Joint Water Purification Pilot Program

Pilot Study of Advanced Treatment Processes to Recycle JWPCP Secondary Effluent

Final Report

A Joint Study by:

Sanitation Districts of Los Angeles County
and
Metropolitan Water District of Southern California

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EXECUTIVE SUMMARY

Background

This pilot project was part of a larger effort to evaluate the feasibility of a regional indirect potable reuse program, which would purify secondary effluent to meet the replenishment needs of local groundwater basins in Southern California. The work was conducted between 2010 and 2012 by the Sanitation Districts of Los Angeles County (Districts) and the Metropolitan Water District of Southern California (MWD) at the Districts' Joint Water Pollution Control Plant (JWPCP) in Carson, CA. The JWPCP has an average dry weather design flow of 400 million gallons per day (MGD), and currently treats approximately 280 MGD of wastewater. Treatment processes include screening, grit removal, primary sedimentation, high purity oxygen activated sludge process, chloramine disinfection, sludge thickening, anaerobic digestion, and dewatering. Treated effluent is currently discharged to the Pacific Ocean.

Objectives

The overall goal of this study was to test advanced water treatment (AWT) processes and to determine whether the product water could meet or exceed the groundwater recharge water quality criteria specified in California Department of Public Health (CDPH) 2008 Draft Title 22 Groundwater Recharge Regulations (DGRR) and other applicable regulatory limits. Two treatment trains were studied. One consisted of the industry-standard system of ultrafiltration (UF), reverse osmosis (RO), and an advanced oxidation process (AOP) with ultraviolet (UV) oxidation and hydrogen peroxide addition. The other consisted of a membrane bioreactor (MBR) followed by RO and UV/hydrogen peroxide AOP.

The specific tasks of the study were the following:

- Conduct a review of similar water recycling projects documenting the experiences of these projects, including membrane operation and treatment of target contaminants.
- Characterize effluent and concentrate water quality from both AWT process trains. Compare effluent water quality to criteria specified in 2008 CDPH DGRR and other applicable regulatory limits.
- Evaluate UV oxidation, with and without hydrogen peroxide addition, for treatment of compounds that are not completely removed by RO membranes.
- Evaluate operating conditions and performance of the AWT membrane processes.
- Determine the effect of biological nitrification on system operations and product water quality.
- Evaluate chemicals/additives (specifically chloramines, anti-scalants, and acids) necessary for membrane fouling control.

Pilot System Description

The ultrafiltration unit used for this project was a Siemens 12M10C continuous filtration unit. This pressurized membrane filtration unit utilized hollow-fiber polyvinylidene fluoride (PVDF) membranes with a nominal membrane pore size of 0.04 μm.

The MBR unit used for this project was a GE/Zenon pilot system. ZeeWeed® 500c hollow fiber membranes (PVDF with a nominal pore size of 0.04 μm) were used for the first year of the study. These membranes, which had been used by the Districts for various studies since 2003, were replaced with new ZeeWeed® 500d membranes (also PVDF with a nominal pore size of 0.04 μm) at the end of 2011.

The UF filtrate and MBR permeate were used as feed streams for the RO units. Two identical RO units were used in the study, each equipped with 21 Hydranautics ESPA2 membrane elements configured in a two-stage 2:2:1:1 array. Stage 1 vessels contained 14 elements (two parallel series of seven elements) while Stage 2 vessels contained seven elements in series.

The AOP system could be fed with either UF-RO permeate or MBR-RO permeate. Most of the AOP testing used three flow-through Trojan UV Max G reactors, each equipped with a single 100W low-pressure high-output amalgam lamp that emitted monochromatic radiation at a wavelength of 254 nm. In selected experiments, a Calgon Carbon Rayox batch UV reactor was used. This reactor could be equipped with a single 40W low-pressure high-output lamp with monochromatic output at 254 nm, or a single 1kW medium-pressure lamp that emitted polychromatic radiation. Hydrogen peroxide could be added to the influent stream of the Trojan reactors, or directly to the Calgon reactor.

Water Quality Sampling Program

Sampling programs were established for three sets of water quality parameters: general parameters, nitrosamines and 1,4-dioxane, and a comprehensive set of parameters referred to as "Title 22+" parameters. The general parameters were routinely sampled and were used to evaluate the performance of the various pilot units. The nitrosamines and 1,4-dioxane were separated from the other parameters in this report, because the removal requirements for these compounds typically drive the design of the AOP system; consequently, the AOP experiments focused on these compounds. The Title 22+ parameters provided performance data for a much broader range of compounds than the general parameters.

The first set of parameters included physical parameters (pH, turbidity, total suspended solids, and total dissolved solids), major cations (calcium, magnesium, sodium, and potassium) and anions (sulfate, chloride, and alkalinity), organic matter (total and soluble COD, TOC), nutrients (ammonia, nitrate, nitrite, total Kjeldahl nitrogen, phosphate), and other parameters of interest (boron, aluminum, iron, barium, silica, strontium, and fluoride). Secondary effluent, UF filtrate, MBR permeate, and RO permeates samples were collected from the two AWT process trains and analyzed for these compounds. The sampling frequency varied from daily to bi-weekly depending on the sampling location and parameter. Concentrate streams produced from RO operations were sampled on a quarterly basis for the same list of parameters.

The second set of parameters included 1,4-dioxane and seven nitrosamine species: N-nitrosodimethylamine (NDMA), N-nitrosodiethylamine (NDEA), N-nitrosodi-n-propylamine

(NDPA), N-nitrosodi-n-butylamine (NDBA), N-nitrosomethylethylamine (NMEA), N-nitrosopiperidine (NDPA), and N-nitrosopyrrolidine (NPYR). These eight compounds were analyzed in bi-weekly samples taken from the secondary effluent, UF filtrate, MBR permeate, and both RO permeates. Samples were also taken during AOP experiments.

The "Title 22+" parameters were a set of 299 parameters that included all of the above parameters, as well as radioactive analytes, UV transmittance, microbiological parameters, volatile and semi-volatile organic compounds, pesticides, herbicides, disinfection byproducts, hormones, industrial endocrine disrupting chemicals (EDCs) and pharmaceutical and personal care products (PPCPs). A total of six Title 22+ sampling events were conducted in the study; two on the UF treatment train and four on the MBR treatment train.

Pilot System Operations

Operation of the pilot-scale system began in June 2010 and ended in June 2012. The study was divided into three phases, which were defined by the operating conditions on the MBR and the RO units (described in more detail in the following paragraphs). Phase 1 for the UF treatment train began in July 2010. Because the MBR system required more modifications before operation, Phase 1 for the MBR train began in December 2010. Phase 1 for both treatment trains ended in March 2011. Phase 2 operations began in July 2011 and ended in December 2011. Phase 3 began in January 2012 and ended with the end of the project in June 2012.

The UF unit was operated at a constant flux of approximately 22 gallons per square foot per day (gfd), or a flow rate of 46 gallons per minute (gpm). Average recovery was 93%. The unit was in productive operation (producing filtrate) for 13,700 hours over 726 days of testing, and treated more than 40 million gallons of secondary effluent. For approximately two years, the unit performed reliably and provided adequate feed for RO treatment. Two types of cleaning were routinely conducted during the study. The chemically enhanced backwash (CEB) was a single backwash with a sodium hypochlorite solution, followed by a 15- to 30-minute soak. Clean-in-place (CIP) consisted of recirculating and soaking the membranes in citric acid and sodium hypochlorite solutions. In the first two operational phases of the study, membrane cleaning intervals were acceptable with CIP required no more frequently than about every four weeks and CEBs not needed more than weekly. In Phase 3, however, the necessary CIP frequency increased to about every two weeks, and CEBs were required almost on a daily basis. Membrane fouling appeared to be worse during the winter, and also during rain events, when the solids content of the secondary effluent was noticeably higher. At the end of the two-year study period, the UF membranes were permanently fouled.

The MBR polished secondary effluent, with both biological treatment and membrane filtration, to provide feed for RO treatment. In Phases 1 and 2, ZeeWeed® 500c membranes (originally installed and used in 2003) were operated at fluxes ranging from 10 to 15 gfd. The mixed liquor suspended solids concentration in the membrane tank was maintained between 3,000 to 4,000 mg/L. The MBR was operated at solids retention times (SRTs) >10 days, and at hydraulic retention times ranging from approximately 70 to 100 minutes. The system performed adequately over the study period except near the end of Phase 2 when membranes approached the end of their service life and became significantly fouled. New ZeeWeed® 500d membranes were used in Phase 3 and operated at 20 gfd. No significant fouling on the new membranes had occurred by the end of the study in June 2012.

Both RO units were operated at an average flux of 12 gfd, and average recovery of approximately 85%. In Phase 1 operation, sulfuric acid was added to lower the RO influent to a target pH of 6.5. The average sulfuric acid doses required for the UF filtrate and MBR permeate were 162 mg/L and 53 mg/L, respectively. At the end of Phase 1 operation, membrane elements from both RO units were extracted for autopsy. A deep cleaning of the RO membranes was then performed prior to Phase 2. In Phase 2 operation, sulfuric acid addition was reduced based on the Langelier saturation index of the RO concentrate. The target pH of the concentrate was set to be 7.2 for the UF-RO and 7.3 for the MBR-RO. The change resulted in a 40% reduction of sulfuric acid usage for the UF-RO treatment train, and a 95% reduction for the MBR-RO treatment train. In Phase 3, new membrane elements were used for both RO units because water quality data collected from Phase 2 and membrane autopsy results both suggested that the RO membranes were fouled and might have been damaged.

Water Quality Sampling Results

General Parameters

The JWPCP produced a non-nitrified secondary effluent with the following characteristics (median values): total COD ~55 mg/L (~85% soluble), TSS ~10 mg/L, TDS ~1,400 mg/L, and TKN ~ 40 mg N/L. Secondary effluent concentrations of several general parameters (barium, boron, chloride, phosphate, strontium, sulfate, TOC, TSS, alkalinity, ammonia and TKN, total and soluble COD, and potassium) increased during the study period.

The UF effectively removed TSS, turbidity, and analytes (such as aluminum and iron), that were associated with solids. Some barium, phosphate, and particulate COD were also removed by UF. In addition to removing solids, the MBR removed an average of 40% of organic matter (COD and TOC) from the secondary effluent and completely nitrified TKN to mostly nitrate nitrogen. The nitrification process consumed approximately three-quarters of the secondary effluent alkalinity. Consequently, the sulfuric acid dose required to lower the MBR permeate to the target pH of the RO feed was much less than that required for the UF filtrate.

Due to the sulfuric acid addition, the median pH values were 5.5 and 5.6 in the UF-RO and MBR-RO permeates, respectively. Because these values were lower than the target range of 6.5-8.5, the RO permeate would likely need to be treated (e.g., with decarbonation and lime) to raise the pH, as is typical for AWT systems.

The RO units effectively removed the majority of the general water quality parameters except boron (15-50% removal). Boron was present in the RO permeates of both treatment trains at concentrations as high as 0.8 mg/L; the Main San Gabriel Basin Plan (Basin Plan) objective concentration for boron is 0.5 mg/L. Source control or other treatment technologies, such as ion exchange, would be required to meet the Basin Plan objective for boron.

For the UF-RO treatment train, the median total nitrogen (TN) level in the RO permeate was ~2 mg N/L and consisted mainly of ammonia nitrogen. The median TN level in the RO permeate for the MBR-RO treatment train was ~3 mg N/L and consisted mainly of nitrate nitrogen. TOC levels in the UF-RO permeate occasionally exceeded the 0.5 mg/L target in Phases 1 and 2, but consistently met the target in Phase 3. TOC concentrations in the MBR-RO permeate were consistently below 0.5 mg/L throughout the study.

Nitrosamines and 1,4-Dioxane

In secondary effluent, five nitrosamines (NDMA, NDEA, NDPA, NDBA, and NPIP) were typically present at levels greater than 100 ng/L, and 1,4-dioxane level was typically ~10 µg/L. The UF had very little effect on any of these compounds except NDEA, which increased in concentration across the UF. The MBR had little effect on 1,4-dioxane, but consistently removed NDPA, NPIP, and NPYR. NDMA and NDBA were removed to a lesser degree, and the removals were not consistently significant. Similar to the UF, the concentrations of NDEA increased across the MBR. Further research is needed to determine the cause(s) of this increase.

The RO membranes were effective at removing most of the compounds to below the target concentrations. The exceptions were NDMA and NDEA, with concentrations consistently above target levels, and NDPA and 1,4-dioxane, with concentrations occasionally above target levels. AOP testing was conducted to determine the conditions under which these four compounds could be removed to below the target concentrations. Because concentrations entering the AOP varied, treatment goals were set as target removals, based on the highest observed RO permeate concentrations and the target concentration. The AOP successfully achieved target removals of 1,4-dioxane, NDMA, and NDPA. However, NDEA targets were not achieved at the tested doses (up to 6 mg/L of hydrogen peroxide and up to 4 kWh/kgal of UV; this UV dose is reactor-specific and does not apply to any other system). The NDEA removal targets could be met by increasing the doses, by reducing the influent concentrations through source control, and/or by choosing a different influent concentration (e.g., the 90th percentile, rather than the maximum value) for design.

