtrate samples were used. The instrument measures turbidity ranges between 0 and 400 NTU. After each sample measurement, a thorough rinse of the turbidity cell was performed to eliminate carryover of particles between samples.

Total Organic Carbon

TOC was measured as nonpurgeable organic carbon according to Standard Method 5310 B (Eaton et al., 2005) by using a Shimadzu TOC-VCSH analyzer (Columbia, MD) that utilized high-temperature combustion with nondispersive infrared detection. Test samples of about 15 to 20 mL were placed in individual vials, and each vial was measured in triplicate to verify that peak areas and corresponding concentrations had a coefficient of variation of <2%. Procedural quality assurance required that laboratory-fortified blanks and matrix-spiked samples were within 25% of the accepted value and were measured once per analytical run.

Microbial Parameters for Viruses (Adenovirus, Rotavirus, Hepatitis A, and Enterovirus)

Virus Collection, Elution, and Concentration

Predisinfection filtrate samples (10–20 L) were filtered through sterile Virosorb® 1MDS Cartridge filters (CUNO Filtration, Carlstadt, NJ). Viruses were eluted from each filter by adding 1 L of a 1.5% beef extract (BBL Microbiology Systems; pH = 9.5) followed by acid flocculation according to the Information Correction Rule procedure (USEPA, 1995). The floc containing the virus particles was centrifuged (3100 rpm) for 15 min, and the supernatant was discarded. The pellet was suspended in a 4-mL sterile solution of sodium hydrogen phosphate (0.15 M; pH 9.5 Na_2HPO_4) and was centrifuged at 4500 rpm (15 min). The supernatant was adjusted to pH 7.2, and the final volume was recorded. Sample concentrates were stored at -80 °C until DNA/RNA extraction.

DNA and RNA Extraction

A QIAGEN QIAamp UltraSens Virus Kit was used to extract viral RNA or DNA. Briefly, the concentrated samples were thawed at room temperature, and 500 µL of each sample was transferred to a 2-mL microcentrifuge tube. An equal volume of 1× phosphate-buffered saline (PBS) was added. Buffer AC from the kit (800 µL) was added to each sample, and 5.6 µL of

Carrier RNA was also added. Samples were mixed by inverting the tubes for 10 s, incubated at room temperature for 10 min, and centrifuged at 2200 × *g* for 3 min. The supernatant was discarded, and 300 µL of prewarmed (60 °C) Buffer AR was added. Proteinase K (20 µl) was added to each sample, vortexed, and incubated at 40 °C for 10 min. The sample was vortexed after 5 min of incubation. A 300-µL volume of binding Buffer AB was added, vortexed thoroughly, and centrifuged briefly (1200 × *g* for 5 s), after which 700 µL of lysate was added to a QIAamp spin column. The column was centrifuged at 4000 × *g* for 1 min. Two separate washes were performed by addition of 500 µL of Buffer AW1, centrifugation at 6000 × *g* for 1 min, and then addition of 500 µL of Buffer AW2 to the spin column followed by centrifugation at 20,000 × *g* for 3 min. The viral nucleic acid in the QIAamp spin column was then eluted by adding 50 µL of Buffer AVE and centrifugation at 6000 × *g* for 1 min. This elution step was repeated with another 50 µL of Buffer AVE to obtain a total DNA or RNA concentrate volume of 100 µL. To each sample, 5 mg of Chelex 100 resin/100 µL (to remove inhibitors) was added followed by vortexing and incubation at room temperature for 1 h. During the 1 h incubation, each sample was vortexed at 1 min intervals. After a 1 h incubation, the Chelex−sample suspension was centrifuged (20,000 × *g* for 5 min) and the supernatant was removed and stored at -20 °C for molecular analyses.