The levels of removal of the various compounds were not affected by hydrogen peroxide alone. NDMA removal increased with increasing UV dose, but hydrogen peroxide had no effect on removal. Removals of NDEA, NDPA, and 1,4-dioxane increased with increasing doses of either UV or hydrogen peroxide. Removals were slightly better in the MBR-RO effluent than in the UF-RO effluent, which could result in lower hydrogen peroxide doses (by 1-2 mg/L) to meet regulatory removal requirements. The LP lamps provided a clear benefit over the MP lamps, with better removal of both NDMA and NDEA at lower UV doses (i.e., lower energy use).

Title 22+ Parameters

A total of 299 parameters were tested in six Title 22+ sampling events. In addition to the general parameters, nitrosamines, and 1,4-dioxane discussed above, the JWPCP secondary effluent contained trace levels of volatile organic compounds (VOCs, e.g., chloroform and phenol), pesticides (e.g., aldicarb sulfone), hormones (e.g., estrone), industrial EDCs (e.g., bisphenol A and alkylphenols), and PPCPs (e.g., sulfamethoxazole and DEET), and other wastewater indicators (e.g., caffeine and TCEP). Excluding the general parameters, nitrosamines, and 1,4-dioxane discussed above, the UF-RO treatment effectively removed all detected chemicals to below their laboratory reporting limits except for several VOCs, chlorate, and formaldehyde. The detected levels of these parameters were well below their target concentrations, for those compounds that had target concentrations. The MBR-RO treatment train performed similarly, except that chlorate was not detected and the species of some VOCs differed.

The AOP processes performed similarly on both trains. Low levels of several metals (copper, lead, and hexavalent chromium) were detected in the AOP effluent from both treatment trains. This was likely due to contamination from the UV reactors or fittings because these metals were not detected in the RO permeates. Formaldehyde concentrations increased for both effluents, but remained well below the target concentration of 100 μg/L. The total THM concentrations in the AOP effluent were slightly lower in the MBR train than in the UF train, but concentrations in both effluents were well below the total THM target concentration of 80 μg/L.

Overall, the Title 22+ sampling results indicated that both AWT trains were effective in removing the trace contaminants present in the JWPCP secondary effluent to either below the laboratory reporting limits or the relevant target concentrations. With the exception of boron, NDEA, and pH, the final product water from both AWT trains met all of the water quality targets for groundwater replenishment.

Comparison of AWT Process Trains

	UF-RO-AOP	MBR-RO-AOP
Operation	Operations of UF was more affected by the secondary effluent water quality; poor secondary effluent water quality increased the chance of fouling and the cleaning requirements	Operation of MBR was less affected by secondary effluent water quality; MBR operated to polish secondary effluent could be operated at a flux similar to the UF flux
Design	Required a smaller footprint	Required aeration tank(s) as well as membrane tank(s)
Chemical Use	Sulfuric acid dose to lower the pH of UF filtrate was higher	Sulfuric acid dose to lower the pH of MBR permeate was much lower because the MBR consumed 75% of the secondary effluent alkalinity during nitrification
Energy Use	Energy to operate the UF system was lower	MBR system required air scouring of the membranes, therefore using more energy; air used for membrane scouring was sufficient to fully nitrify the secondary effluent in this study
Effluent Water Quality	Median total nitrogen concentration was ~2 mg NH_3-N/L TOC concentration was occasionally higher than the target of 0.5 mg/L	Median total nitrogen concentration was ~3 mg NO_3-N/L TOC concentration was consistently below the target of 0.5 mg/L AOP removal of nitrosamines and 1,4-dioxane was slightly better because of lower alkalinity and/or higher UVT in the RO permeate.

Conclusions

- With JWPCP secondary effluent as the source water, the UF-RO-AOP process train produced a high quality recycled water that consistently met the water quality criteria in 2008 CDPH DGRR except for TOC. TOC concentrations in the final product water occasionally exceeded the DGRR limit of 0.5 mg/L. In addition, boron concentrations in the final product water often exceeded the Basin Plan limit of 0.5 mg/L. Source control or additional treatment processes would be required to lower the boron concentration to below this limit if the final product water was to be used for groundwater replenishment. Finally, the pH was lower than the target of 6.5-8.5; the RO permeate would likely need to be treated (e.g., with decarbonation and lime) to raise the pH, as is typical for AWT systems.

  The AOP tested in the study was effective in removing emerging contaminants of concern such as nitrosamines and 1,4-dioxane. The required UV and hydrogen peroxide doses would be determined based on NDEA removal requirements.

- The MBR-RO-AOP process train proved to be an intriguing alternative to the UF-RO-AOP process train. UF membranes used for treating secondary effluent from a low SRT activated sludge process often suffer from fouling problems, as observed in this study. The MBR could be operated to polish the secondary effluent by removing biodegradable organic matter and reducing the potential for membrane fouling. In this study, the MBR membranes were operated at a flux comparable to that of the UF membranes for approximately six months (Phase 3). There were no membrane fouling problems during this time period. More time would be required to verify that the MBR could be operated under these conditions without fouling.

  The MBR-RO-AOP process train also produced a high quality recycled water that consistently met the water quality criteria in 2008 CDPH DGRR, including TOC. Boron concentrations in the final product water often exceeded the Basin Plan limit of 0.5 mg/L. Source control or additional treatment processes would be required to lower the boron concentration to below this limit if the final product water was to be used for groundwater replenishment. In addition, the pH was lower than the target of 6.5-8.5; the RO permeate would likely need to be treated (e.g., with decarbonation and lime) to raise the pH.

  The AOP tested in the study was effective in removing emerging contaminants of concern such as nitrosamines and 1,4-dioxane. The required UV and hydrogen peroxide doses would be determined based on NDEA removal requirements.

- Decreasing NDEA concentrations in the RO permeate would reduce the size and cost of the AOP system at the JWPCP. NDEA was present in the secondary effluent, and its concentration increased across both the UF and MBR units. The increase across the UF may be due to chloramination of the secondary effluent, but the MBR permeate samples were not chloraminated. More work is needed to better understand the formation mechanisms of NDEA.

1. INTRODUCTION

1.1 BACKGROUND ON ADVANCED WATER TREATMENT

Advanced water treatment technologies have been successfully used in a number of water recycling projects. These projects typically include microfiltration (MF) or ulftrafiltration (UF) followed by reverse osmosis (RO), and advanced oxidation processes (AOP) where required. Table 1-1 summarizes water recycling facilities in Southern California, the types of membranes used, design fluxes, and applications. Typical operating conditions for MF/UF membranes treating secondary effluent are 18 – 20 gallons per square foot per day (gfd) flux and 85-93% recovery. These operating conditions typically ensure effluent quality that can yield 10 – 12 gfd flux and 85% recovery for downstream RO membranes. At most facilities, biofouling of both MF/UF and RO membranes is controlled through the use of chloramines. Commercially available anti-scalants and other chemicals are used on RO membranes to control inorganic fouling caused by sparingly soluble salts.

1.2 PROJECT OVERVIEW

The Joint Water Purification Pilot Program was a collaborative effort between the Sanitation Districts of Los Angeles County (Districts) and the Metropolitan Water District of Southern California (MWD). The objective of the project was to evaluate the feasibility of a regional indirect potable reuse program to purify treated wastewater from the Districts' Joint Water Pollution Control Plant (JWPCP) that is currently discharged to the Pacific Ocean. The purified water produced would be conveyed either through a distribution system to meet replenishment needs of multiple local groundwater basins or to a single groundwater basin that would act as an environmental buffer prior to recovery and blending with raw water influent to one or more MWD treatment plants. As part of the program, the Districts and MWD initiated *Pilot Study of Advanced Treatment Processes to Recycle JWPCP Secondary Effluent* to test advanced water treatment (AWT) processes and to determine the requirements to achieve water quality that surpassed drinking water standards.

Two parallel AWT process trains were tested to determine their effectiveness in producing recycled water that met or exceeded the groundwater recharge water quality criteria specified in Title 22 of the California Code of Regulations. One AWT process train consisted of the industry-standard system of UF/RO/AOP, which is employed by several agencies in Southern California (Table 1-1). The second AWT process train consisted of a membrane bioreactor (MBR) followed by RO and AOP.

MBRs typically treat raw sewage or primary effluent. However, this pilot MBR was operated as a "tertiary MBR" that polished secondary effluent and produced a nitrified permeate as RO feed. Prior to this project, a tertiary MBR had been pilot-tested once, to improve nutrient removal and expand a conventional wastewater treatment plant in Hamilton, Ontario, Canada (Constantine, et al., 2010); however the application of a tertiary MBR as RO pretreatment was novel and had not been tested previously. Similar to the UF, this MBR provided permeate filtered through UF membranes; however, the MBR also provided biological nitrification of the effluent, which offered potential advantages over UF.

Table 1-1. Advanced Water Treatment/Reclamation Facilities in Southern California

Agency	Plant	Source Water	Year Started	Capacity (MGD)	MF/UF Membrane	MF/UF Flux (gfd)	RO Membranes	RO Flux (gfd)	AOP	Use
Carlsbad MWD	Carlsbad Water Recycling	Encina WPCF	2005	4.0	Siemens PP	35	Hydranautics ESPA 2	NA	None	NA
Exxon-Mobil	Exxon-Mobil WRF	EC Little WRP, tertiary	1999	3.2	Siemens PP	22	Hydranautics ESPA 2	10	None	Boiler feed
LADPW	Terminal Island	Terminal Island, tertiary	2002	4.5	Siemens Memcor PP	18	Hydranautics ESPA 2	10	None	Seawater barrier
WBMWD	CRWRF	EC Little WRP, tertiary	2000	5.0	Siemens PP	22	Hydranautics ESPA 2	12	None	BP boiler feed
OCWD	GWRS	OCSD Plant 1, secondary	2008	70	Siemens PP	20	Hydranautics ESPA 2	12	Trojan UV + peroxide	Groundwater recharge; seawater barrier
WBMWD	El Segundo, Phase I	Hyperion, secondary	1995	5.0	Siemens PP	18	Hydranautics ESPA 2	12	None	Seawater barrier
WBMWD	El Segundo, Phase II	Hyperion, secondary	1997	2.5	Siemens PP	18	Hydranautics ESPA 2	12	None	Seawater barrier
WBMWD	El Segundo, Phase III	Hyperion, secondary	2001	4.3	Siemens PP	18	Hydranautics ESPA 2	12	None	Chevron boiler feed
WBMWD	El Segundo, Phase IV	Hyperion, secondary	2006	3.5	Siemens PP	20	Hydranautics ESPA 2	12	Trojan UV + peroxide	Seawater barrier
WRD	Leo Vander Lans	Long Beach WRP, Tertiary	2005	3.0	Pall Microzoa PVDF	40	Hydranautics ESPA 2	10	Trojan UV	Ground-water recharge

GWRS: Groundwater Replenishment System; LADWP: Los Angeles Department of Public Works; OCSD: Orange County Sanitation District; OCWD: Orange County Water District; PP: Polypropylene; PVDF: Polyvinylidene Fluoride; WBMWD: West Basin Municipal Water District; WPCF: Water Pollution Control Facility; WRD: Water Replenishment District; WRF: Water Reclamation Facility; WRP: Water Reclamation Plant.

Biological activity in the MBR may reduce levels of organics and other compounds of concern, and provide a higher quality water for RO and AOP. This additional treatment (and the fact that the MBR membranes are designed to operate in a solution with relatively high solids and organics) may also reduce fouling, which has been an issue in some full-scale UF systems. In addition, nitrification is known to consume alkalinity and lower pH, both of which reduce acid requirements (and thus, chemical costs) for the downstream RO process. Finally, alkalinity is a known scavenger of the hydroxyl radicals that are active in AOPs; therefore, the reduction in alkalinity has the potential to also improve the performance of the downstream AOPs. These potential advantages and cost savings may more than offset the increased cost and complexity of using MBR for RO pretreatment, relative to using UF.

1.3 OBJECTIVES

The main objective of the pilot program was to evaluate the ability of the two AWT process trains to treat JWPCP secondary effluent and produce purified recycled water that met or exceeded the groundwater recharge water quality criteria specified in California Department of Public Health (CDPH) 2008 Draft Title 22 Groundwater Recharge Regulations (DGRR). Note that a newer draft was released in November 2011; however, the targets in this report are largely based on the 2008 DGRR requirements. An additional objective was to evaluate the operational performance of the AWT technologies that comprise the process trains.

The specific tasks of the study were the following:

1. Conduct a review of similar water recycling projects documenting the experiences of these projects (e.g., design criteria, operating challenges, reliability, etc.) including membrane operation and treatment of target contaminants (e.g., N-nitrosodimethylamine, NDMA, and 1,4-dioxane).
2. Characterize effluent and concentrate water quality from both AWT process trains; water quality parameters of interest include TOC, nitrogen compounds, disinfection byproducts (DBPs), pharmaceuticals and personal care products, pesticides, herbicides, and other volatile and semi-volatile compounds. Compare effluent water quality to criteria specified in 2008 CDPH DGRR and other applicable regulatory limits.
3. Evaluate UV oxidation, with and without hydrogen peroxide addition, for treatment of compounds that are not completely removed by RO membranes.
4. Evaluate operating conditions (specific flux, backwash rates, chemical cleaning requirements, and feed/pressure energy requirements) and performance (fouling, recovery rate, and rejection of target contaminants) of the AWT membrane processes.
5. Determine the effect of biological nitrification on system operations and product water quality.
6. Evaluate chemicals/additives (specifically chloramines, anti-scalants, and acids) necessary for membrane fouling control.

1.4 TEST LOCATION

The study was conducted at the Districts' JWPCP, which is located in Carson, CA. The JWPCP has a dry weather average flow design capacity of 400 million gallons per day (MGD) of secondary treatment and a peak design capacity of 540 MGD of secondary treatment. The JWPCP currently treats approximately 280 MGD of wastewater. The sources of wastewater are approximately 3.5 million residents, commercial businesses, and over 1,500 permitted industrial users. The treatment processes at JWPCP include screening, grit removal, primary sedimentation, high purity oxygen activated sludge, secondary clarification, anaerobic sludge digestion, and sludge dewatering. Treated effluent is disinfected prior to discharge through a tunnel and outfall system to the Pacific Ocean.

For this project, a test site was developed from a paved location on the eastern side of the JWPCP (Figure 1-1). The site was selected for its proximity to a 12-inch pressurized line carrying unchlorinated JWPCP secondary effluent to the solids processing area of the plant. The site was also selected because a drainage channel is present that allows project effluent to be discharged directly into a trunk sewer that flows into the JWPCP. From March to June, 2010, the Districts staff developed the test site by installing electrical power, and building or moving on-site various structures and containers to house equipment and instruments, data collection devices, chemicals, parts and tools. A picture of the developed project site is shown in Figure 1-2.

Figure 1-1. Pilot Plant Location at JWPCP

Figure 1-2. Pilot Plant Test Area

1.5 PROJECT DURATION AND PHASING

Operation of the pilot-scale system began in June 2010, and ended in June 2012. The two-year operational period was divided into three phases, which are summarized in Table 1-2. For Train 1, Phase 1 began after the UF and RO units had reached steady state, which was defined by stable operating parameters and water quality concentrations. Because more work was required to modify the MBR for operation, Phase 1 for Train 2 began later. Phase 1 ended when the RO membranes on each train were removed for autopsy. Phase 2 began after a deep clean of the RO membranes on both trains. Phase 2 ended for Train 1 when the RO unit was taken out of service to replace the membranes. Phase 2 ended for Train 2 when the MBR was shut down for reconfiguration. Phase 3 began after the MBR reconfiguration was complete, the RO membranes on both trains were replaced, and all units had reached steady state operation. Phase 3 ended for Train 1 when the UF unit was shut down due to operational difficulties. Phase 3 ended for Train 2 with the end of the project.

Table 1-2. Operational Phases

	Phase 1	Phase 2	Phase 3
Train 1: UF-RO			
Start Date	7/9/10	7/5/11	1/20/12
End Date	3/18/11	12/15/11	6/28/12
Train 2: MBR-RO			
Start Date	12/8/10	7/5/11	1/20/12
End Date	3/30/11	12/6/11	6/30/12

1.6 SUMMARY OF LITERATURE REVIEW

A literature review on indirect potable reuse (Appendix B) was prepared by MWD, to summarize key findings regarding the implementation of indirect potable reuse. The review provided an overview of regulatory and permit requirements for recycled water in California. It also provided case studies of indirect potable reuse projects in California, Western Australia, and Virginia. The three California-based case studies were full-scale operations: the Groundwater Replenishment System in Fountain Valley, the West Coast Barrier Project in El Segundo, and the Alamitos Barrier Recycled Water Project in Long Beach. For Western Australia, the two case studies were the full-scale Kwinana Water Reclamation Plant and a pilot plant at the Beenyup Wastewater Treatment Plant. The last case study was the Millard H. Robbins, Jr. Water Reclamation Plant in Centreville, Virginia, which discharged to surface waters feeding the Occoquan Reservoir.

The first five cases were all indirect potable reuse projects that treated secondary or tertiary wastewater effluents with a combination of MF, RO, or UV. The Groundwater Replenishment System and the West Coast Barrier Project also included hydrogen peroxide with the UV treatment, as an AOP. The Millard H. Robbins, Jr. Water Reclamation Plant was designed for nutrient removal to improve the water quality of the Occoquan Reservoir; this plant treated secondary effluent with lime clarification, media filtration, carbon contactors, and chlorine disinfection.

Each case study covered

- key permit requirements,
- treatment processes,
- water quality of the source and final product water,
- compliance with all Federal and State maximum contaminant levels (MCLs), notification levels, and water treatment and disinfection by-products rules,
- removal of non-regulated compounds, such as pharmaceuticals and personal care products (PPCPs) and endocrine disrupting compounds (EDCs),
- any special studies conducted on health effects or treatment process selection, design, or operation.

All six plants successfully met their permit requirements; details are provided in Appendix B.

1.7 REPORT ORGANIZATION

The following two chapters provide a description of the pilot system (Chapter 2), and the sampling programs for the project and experimental conditions for the AOP experiments (Chapter 3). The operational performance (e.g., fluxes, fouling, maintenance) of the UF, MBR, and RO units is discussed in Chapter 4. Water quality results are divided into three chapters. General water quality parameters are discussed in Chapter 5. Nitrosamines and 1,4-dioxane are discussed separately in Chapter 6, because these compounds typically drive the AOP requirements for AWT. Chapter 7 provides the results for a set of samples referred to as “Title 22+” samples, which were taken on six days and were analyzed for more than 300 parameters. These samples provided data for a much broader range of compounds than the routine or AOP samples. Finally, the results and conclusions for the project are summarize in Chapter 8.

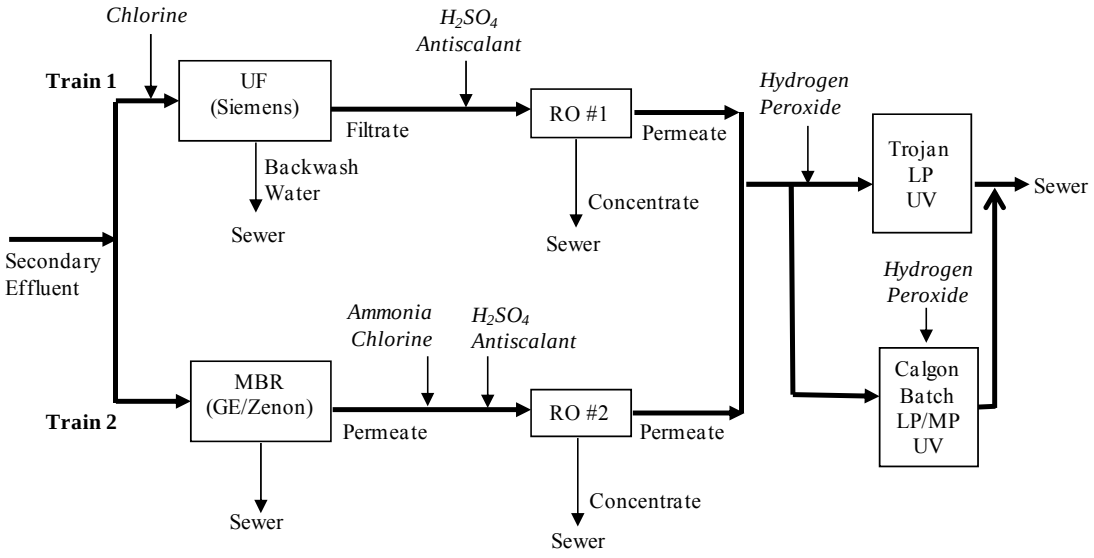
DESCRIPTION OF PILOT SYSTEM

2.1 OVERVIEW OF PILOT SYSTEM

The pilot-scale system consisted of two parallel treatment trains that treated JWPCP secondary effluent. The secondary effluent was first sent through three 2-inch Eaton-Hayward strainers, operated in parallel. The strainers contained stainless steel baskets with 30 mesh (595 micron) liners. Prior to Phase 3 of the project, a second set of 40 mesh (400 micron) strainers was installed upstream of the UF/RO process train, to reduce the suspended solids loading.

A simplified schematic diagram of the two treatment trains is shown in Figure 2-1. Train 1 is referred to as the "UF train" throughout this report, and consisted of a Siemens system equipped with ultrafiltration (UF) membranes, followed by a reverse osmosis (RO) pilot system. This RO system is referred to as the "UF-RO" throughout the report. Train 2 is referred to as the "MBR train" throughout this report, and consisted of a modified GE/Zenon membrane bioreactor (MBR) followed by a second RO pilot system, which is referred to as the "MBR-RO" throughout this report. RO permeate generated from each of the two trains could be further treated by one of two UV AOP systems. The following sections provide more detail on each of the unit processes: the UF system (Section 2.2), the MBR system (Section 2.3), the RO systems (Section 2.4), and the two AOP systems (Section 2.5).

Figure 2-1. Schematic Diagram of Treatment Process Trains



2.2 SIEMENS MEMBRANE FILTRATION (UF) UNIT

For this project, MWD provided a Siemens 12M10C continuous filtration unit (Figure 2-2), which could treat up to 60 gallons per minute (gpm) of flow. This pressurized membrane filtration unit utilized hollow-fiber membranes to provide removal of suspended solids, particles, colloids, and bacteria. The unit was originally outfitted with polypropylene (PP) MF membranes with a nominal pore size of 0.2 micron. These membranes are in common use at several local water reuse projects, including facilities at Orange County Water District (OCWD), West Basin Municipal Water District (WBMWD) and the Terminal Island Water Reclamation Plant

(TIWRP). However, for this project, the unit was upgraded to L10V polyvinylidene fluoride (PVDF) UF membranes, which offered the advantage of a more durable membrane material, with greater chlorine resistance, and the ability to use strong solutions of sodium hypochlorite as a routine cleaning chemical. The characteristics of the PVDF membranes are given in Table 2-1.

Figure 2-2. Siemens 12M10C Continuous Membrane Filtration Unit

Table 2-1. Siemens PVDF UF Membranes

Parameter	Units	Value
Sub-module Type	-	L10V
Membrane Material	-	PVDF
Membrane Type	-	Hollow fiber
Filtration Direction	-	Outside to inside
Pore Size (nominal)	micron	0.04
No. of Fibers per Element	-	9,600
Ave. Active Membrane Area (OD)	ft^2	252
Operating Temperature Range	^oC	>0 - 40
Maximum Temperature	^oC	45
Operating pH Range	-	2 - 10
Max. Trans-Membrane Pressure (TMP)	psi	22
Max. Exposure to Chlorine/Chloramine	ppm	1,000

A programmable logic controller (PLC) was used for the UF and provided automatic control of the pneumatic system, which controlled the air supply, regulated air pressure for the backwash and re-wetting cycles, and provided proper pressure for operating the membrane integrity tests. The PLC ran an air pulse backwash regime that allowed continuous operation of the unit, and also monitored the operating status of the unit. Operating parameters from the system were monitored, displayed continuously, and stored in a data logging system. Recorded data included

feed and filtrate pressure, transmembrane pressure (TMP), flow resistance, feed flow, feed pump speed, feed temperature and pH, filtrate flow, flow totals, filtrate runtime, pressure decay from integrity tests, backwash intervals, pneumatic system/air compressor status, feed valve positions, feed tank fill and drawdown times, and other pertinent observations. In addition, total chlorine residual concentrations were measured and the data recorded with hypochlorite delivery rate. The unit was checked and key data manually recorded twice a day during weekdays and at least once each weekend.

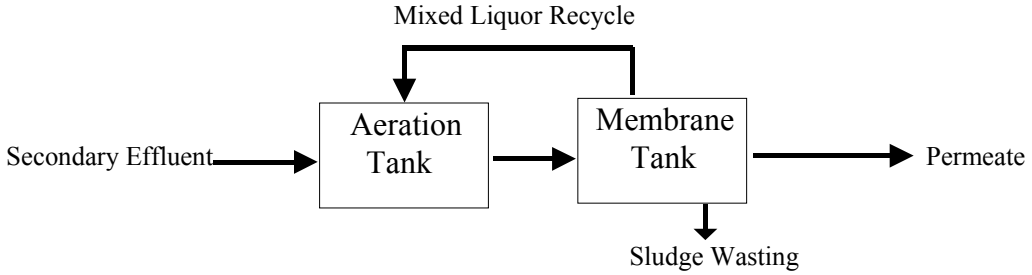
The PLC was located on the main skid, along with the influent tank, feed pump, and filtration modules. In addition to the main skid, the pilot system included a 500-gallon backwash tank and an air compressor/receiver. Clean-in-place (CIP) procedures used an external CIP skid with a heated 100-gallon tank that was built for RO system cleanings. UF filtrate was stored in an 800-gallon break tank, which stabilized chlorine residual levels in the influent to the RO system; otherwise, residuals would have fluctuated during production interruptions, e.g., when the membranes were backwashed.

2.3 GE/ZENON MBR UNIT

2.3.1 Overview

A schematic of GE/Zenon MBR pilot system used in this project is shown in Figure 2-3. Secondary effluent from the JWPCP was pumped into an aeration tank where it was mixed with the recycled mixed liquor from the membrane tank and aerated. The contents of the aeration tank were pumped to the membrane tank, and a self-priming centrifugal pump drew permeate through the membranes. A small portion of the mixed liquor in the membrane tank was continuously wasted, to control the solids retention time (SRT) of the system.

Figure 2-3. Schematic Diagram of GE/Zenon MBR Pilot Plant



Pictures of the MBR system are shown in Figure 2-4. Figure 2-4a shows the system as it was configured in Phases 1 and 2. The cylindrical aeration tank (painted beige) can be seen on the left side of the picture. The rectangular stainless steel membrane tank can be seen in the middle of the picture, along with the overflow channel connecting the membrane and aeration tanks; mixed liquor was recycled back to the aeration tank by gravity overflow through this channel. Two interconnected cylindrical tanks for permeate storage can be seen on the right side of Figure 2-4a. Figure 2-4b shows the membrane tank and overflow channel used in Phase 3, after modifications that are described in Section 2.3.2. The following sections describe the major components of the MBR system: the aeration tank (Section 2.3.1), the membrane tank (Section 2.3.2), and the permeate tanks (Section 2.3.3).