RT-PCR

The reagents for RT-PCR were purchased from Promega (Madison, WI), and the Access RT-PCR system (catalog no. A1250) was used as recommended by the manufacturer with the use of 25-µL reaction volumes for individual detection of enterovirus, hepatitis A virus, and rotavirus. On the other hand, adenovirus DNA was detected by using the Perfecta SYBR Green FastMix kit (Quanta Biosciences). To synthesize the first-strand copy DNA, the mixture was incubated at 45 °C for 40 min. The template was denatured at 94 °C for 2 min and thereafter was subjected to thermal cycling as summarized in Table 1 by using the Roche LightCycler 480 system II RT-PCR device (Roche Diagnostics, Indianapolis, IN). The RT-PCR product curves were examined, and their threshold cycle (namely, the number of cycles at which the fluorescence generated within a reaction crosses the threshold, referred to as the crossing point [Cp] value) was evaluated. The PCR products were loaded into individual wells of a 1.6% agarose gel and separated by electrophoresis (application of 100 volts across the loaded gels) for 1 h. The electrophoresed PCR products were stained with 0.25 µg per mL of ethidium bromide, and the separated DNA bands were visualized under UV light.

PCR for Adenovirus

The hexon gene was amplified in a LightCycler 480 II (Roche Diagnostics, Mannheim, Germany) by using a protocol modified from Allard et al. (2001). PCRs were carried out in 20-µL reaction mixtures containing 1 U of Perfecta SYBR Green FastMix kit (Quanta Biosciences), 10 pmol of each primer, and 8 µL of template DNA. PCR products were made visible on ethidium bromide-stained 1.6 % agarose gels and were observed under UV light.

Table 1. RT-PCR Conditions for Different Viruses

Target Virus	Primer and Probe	Primer Quantity	RT-PCR Conditions	Reference
Enterovirus	EV-F, EV-R, EV-Probe	300 nM	Incubate at 65 °C (2 min); 48 °C (40 min); 95 °C (10 min); [60 cycles of denaturation at 94 °C (15 s) and amplification at 58–61 °C (1 min)]	Wang et al., 2002
HAV	HAV1, HAV2, HAV3, HAV Probe	300 nM	Incubate at 65 °C (2 min); 45 °C (40 min); 95 °C (5 min); [50 cycles of denaturation at 94 °C (15 s) and amplification at 60–62 °C (1 min)]	Modified from Costa-Mattioli et al., 2002
Rotavirus	Rota-F, Rota-R, Rota-Probe	200 nM	Incubate at 65 °C (2 min); 45 °C (40 min); 95 °C (10 min); [50 cycles of denaturation at 94 °C (20 s) and amplification at 47–61 °C (1 min)]	Modified from Zeng et al., 2008
Adenovirus	Hex1, Hex2	500 nM	Incubate at 94 °C (3 min); [35 cycles of denaturation at 94 °C (30 s); 55 °C (30 s); 72 °C (30 s) and final extension at 72 °C (5 min)]	Modified from Allard et al., 2001

DNA Sequencing

PCR products were purified by using ExoSAP-IT (USB Products, Affymetrix, Cleveland, OH) and were sequenced at Genewiz, Inc. (South Plainfield, NJ) by using an ABI 3730xl DNA Analyzer with appropriate internal primers. Sequences were aligned and were analyzed with published reference sequences by using Clustal W (Thompson et al., 1994).

Cryptosporidium and *Giardia*

The Envirochek HV filters (1.0-µm nominal pore size) were used to collect 10-L samples of MBR predisinfection filtrates at flow rates ranging from 2–4 L per min. The sampling and elution procedures have been described in detail previously for Method 1623 (USEPA, 2005). Briefly, Laureth-12 buffer was added to the capsule, shaken to recover entrapped oocysts and cysts in a total elution buffer volume of 250 mL, which was subsequently concentrated to 10 mL, and subjected to immunomagnetic separation to specifically recover the target organisms. *Cryptosporidium* oocysts and *Giardia* cysts were fixed onto glass slides, stained with fluorescence-conjugated monoclonal antibodies, and viewed and enumerated by Long Term 2-Enhanced Surface Water Treatment Rule (LT2)-certified analysts who used an Olympus fluorescence microscope. The microscope was equipped with a blue filter block (excitation, 490 nm; emission, 510 nm) for viewing of oocysts and cysts labeled with fluorescein isothiocyanate at 200× magnification. Confirmation of oocysts and cysts was achieved at 400× magnification by using a UV filter block (excitation, 400 nm; emission, 420 nm) for viewing of 4′-6′-diamidino-2-phenylindole staining of nuclei. The internal morphology of oocysts and cysts was observed by using Nomarski-DIC microscopy.

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