Figure 2-4. GE/Zenon Membrane Biological Reactor.
(a) Phases 1 and 2, (b) Modified Membrane Tank in Phase 3.

(a) (b)

2.3.2 Aeration Tank

The MBR system for this project was previously used to treat primary effluent, similar to most MBR systems; however, for this project, the MBR was used to nitrify secondary effluent. The 6,700-gallon (gal) aeration tank that was originally supplied with the system was far larger than needed for nitrification. Therefore, the original aeration tank was replaced with a 800-gal polyethylene cylindrical tank before Phase 1. The decrease in size reduced the hydraulic residence time (HRT) and energy consumption. The aeration tank was equipped with a coarse bubble diffuser (maximum air flow rate of 5 standard cubic feet per minute, or scfm) for mixing and a fine bubble diffuser (maximum air flow rate of 28 scfm) for aeration. The tank was painted to reduce exposure of the mixed liquor to sunlight, which would promote algae growth.

2.3.3 Membrane Tank

The membrane tank supplied with the system had a working volume of 1,588 gal, and was used for Phases 1 and 2. The membrane tank was modified for Phase 3. To achieve the desired flux (see Section 4.2.1 for details), new membranes were required, and these membranes were taller than the previous modules. Consequently, the membrane tank was made deeper by the addition of an eighteen-inch collar extension, and the overflow flume was modified to accommodate a higher overflow elevation. The modifications for Phase 3 increased the working volume of the tank to 2,075 gallons.

Details on the membranes and modules within the membrane tank are provided in Tables 2-2 and 2-3. The membrane tank originally contained two cassettes, which were approximately eight years old at the time the project began; they were previously used to treat primary effluent at another plant operated by the Districts. Each cassette contained ten ZeeWeed® 500c modules; the two cassettes (also referred to as "packs") were designated as the "north" and "south" packs. Phase 1 used both cassettes, but Phase 2 used only one of the cassettes, to increase the operating flux; the cassette in service was alternated between the north and south pack. Phase 3 used a single cassette containing eight new ZeeWeed® 500d modules; the 500d membranes are less prone to fouling and offer more capacity than the 500c membranes. This cassette replaced one of the two packs previously in the membrane tank; the other pack was replaced by an auxiliary air diffuser, which provided both aeration and mixing.

Table 2-2. GE/Zenon ZeeWeed® Membranes

Parameter	Unit	Phases 1 and 2	Phase 3
Membrane Name	-	ZeeWeed® 500c	ZeeWeed® 500d
Membrane Material	-	PVDF	PVDF
Membrane Type	-	Hollow fiber	Hollow fiber
Filtration Direction	-	Outside to inside	Outside to inside
Pore Size (nominal)	micron	0.04	0.04
Operating Temperature Range	°C	0.1 - 40	0.1 - 40
Maximum Temperature	°C	54*	40
Operating pH Range	-	5.0 – 9.5	5.0 – 9.5
Max. TMP	psi	10*	8
Max. Chlorine Concentration	ppm	2,000*	1,000

*Based on conversations with the manufacturer.

Table 2-3. MBR Membrane Configuration

Parameter	Units	Phase 1	Phase 2	Phase 3
Membrane Tank Volume	gal	1,588	1,588	2,075
Modules				
Module Height	ft	6.6	6.6	7.2
Module Width	ft	2.8	2.8	2.8
Module Length	ft	0.7	0.7	0.7
Cassettes				
Number of Cassettes in Service	-	2	1	1
Number of Modules/Cassette	-	10	10	8
Total Number of Modules	-	20	10	8
Total Active Membrane Area	ft^2	4,730	2,365	2,720

2.3.4 Permeate Tanks

The permeate generated from the membrane tank was stored in two 800-gal permeate tanks (Figure 2-4), which were interconnected so that water could flow freely between the two tanks. The tanks were painted to reduce exposure of the permeate to sunlight, which would promote algae growth. MBR permeate from the tanks was used to feed the RO pilot system and was also used during membrane backpulse procedures and maintenance cleaning operations (see Section 4.2.1.3 for details on backpulses and cleanings).

2.4 REVERSE OSMOSIS (RO) PILOT SYSTEM

The RO system was the second step of treatment in both the UF and MBR trains (see Figure 2-1); the two RO systems were identical. Each consisted of chemical metering pumps for acid and anti-scalant addition, a 5-µm cartridge filter, a high-pressure pump, and a two-stage pressure vessel array. The pressure vessels were configured in a 2:2:1:1 array, containing a total of 21 spiral wound membrane elements (4-inch diameter, 40-inch length). The configuration is shown in Figure 2-5.

Stage 1 vessels contained 14 elements (two parallel series of seven elements) while Stage 2 vessels contained seven elements in series. Hydranautics ESPA2 membrane elements were used in all three operational phases; a new set of membranes was installed on each RO unit between Phases 2 and 3. A photograph of the RO unit is shown in Figure 2-6, and design specifications of the RO units are listed in Table 2-4.

Figure 2-5. RO Pilot System Configuration

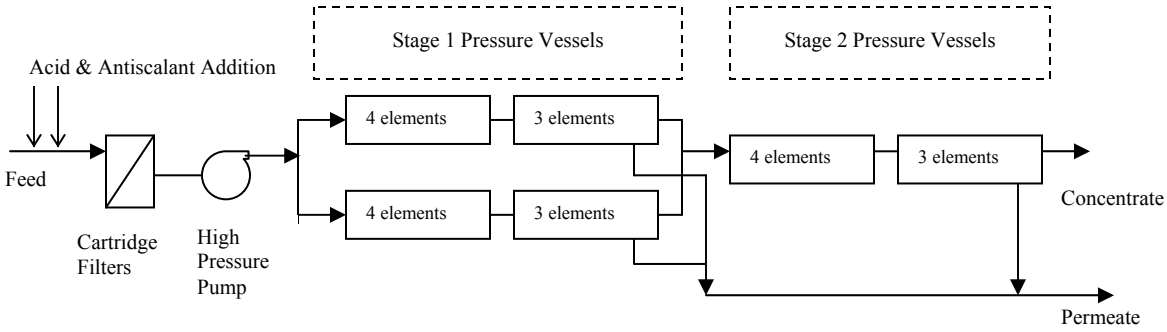


Figure 2-6. RO Pilot Unit

Table 2-4. RO Pilot System

Parameter	Description
Membranes and Housing	
RO membranes	4-inch diameter – Hydranautics ESPA2
Filter Housing	Bekaert PROTECT™ Model PRO-4-300-SP
Maximum Pressure	300 psig
Prefilter	5 micron cartridge
Power	
RO Skid	480V/3 phases/60Hz
Pump	7.5 hp
Instrumentation and Controls	
RO Control System	R&D Specialties Series 250 PLC controller with communication package, status lamps and pump motor stater
Instrumentation	Influent flow, permeate and concentrate flow meters, conductivity sensors, pH meter and pressure sensors
Liquid Filled Pressure Gages	Panel mount for pump effluent, membrane feed and final concentrate
Antiscalant System	
Chemical Addition Tanks	Two 25-gallon tanks
Chemical Addition Pumps	Two Pulsafeeder chemical pumps

Operation was controlled by a pre-programmed control system specifically designed for the RO unit. The RO system was equipped with a high-pressure pump and flow control valves to manually control permeate and concentrate flow rates, and valves to allow sampling of the RO feed (after chemical addition), permeate, and concentrate.

The RO unit was also equipped with instrumentation to electronically monitor and record key process data in loggers: flow, pressure, conductivity, pH, and temperature data at key locations throughout the RO process. In addition to the automatically logged data, data were manually recorded in the event that the internally stored data became corrupt or lost.

2.5 ADVANCED OXIDATION PROCESS (AOP)

For the advanced oxidation process (AOP) in this study, hydrogen peroxide was added to RO permeate and followed by UV oxidation. Two different UV systems were used in this project: a set of three flow-through Trojan UV Max G reactors (Trojan Technologies, London, Ontario) operated in parallel, and a batch Calgon Rayox reactor (Calgon Carbon Corporation, Pittsburgh, PA). Section 2.5.1 provides more details on the Trojan reactors, and Section 2.5.2 provides more details on the Calgon reactor.

It should be noted that UV doses are highly specific for each reactor design (e.g., reactor configuration and hydraulics); a dose determined for this reactor system cannot be applied to another system. Results from this system are intended to demonstrate the level of treatment that can be achieved with this technology, and cannot be used to design a full-scale system.

2.5.1 Trojan UV Max G Reactors

Most experiments used the Trojan system. A schematic diagram of the system is shown in Figure 2-7 and a photo is shown in Figure 2-8. Each of the three UV reactors was equipped with a single low-pressure high-output (LPHO) 100-W amalgam lamp that emitted monochromatic radiation at a wavelength of 254 nm. The AOP system could be fed with either UF/RO permeate or MBR/RO permeate. Adjustable-flow peristaltic pumps were used to spike this influent stream with NDMA and/or 1,4-dioxane, and were also used to add hydrogen peroxide. Static mixers were used to quickly mix in these compounds with the RO permeate. The water was then directed through the UV reactors; UV dose was determined by setting the flow rate through the reactor(s).

Figure 2-7. Schematic Diagram of Trojan AOP System

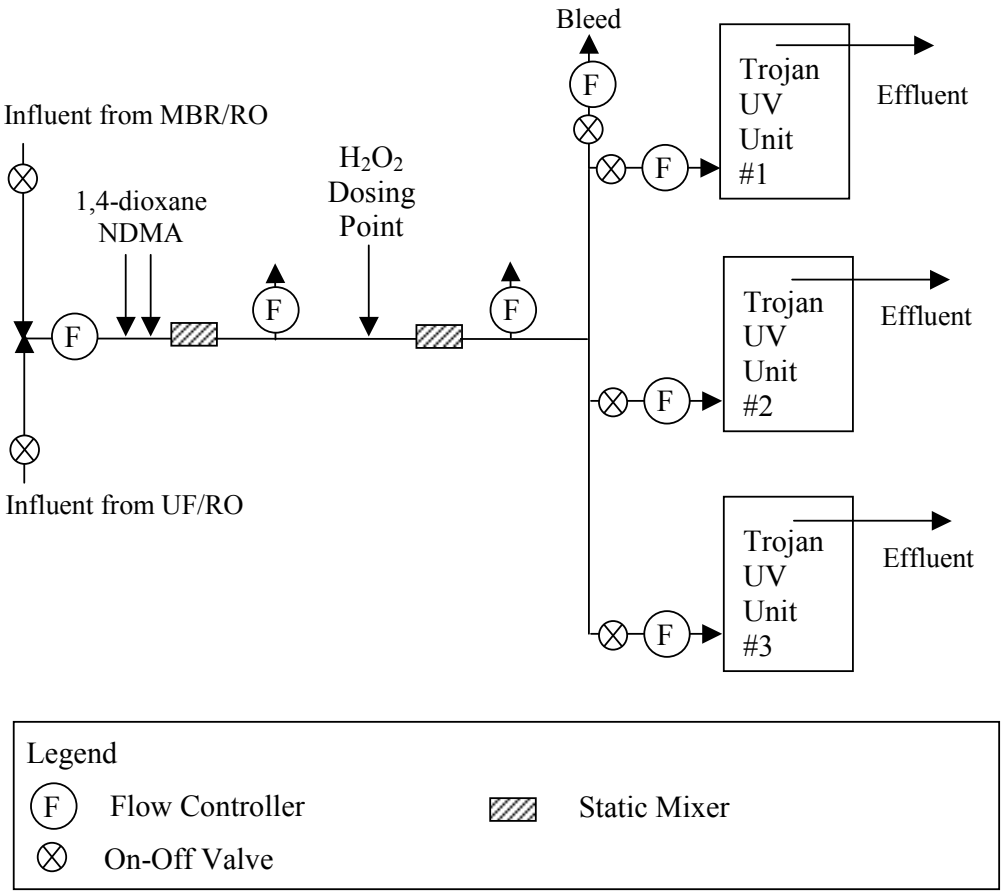
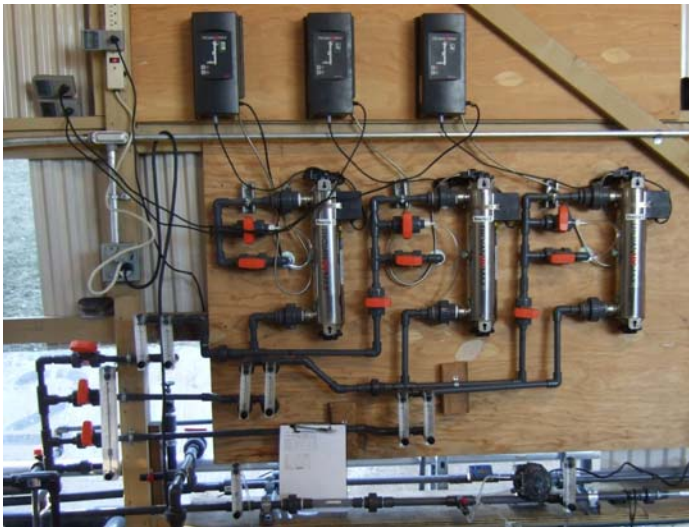


Figure 2-8. Trojan AOP System



2.5.2 Calgon Rayox UV Reactor

Figure 2-9 shows the Calgon Rayox unit, with the control panel on the left and the 11-gal reactor on the right. This system became available during Phase 3, and was used only for Title 22+ testing in this phase (see Section 3.4). The reactor could be configured with either a LPHO or a medium pressure (MP) lamp. The LPHO lamp was a 40-W lamp that emitted monochromatic radiation at a wavelength of 254 nm. The MP lamp was a 1-kW lamp that emitted polychromatic radiation.

Figure 2-9. Calgon AOP System

As with the Trojan system, the Calgon reactor could be filled with either UF/RO permeate or MBR/RO permeate. Before each test, the reactor was filled and emptied twice with the test water to flush out the system. NDMA, 1,4-dioxane, and/or hydrogen peroxide could be spiked into the reactor through a port at the top. Water in the reactor was mixed by a propeller, and a pneumatically controlled shutter was used to set the UV dose, i.e., the duration of exposure to UV radiation. The shutter could be opened and closed manually, or automatically on a timer. Heat from the medium pressure lamp could be removed and water temperature could be controlled by pumping water from an ice bath through cooling coils in the reactor. Samples were taken from either a sampling port on the side of the reactor, or from the bottom drain; both sites were flushed before samples were taken.

3. WATER QUALITY SAMPLING PROGRAM AND TARGETS

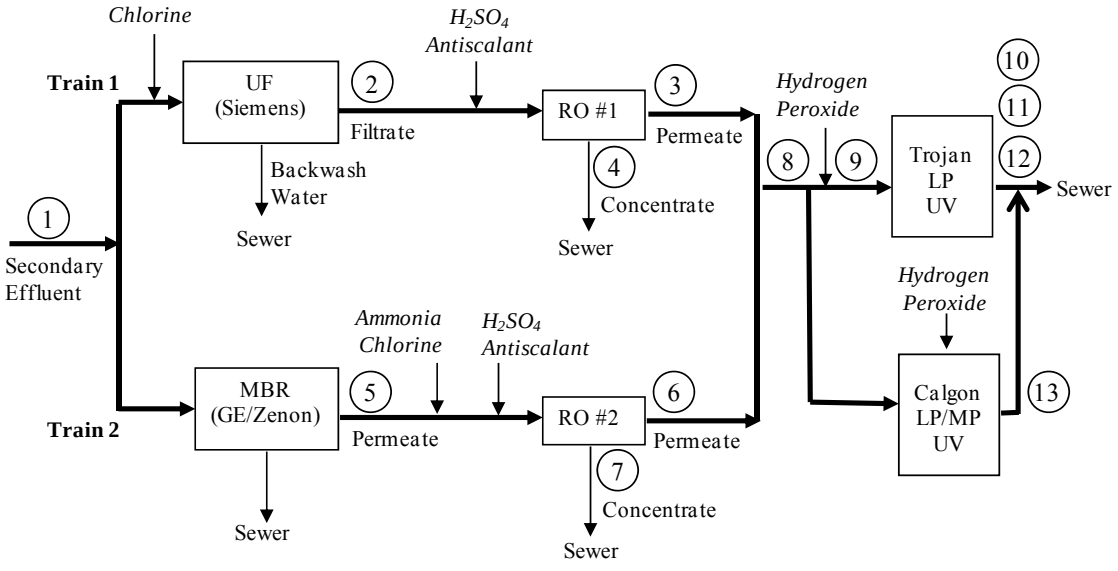
This chapter discusses the water quality sampling program for this project, and the water quality targets. Section 3.1 describes the sampling locations. The other sections in this chapter describe different sampling programs at these locations. Section 3.2 covers routine samples that were taken for 26 parameters on a daily, weekly, or bi-weekly basis. Section 3.3 covers samples taken for 1,4-dioxane and nitrosamine analysis, and samples taken during the AOP experiments. Section 3.4 covers an extensive list of almost 300 parameters (referred to as the "Title 22+" parameters) that were analyzed during six special sampling events. Section 3.5 covers water quality targets for the analyzed compounds. The analytical methods for all parameters are provided in Appendix C.

3.1 SAMPLING LOCATIONS

Figure 3-1 shows a schematic of the pilot-scale system with the sampling locations labeled. Samples were taken from the secondary effluent (Location 1), and at three locations on the UF train: UF filtrate (Location 2), UF-RO permeate (Location 3), and UF-RO concentrate (Location 4). Samples were also taken at three locations on the MBR train: MBR permeate (Location 5), MBR-RO permeate (Location 6), and MBR-RO concentrate (Location 7).

Locations 8-13 were on the UV reactors. Locations 8-12 were for the three Trojan UV reactors, which are described in Section 2.5.1. Location 8 provided the influent samples for the UV reactors, and was downstream of the additions points for NDMA and 1,4-dioxane. Location 9 was located downstream of the hydrogen peroxide addition point, and provided samples treated by hydrogen peroxide alone. Locations 10-12 were located downstream of each of the three UV reactors, and provided samples treated by UV alone or the combination of UV and hydrogen peroxide. Location 13 was on the Calgon Rayox batch reactor, which is described in Section 2.5.2. Samples from Location 13 were taken at different time points to provide concentration data for the "influent" samples and "effluent" samples (after varying doses of hydrogen peroxide and/or UV radiation).

Figure 3-1. Schematic Diagram of Sampling Locations



3.2 ROUTINE ANALYSIS

The locations and frequency of the routine samples are listed in Table 3-1. Most analytes were sampled bi-weekly in the secondary effluent, UF filtrate, UF-RO permeate, MBR permeate, and MBR-RO permeate (Locations 1, 2, 3, 5, and 6). To monitor the unit processes on a finer time scale, several parameters were sampled daily or weekly: turbidity, pH, the nitrogen species (ammonia, total Kjeldahl nitrogen, nitrate, nitrite), total organic carbon (TOC), total and soluble chemical oxygen demand (COD), and total suspended solids (TSS). The concentrate streams from the UF-RO and MBR-RO systems were sampled and analyzed quarterly. Some analytes were eliminated at selected locations. For example, because particles were expected to be largely removed by the UF or MBR membranes, turbidity and TSS were not after these units. Soluble COD was expected to be identical to total COD in the MBR permeate due to the removal of TSS, consequently it was not measured.

Table 3-1. Water Quality Parameters: Sampling Frequency

	Sampling Locations						
		UF Train			MBR Train		
Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**
pH	D	D	W	Q	D	W	Q
Turbidity	D	D	--	--	D	--	--
Alkalinity	BW	BW	BW	Q	BW	BW	Q
Calcium	BW	BW	BW	Q	BW	BW	Q
Magnesium	BW	BW	BW	Q	BW	BW	Q
Sodium	BW	BW	BW	Q	BW	BW	Q
Potassium	BW	BW	BW	Q	BW	BW	Q
Sulfate	BW	BW	BW	Q	BW	BW	Q
Chloride	BW	BW	BW	Q	BW	BW	Q
TDS	BW	BW	BW	Q	BW	BW	Q
TSS	D	--	--	--	--	--	--
COD (Total)	D	--	--	Q	D	--	Q
Soluble COD (sCOD)	D	--	--	--	--	--	--
TOC	W	W	W	Q	W	W	Q
Ammonia	D	W	W	Q	D	W	Q
Nitrate	W	W	W	Q	D	W	Q
Nitrite	W	W	W	Q	D	W	Q
TKN	D	W	W	Q	W	W	Q
Phosphate	BW	BW	BW	Q	BW	BW	Q
Boron	BW	BW	BW	Q	BW	BW	Q
Silica	BW	BW	BW	Q	BW	BW	Q
Barium	BW	BW	BW	Q	BW	BW	Q
Strontium	BW	BW	BW	Q	BW	BW	Q
Fluoride	BW	BW	BW	Q	BW	BW	Q
Iron	BW	BW	BW	Q	BW	BW	Q
Aluminum	BW	BW	BW	Q	BW	BW	Q

Frequency abbreviations: D – Daily, W- Weekly, BW – Bi-weekly, Q - Quarterly

3.3 NITROSAMINES, 1,4-DIOXANE, AND AOP TESTING

This section discusses sampling for nitrosamines and 1,4-dioxane, and the AOP experiments. Seven nitrosamine species were analyzed: N-nitrosodimethylamine (NDMA), N-nitrosodiethylamine (NDEA), N-nitrosodipropylamine (NDPA), N-nitrosodibuylamine (NDBA), N-nitrosomethylethlyamine (NMEA), N-nitrosopiperidine (NDPA), and N-nitrosopyrrolidine (NPYR). The nitrosamines and 1,4-dioxane were analyzed in bi-weekly samples taken from the secondary effluent, MBR permeate, and both RO permeates.

Because these compounds typically determine the AOP requirements for AWT systems, much of the sampling was focused on the AOP experiments. The AOP system was not operated continuously; instead, discrete experiments were conducted to determine the effects of UV electrical energy doses (EEDs) and hydrogen peroxide doses on the removal of nitrosamines and 1,4-dioxane. Literature indicates that UV radiation removes NDMA, hydrogen peroxide has insignificant effect on NDMA, and both UV and hydrogen peroxide are necessary to remove 1,4-dioxane.

Based on this information, experiments were split into three basic tasks: to determine the approximate UV dose required for adequate NDMA removal, to determine the approximate hydrogen peroxide dose required for adequate removal of 1,4-dioxane, and to investigate the effects of combining UV and peroxide. These three tasks were run on both the UF and MBR trains (six tasks total). Most tasks were run twice, except for Task 6 (which had some analytical issues and was run three times), for a total of 13 AOP experiments. Experiments were conducted during Phase 1, and the results of all 13 experiments were combined for the analysis (Chapter 6).

Table 3-2 summarizes the AOP tasks, with the UV electrical energy doses (EEDs) and peroxide doses. EEDs were calculated using the following equation:

$$\text{EED, kWh/kgal} = \left(\frac{\text{UV Power, kW}}{\text{Flow Rate (gpm)}}\right)\left(\frac{1{,}000\ \text{gal}}{\text{kgal}}\right)\left(\frac{1\ \text{hr}}{60\ \text{min}}\right)$$

It should be noted that the EED values used in this study are specific to these UV reactors, and their reactor geometry and flow hydraulics. Therefore, these EED values cannot be scaled up or applied to other UV systems.

Table 3-2. Summary of AOP Experiments.

Experiment Number		Goal:	Tested UV EEDs	Tested H_2O_2 Doses
UF/RO	MBR/RO	Determination of	kWh/kgal	mg/L
1	2	Approximate UV dose	0.5-7.0	0
3	4	Approximate H_2O_2 dose	~4	0-5
5	6	Effects of Combined UV/H_2O_2	0-6	0-6

Although the AOP experiments focused on the nitrosamines and 1,4-dioxane, other water quality parameters were analyzed in selected samples: ammonia, total Kjeldahl nitrogen (TKN), nitrite, nitrate, total organic carbon (TOC), chemical oxygen demand (COD), UV transmittance (UVT), pH, and temperature. The effects of AOP on these parameters are discussed in Chapter 5.

3.4 TITLE 22+ SAMPLING

For the Title 22+ sampling events, 299 parameters were analyzed. There are EPA or CDPH drinking water standards for most of these parameters, or monitoring was required by the CDPH DGRR (e.g., for Priority Toxic Pollutants), although commonly studied trace organic constituents such as pharmaceuticals were also measured. The parameters included all of the compounds listed in Table 3-1, the seven nitrosamine species, 1,4-dioxane, radioactive analytes, UV transmittance, microbiological parameters, volatile and semi-volatile organic compounds, pesticides, herbicides, disinfection byproducts, hormones, and pharmaceutical and personal care products. Appendix C provides a full list of the compounds, the analytical methods used to quantify them, and their reporting limits. Samples were collected on two days each from the UF train during Phase 1, the MBR train during Phase 1, and the MBR train during Phase 3.

The average UF flux was approximately 22 gfd throughout the study (see Section 4.1.1 for details). During Phase 1, samples were collected from the secondary effluent, UF filtrate, UF-RO permeate, and the AOP effluent on February 16, 2011. Samples were also collected at the first three locations (all except the AOP effluent) on February 23, 2011. AOP testing used the Trojan UV Max G reactor (described in Section 2.5.1), with a reactor-specific EED of 4 kWh/kgal, and a hydrogen peroxide dose of 4 mg/L.

The average MBR flux during Phase 1 was 10 gfd, approximately half that of the UF. Samples were collected from the secondary effluent, MBR permeate, MBR-RO permeate, and AOP effluent on March 2, 2011. Samples were also collected at the first three locations (all except the AOP effluent) on March 9, 2011. AOP testing used the Trojan UV Max G reactor, with a reactor-specific EED of 4 kWh/kgal, and a hydrogen peroxide dose of 4 mg/L.

The average MBR flux during Phase 3 was 20 gfd, similar to that of the UF. Samples were collected on May 15 and 22, 2012, from the secondary effluent, MBR permeate, MBR-RO permeate, and AOP effluent. AOP testing used the Calgon Rayox batch reactor (described in Section 2.5.2), and both low pressure (LP) and medium pressure (MP) lamps were tested. The reactor-specific EED was 0.9 kWh/kgal for the LP lamps and 1.5 kWh/kgal for the MP lamps. The hydrogen peroxide dose was 4 mg/L for all tests with the Calgon reactor. Note that the laboratory changed the hormone analysis method between Phases 1 and 3, so the hormones measured on these sampling dates were slightly different from the other dates: progesterone was not analyzed, but estriol, equilin, testosterone and androstenedione were analyzed.

3.5 WATER QUALITY TARGETS

Targets for water quality were based on requirements for groundwater recharge, and were set to the lowest of the following values for each parameter:

- EPA primary maximium contaminant levels (MCLs) and secondary MCLs for drinking water,
- CDPH primary and secondary MCLs, and notification levels (NLs) for drinking water,
- CDPH DGRR levels for total nitrogen, TOC, and turbidity,
- local basin plan objectives for Western Sub-basin of the Main San Gabriel Basin,
- SWRCB monitoring trigger levels for chemicals of emerging concern (note that these levels are guidelines, not regulatory requirements).

In addition to these limits, removal requirements for N-nitrosodimethylamine (NDMA) and 1,4-dioxane from the 2008 CDPH DGRR were applied to the AOP portion of the study; the 2011 DGRR (released partway through this project) eliminated the NDMA requirement, but it was kept for this project. Tables 3-3 and 3-4 list the target concentrations for analytes detected in this study. A full list of the compounds analyzed, the various limits (e.g., MCLs), and the target concentrations can be found in Appendix C.

Table 3-3. Target Effluent Concentrations for General Physical and Mineral Parameters, Trace Metals, and Radiological Analytes

Category	Constituent	Target Conc.	Units
General Physical and Mineral Parameters	Chloride	100	mg/L
	Color	15	ACU
	Conductivity	1,600	umho/cm
	Fluoride	2	mg/L
	Foaming Agents (MBAS)	1	mg/L
	Nitrate	10	mg N/L
	Nitrite	1	mg N/L
	Odor	3	TON
	pH	6.5-8.5	-
	Sulfate	100	mg/L
	TDS	450	mg/L
	Total Nitrate + Nitrite	10	mg N/L
	Total Nitrogen	10	mg N/L
	Total Organic Carbon	0.5	mg/L
	Turbidity	2	NTU
Trace Metals	Aluminum	50	µg/L
	Antimony	6	µg/L
	Arsenic	10	µg/L
	Barium	1,000	µg/L
	Boron	0.5	mg/L
	Chromium (Total)	50	µg/L
	Copper	1300	µg/L
	Iron	0.3	mg/L
	Lead	15	µg/L
	Manganese	50	µg/L
	Nickel	100	µg/L
	Selenium	50	µg/L
Radiological	Gross Beta	50	pCi/L
	Uranium	20	pCi/L

Table 3-4. Target Effluent Concentrations for Other Parameters

Category	Constituent	Target Conc.	Units
1,4-Dioxane and Nitrosamines	1,4-Dioxane[1]	1	µg/L
	N-Nitrosodimethylamine (NDMA)[2]	10	ng/L
	N-Nitrosodiethylamine (NDEA)	10	ng/L
	N-Nitrosodi-n-propylamine (NDPA)	10	ng/L
	N-Nitrosopyrrolidine (NPYR)	20	ng/L
Hormones and EDCs	17β -estradiol	1	ng/L
	Bisphenol A	350,000	ng/L
	Nonylphenol	500,000	ng/L
	Octylphenol	50,000	ng/L
PPCPs and Wastewater Indicators	Acetaminophen	350,000	ng/L
	Azithromycin	3,900	ng/L
	Carbamazepine	1,000	ng/L
	Gemfibrozil	45,000	ng/L
	Ibuprofen	34,000	ng/L
	Meprobamate	260,000	ng/L
	Sulfamethoxazole	35,000	ng/L
	Triclosan	350	ng/L
	DEET	2,500	ng/L
	Caffeine	350	ng/L
	Iopromide	750,000	ng/L
	TCEP	2,500	ng/L
VOCs[3]	Dichloromethane	5	µg/L
	MTBE	5	µg/L
	Total THMs	80	µg/L
SVOCs[3]	Di (2-Ethylhexyl) Phthalate	4	µg/L
Pesticides	3-hydroxycarbofuran	0.42	µg/L
Other	Formaldehyde	100	µg/L
	Tertiary Butyl Alcohol	12	µg/L
	Carbon disulfide	160	µg/L
	Chlorate	800	µg/L

[1] 1,4-dioxane had an additional treatment requirement of 0.5-log removal in both the 2008 and 2011 DGRRs.

[2] NDMA had an additional treatment requirement of 1.2-log removal in the 2008 DGRR; this requirement was removed in the 2011 draft, but was kept as a target for this project.

[3] VOCs refer to volatile organic compounds, and SVOCs refer to semi-volatile organic compounds.

4. SYSTEM OPERATION

This chapter discusses the operation of the two advanced treatment process trains, including data collected and maintenance performed. The UF treatment train is presented in Section 4.1, and includes the UF unit (Section 4.1.1) and the UF-RO system (Section 4.1.2). The MBR treatment train is presented in Section 4.2, and includes the MBR unit (Section 4.2.1), and the MBR-RO system (Section 4.2.2).

4.1 UF TREATMENT TRAIN

4.1.1 UF Operation

The components of the membrane filtration system were received from MWD in mid-April 2010. New UF membranes were purchased and installed in early June 2010. A strong sodium hypochlorite solution (1,000 ppm) was circulated through the unit prior to the installation of new UF membrane elements to ensure that all connecting headers, piping and vessels were free of algae.

The UF unit was operated from June 25, 2010 to June 28, 2012, and treated a total flow of more than 40 million gallons; note that these dates (and the total flow value) reflect the total operational time, including time before the UF and RO systems came to steady state, and the time between phases. The unit was in productive operation (producing filtrate) for 13,700 hours over 726 days of testing. For the duration of the study, the UF was able to successfully produce more filtrate than was required for RO operations, despite some operational difficulties (described in Sections 4.1.1.2 and 4.1.1.3).

Operation of the UF was occasionally interrupted by power or flow outages, membrane cleanings, and maintenance. Some of the downtime was unplanned, caused by failures of the project feed piping at the manifold upstream and downstream of the basket strainers. The failures typically occurred in three-inch PVC fittings. To correct the problem, several water hammer arrestors and a pressure regulator were installed to alleviate stress from valve cycling, and PVC fittings and piping in the strainer manifold were replaced with steel components.

4.1.1.1 UF System Operating Parameters

The recommended operating parameters for the UF unit are summarized in Table 4-1, along with the actual range of operating values for the entire test period; a description of the cleaning procedures is given in Section 4.1.1.3. The UF unit was operated at a constant flux of approximately 22 gfd, which required a feed flow rate of 46 gpm. The flux and flow rate were maintained throughout most of the study.

Throughout the study, the total chlorine residual of the UF filtrate was maintained at an average of 3.4 mg Cl_2/L (within the target range of 3.0 - 4.0 mg Cl_2/L); approximately 6 - 10 mg Cl_2/L (an average of 8.4 mg/L) of sodium hypochlorite (NaOCl) was added to the secondary effluent to achieve the target residual.

Table 4-1. UF System: Flows, Fluxes, and Maintenance

Parameter	Units	Recommended Value	Actual Value
Flows			
Feed	gpm	40-50	46
Waste/Backwash*	gpm	3-4	3-4
Net Filtrate/Permeate	gpm	37-46	42-43
Flux and Recovery			
Flux	gfd	19-24	22
Recovery (for L10V Module)	%	93	91-93
Backwash			
Frequency	min	30	15-22
Flow	gpm	120	100
Co-current Duration	sec	23	23
Counter Current Duration	sec	23	23
Chemically Enhanced Backwash (CEB)			
Frequency	days	7	2-18
NaOCl Concentration	mg/L	500	500-1000
Soak Duration	min	30	15-30
Rinse Duration	sec	50	90-120
Clean in Place (CIP)			
Frequency	days	30	14-36
Citric Acid Concentration**	%	2	2
NaOCl Concentration	mg/L	500	500-1000
Duration	hrs	6	6

***** Equivalent continuous flow rate
** Citric acid solutions were heated to 100°F (38°C), per the manufacturer's recommendation.

4.1.1.2 UF System Performance Data

Operation of the UF system was evaluated based on cleaning frequency and other key parameters: feed and filtrate pressure, TMP, permeability, flux, and membrane integrity. Operating parameters are discussed in this section, and cleaning requirements are discussed in the Section 4.1.1.3. Flow, flux, and pressure data in this section were daily averages calculated from the 5-min data collected automatically by the system loggers. Data taken during operational interruptions (e.g., backwashes) were excluded from the calculation of the daily average values. Table 4-2 presents the average, minimum, and maximum values for relevant operating parameters from the manually recorded data, for the three operational phases in this study (Section 1.5). Although temperature data are not included in this section, a sensitivity analysis indicated that temperature was unlikely to have a strong impact on the UF performance.

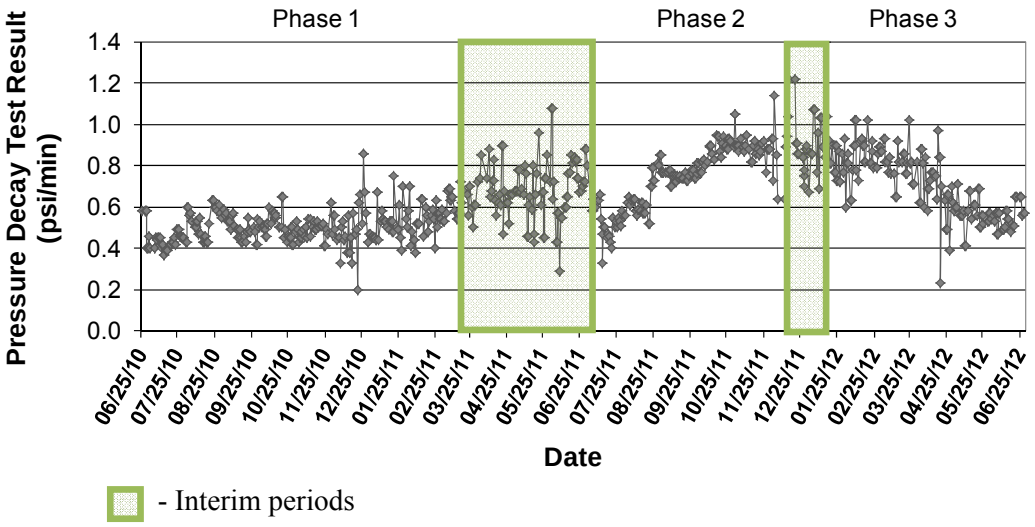
Membrane Integrity

Membrane integrity was measured daily through a pressure decay test; high values can indicate damage to the membrane fibers. Results are plotted in Figure 4-1. The high and low decay rate spikes are related to unusual membrane pressure conditions related to cleaning events (discussed in detail in the next section). All tests were successful; the decay rate was always < 1.5 psi/min, which was defined by the manufacturer as the maximum acceptable value for drinking water treatment, and showed no signs of membrane damage.

Table 4-2. Selected UF System Operating Data by Phase

		Phase 1			Phase 2			Phase 3		
Monitored Parameter	Units	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max
Operating Times										
Days of Operation	days	252	--	--	163	--	--	160	--	--
Total Filtrate Run Time	hours	5,040	--	--	3,218	--	--	2,576	--	--
Flows and Related Parameters										
Total Flow Processed	MG	14.0	--	--	9	--	--	7.4	--	--
Feed Flow	gpm	46.1	45.3	52.5	46.2	45.3	52.1	45.7	43.5	48.4
Flow Set Point	gpm	46	46	46	46	46	46	46	46	46
Filtrate Flow	gpm	45.5	44.9	49.7	45.8	44.6	48.7	45.6	43.2	48.8
Pressures and Related Parameters										
Feed Pressure	psi	18.4	13.2	27.5	20.4	14.2	27.8	24.0	17.0	28.9
Filtrate Pressure	psi	11.1	10.0	19.9	11.2	10.0	13.2	10.9	10.1	11.7
TMP	psi	7.4	2.2	16.5	9.2	3.5	16.7	13.1	5.8	18.6
Flow Resistance	-	3.5	1.0	7.8	4.4	1.7	7.9	6.2	2.7	8.8
Pressure Decay	psi/min	0.5	0.2	0.9	0.7	0.3	1.1	0.7	0.2	1.0
Other Parameters										
Set Point, Time Between Backwash	min	21.7	17.0	22.0	22.0	22.0	22.0	17.5	15.0	18.0
NaOCl Delivery Rate	mL/min	11.3	5.0	15.0	13.2	10.0	16.0	11.0	7.5	14.0
Total Chlorine Residual	mg/L	3.5	1.3	5.5	3.4	2.8	4.9	3.2	0.5	4.0

Figure 4-1. UF System Membrane Integrity



Feed Pressure, Filtrate Pressure, and TMP

Feed and filtrate pressure data for the UF system are shown in Figure 4-2, and TMP values are shown in Figure 4-3; the TMP is simply the difference between the feed and filtrate pressures. The filtrate pressure was maintained just over 10 psi, and feed pressures typically peaked between 25 and 30 psi. TMP values typically peaked around 17 psi, at which point the membranes were cleaned. The feed pressures and TMPs decreased following cleaning (see Section 4.1.1.3 for details on the cleanings) because less pressure was required to maintain the target flux.

During Phases 1 and 2, minimum feed pressures were roughly 15 psi and minimum TMP values were generally < 5 psi. These values increased during the winter, but decreased again in the spring. This trend was likely due to increased fouling caused by a decline in water quality that was observed during the winter, followed by increased cleaning and improved values in the spring (see Section 4.1.1.3 for details on fouling and cleanings). During Phase 3, the feed pressure increased to > 25 psi, and the TMP increased to > 15 psi.

Figure 4-2. UF System Feed and Filtrate Pressure

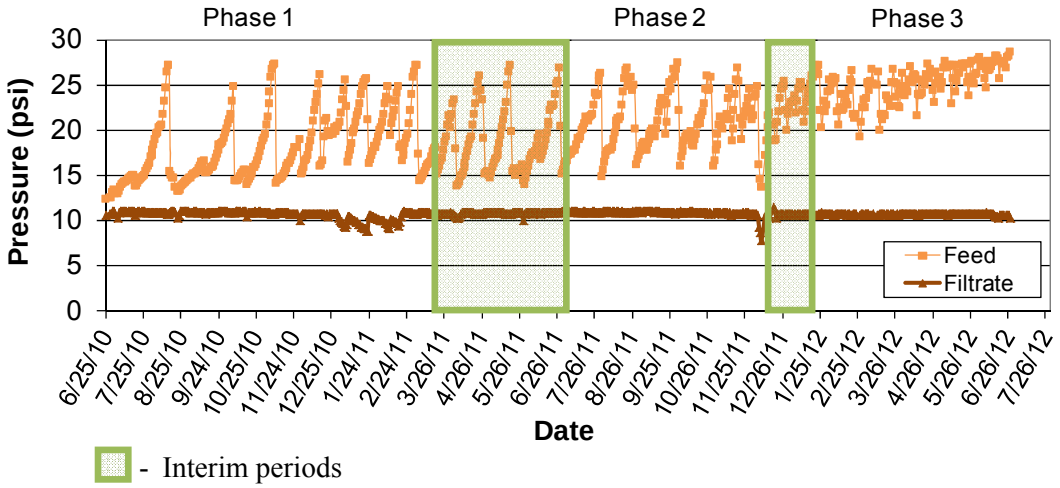
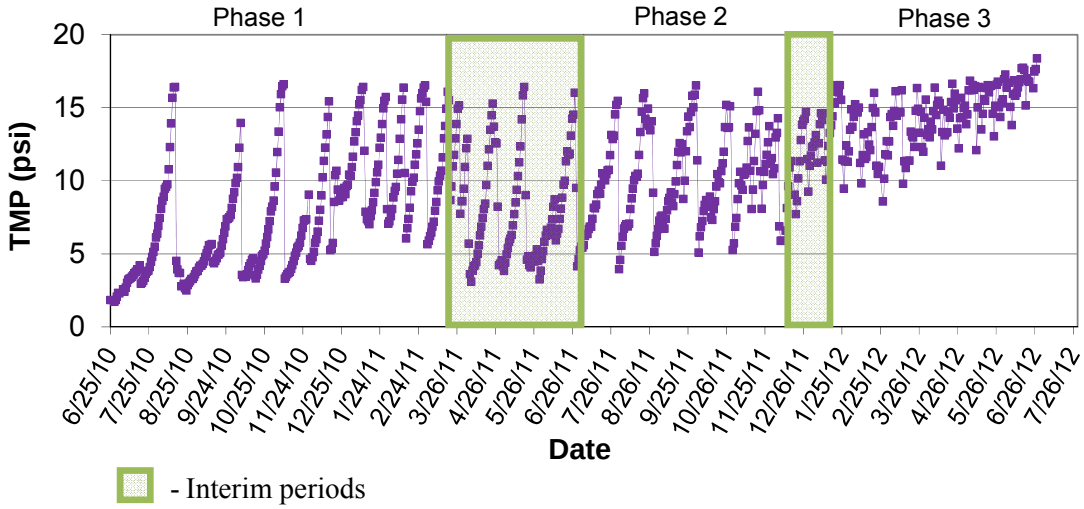


Figure 4-3. UF System TMP



Flux and Permeability

Membrane flux is plotted in Figure 4-4; the UF system was operated at a target flux of 22 gfd. Figure 4-5 shows the observed permeability, as well as temperature-corrected values, which were calculated from equations provided by the manufacturer. Both parameters declined over time, particularly during Phase 3. The flux declined to slightly below the target flux of 22 gfd over the course of the two years of operation, and declined more quickly during the final months of Phase 3 operation. For membrane permeability, temperature did not have a strong effect, as shown by the comparison of the two series plotted in Figure 4-5. Permeability increased each time the membranes were cleaned, but the maximum value after cleaning declined over time and could not be restored to above the lower acceptable minimum (2 gfd/psi) by the middle of Phase 3.

Figure 4-4. UF System Membrane Flux

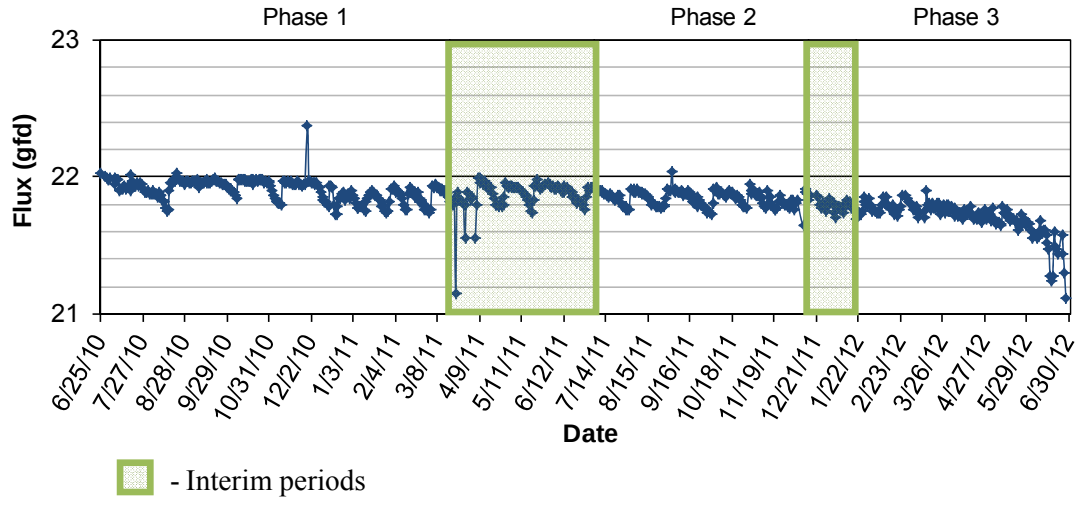
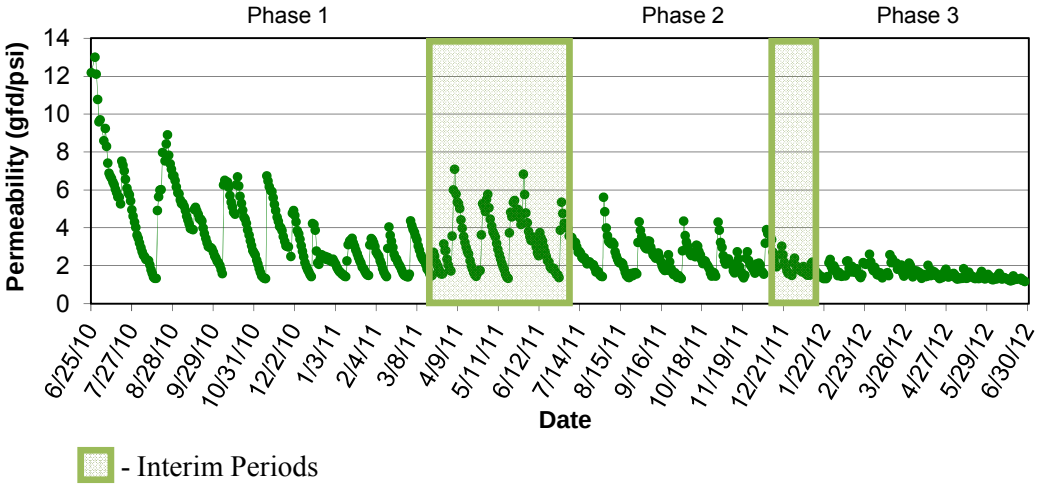


Figure 4-5. UF System Membrane Permeability



Although the cause of the poorer performance in Phase 3 was not definitively identified, a decline in water quality likely contributed to the increase in fouling. Concentrations of several constituents in the secondary effluent increased significantly between Phases 2 and 3: TSS, turbidity, TOC, COD, ammonia and TKN, alkalinity, and potassium (Chapter 5). Despite the fouling issues, the UF unit continued to produce consistent, high-quality filtrate, with average turbidity values in the product filtrate actually decreasing slightly through the study.

4.1.1.3 Cleaning of the UF System

Description of Cleanings

Four types of cleanings were conducted during this study. The chemically enhanced backwashes (CEBs) and clean-in-place (CIPs) were regularly scheduled; details on the cleaning solutions are listed in Table 4-1. The CEB procedure was a single backwash with a 500-1,000 mg/L sodium hypochlorite solution, followed by a 15-30 min soak. This procedure was improved at the beginning of Phase 3 by replacing the single backwash with a series of 2-3 backwashes with soaks. The total CEB run time remained the same (~30 min), but the resulting TMP values were lower. The CIP consisted of recirculating and soaking the membranes in two separate solutions: one was 2% citric acid and the other was 500-1,000 mg/L sodium hypochlorite. The total duration of each CIP was approximately 6 hours.

In addition to the regularly scheduled CEBs and CIPs, two other types of cleanings were conducted as time allowed, e.g., during shutdowns. The extended cleanings (ECs) were similar to the CEBs, but also included 0.5-2.0% Micro-90 surfactant. Recirculation was extended and the membranes were soaked overnight; the total duration of each EC was 3-5 days. The second type of cleaning was the hypochlorite soak, which was similar to the CIP, but recirculation and soak times were extended, with soaks often conducted overnight.

A summary of cleaning intervals, unit availability and recovery for each of the designated study phases is shown in Table 4-3. Figures 4-6 through 4-10 show the different types of cleaning events, and their frequency throughout the study. Note that the x-axis on Figures 4-9 and 4-10 cover only three months (compared to six months for the other graphs), to better show the high frequency of cleanings during Phase 3.

Table 4-3. UF Unit: Cleaning Intervals, Availability, Filtrate Production and Recovery Values

Study Period	*Units*	*Phase 1*	*Interim*	*Phase 2*	*Interim*	*Phase 3*	*Selected Total Values*
No. Days in Period		253	108	164	35	162	722
Cleaning Intervals for UF Unit							
No. CIPs (Citric, NaOCl)	-	6	3	5	2	11	27
No. ECs (Citric, NaOCl, Micro-90)	-	0	1	1	0	0	2
No. Soaks (NaOCl, overnight)	-	8	5	1	1	4	19
No. CEBs (NaOCl, 30 min)	-	0	7	26	6	75	114
Interval, CIPs & ECs	days	36		27	15		
Interval, Soaks & CEBs	days	18		6	2		
Operational Availability of UF Unit							
Filtration Time	hours	5,044		3,218		2,722	
Filtration Time	days	210		134		113	
Percent Filtration Time	%	82		82		69	
Ave Backwash Interval	min	22		22		17	
Backwash Time (2.25 min Backwashes)	hours	516		329		358	
Total Operation Time	days	232		148		128	
Percent Operation Time	%	90		90		78	
Filtrate Production and Recovery/Yield							
Ave Daily Flow Processed,	gpd	58,578	57,749	58,981	59,082	49,877	
Total Flow Applied/Processed	MG	15.1	6.2	9.7	1.9	8.2	41.1
Total Filtrate Produced	MG	14.0	5.8	9.0	1.7	7.4	37.9
Backwash Water Usage	MG	1.1		0.7		0.8	2.6
Recovery/Yield	%	93		93		90	

Figure 4-6. UF System Cleaning Events During the First Half of Phase 1: June – December, 2010

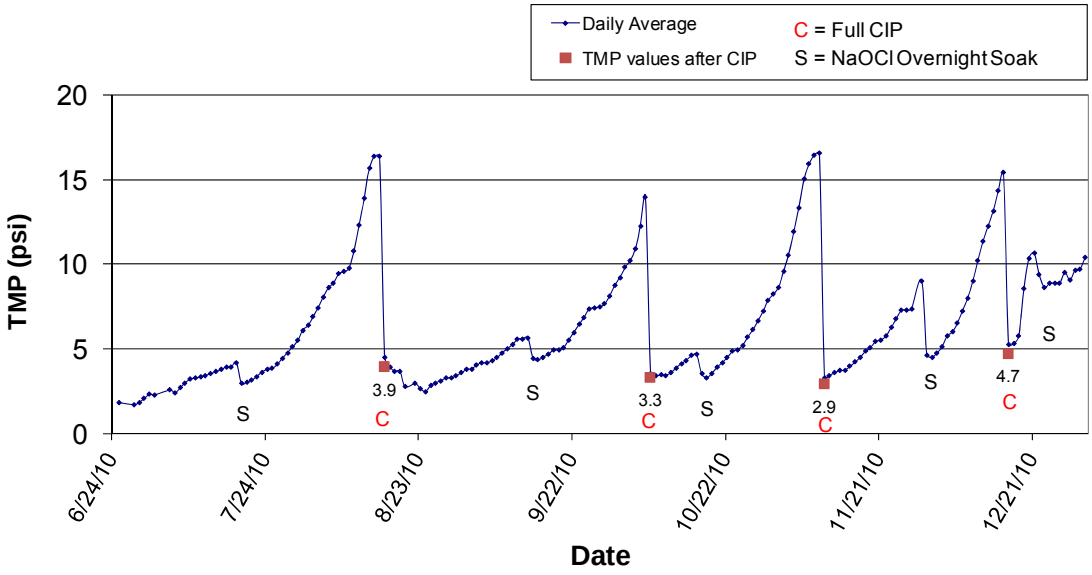


Figure 4-7. UF System Cleaning Events During the Second Half of Phase 1 and the Interim Period: January – June, 2011

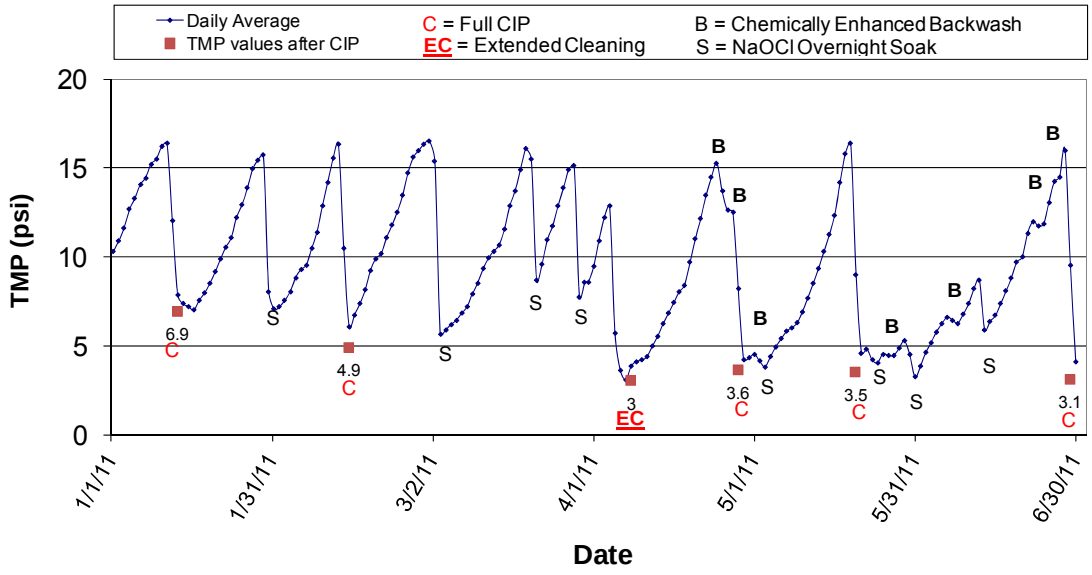


Figure 4-8. UF System Cleaning Events During Phase 2: July – December, 2011

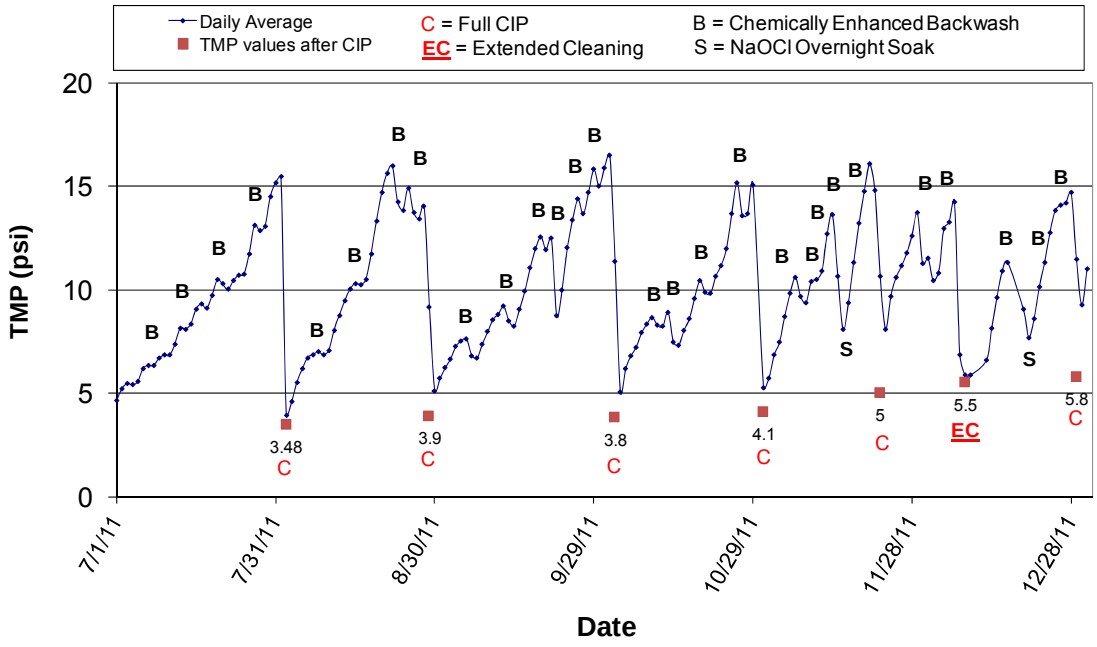


Figure 4-9. UF System Cleaning Events During the First Half of Phase 3: January – March, 2012

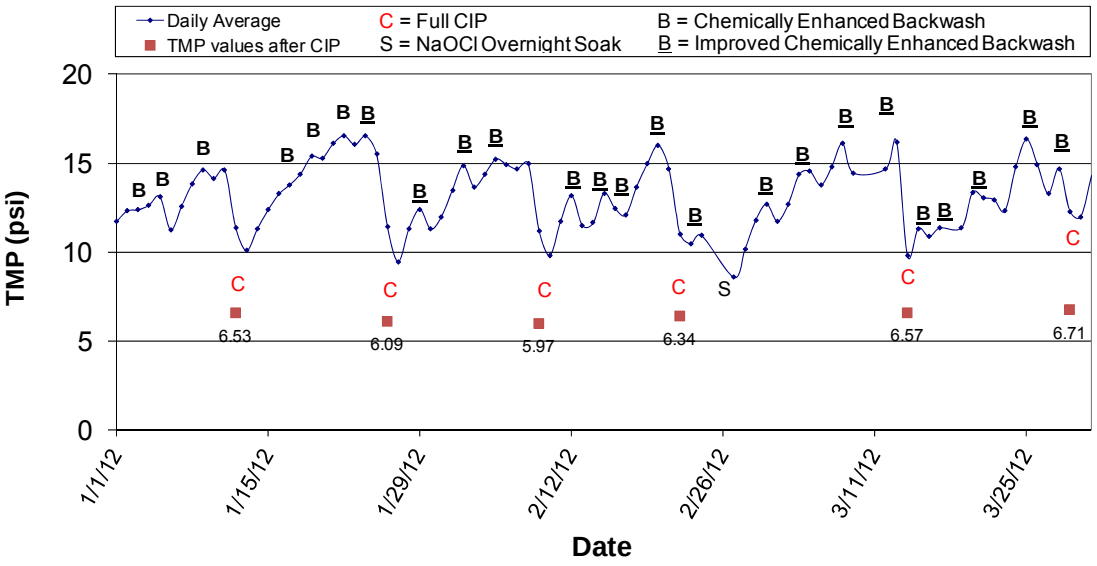
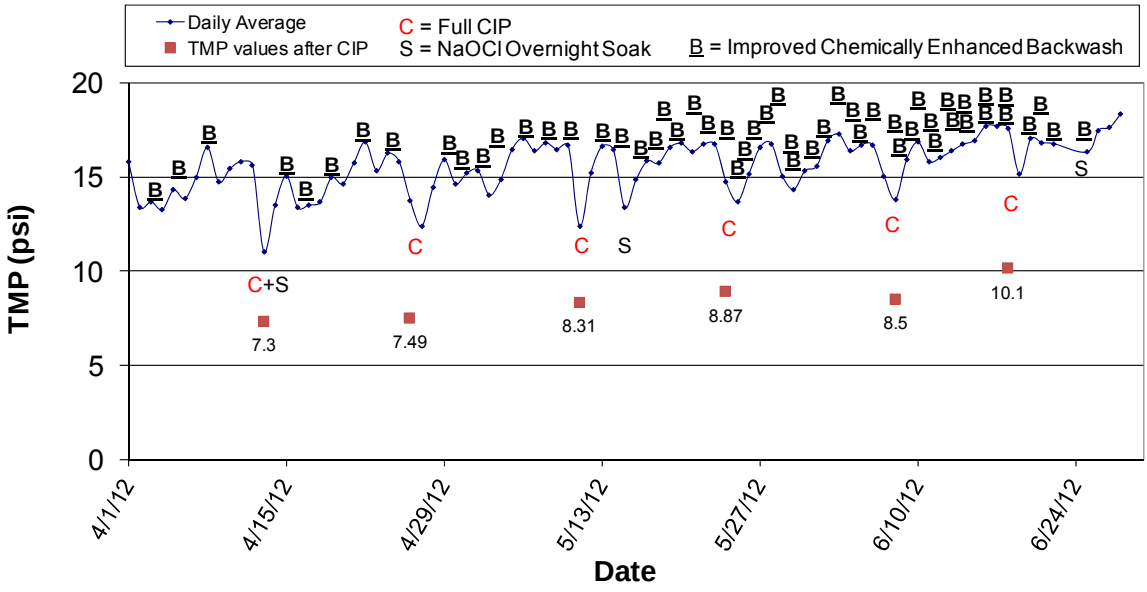


Figure 4-10. UF System Cleaning Events During the Second Half of Phase 3: April – June, 2012



Fouling and the Effects of Cleanings

During Phase 1, full chemical clean-in-place (CIP) or extended cleans (ECs) were required about every 5 weeks, and sodium hypochlorite (NaOCl) soaks or NaOCl chemically enhanced backwashes (CEBs) were performed every 18 days on average. The TMP immediately after the CIPs was generally below 5 psi. During Phase 2, the need for CIPs or ECs increased to every 4 weeks, with CEBs or soaks done every 6 days. As in Phase 1, the TMP immediately after the CIPs was generally below 5 psi. During Phase 3, CIPs were performed every 2 weeks and CEBs or soaks were done every other day, on average. To maintain operation during the final two weeks of the study, CIPs were needed weekly and CEBs were needed 1-2 times a day. Even after performing multiple CIPs, the TMP could not be reduced to lower than about 9 psi.

These results are consistent with a 2009 Orange County Water District study (Knoell, 2011) that compared Siemens membranes made of two different materials: polypropylene and PVDF (similar to the ones used in this project). Cleaning was required at least twice as often for the PVDF membranes, with no flux advantage. By the end of the six month study, CIPs were needed as frequently as every three days along with daily CEBs.

In addition to the membrane fouling that occurred during Phase 3, rain events and winter conditions also adversely affected the feed water quality and UF performance. During these times, the amount of material increased in the basket strainers upstream of the UF; some of this material went through the strainers and caused additional loading on the UF membranes. In addition, TMP values were > 5 psi immediately after cleaning, even with increased cleaning frequencies. For example, a major rain event occurred during December 2010 (Phase 1), and TMPs were restored to normal levels only after removing the unit from service for several days in the spring of 2011 to do more thorough, extended cleanings.

Productivity

Overall, the UF unit was in productive operation about 90 percent of the time during test Phases 1 and 2 and about 80 percent of the time during Phase 3. On average, the interval between backwashes was 22 minutes in Phases 1 and 2, but decreased in Phase 3 to 15minutes. At the end of Phase 3, the longest backwash interval was only 15 minutes (immediately after the CIPs), and within several days decreased to about four minutes, which was the minimum value allowed by the UF control program. The resulting downtime from the more frequent backwashes (and other cleaning events) decreased the overall average daily filtrate production by approximately 15%, from about 59,500 gpd in Phases 1 and 2 to about 50,700 gpd in Phase 3. At the shortest backwash interval of four minutes, filtrate production was approximately 30,000 gpd, approximately half of the normal (non-fouled membrane) production. The backwash water requirements were typically 7% of the total amount of feed water treated by the unit during Phases 1 and 2, as expected. This value increased to an average of 9% during Phase 3, and was as high as 47% at the end of Phase 3.

It should be noted that the UF unit, even at the end of the study, was still producing adequate amounts of filtrate, and likely could have continued to do so for some amount of time. However, continuing operation would not have been practical for long, due to the need for daily cleaning procedures, an increased number of backwashes, and the decreased filtrate production.

Based the inability of repeated cleanings to maintain membrane permeability, TMP, and flux, the membranes were considered to be irreversibly fouled at the end of the two-year study period. This service life was much shorter than the expected value of five years.

4.1.2 RO Operation

4.1.2.1 UF-RO Operating Parameters

The UF-RO system was in operation for approximately 2 years (> 12,000 hours), from July 6, 2010 through June 28, 2012 and treated over 14.7 million gallons of UF filtrate; note that these dates reflect the total operational time, including time before the UF and RO systems came to steady state, and the time between phases. Average operating conditions for the RO system are shown in Table 4-4. Throughout the study, the flux was maintained at approximately 12 gfd, and recovery was approximately 85%. To help control inorganic fouling, the target dose of antiscalant (Pretreat Plus™ 0100, King Lee Technologies) was 6.5 mg/L throughout the study, per the manufacturer's recommendation. Sulfuric acid was also used to lower the pH of the feed water to reduce the precipitation of sparingly soluble salts.

A single set of RO membranes was used during Phase 1. At the end of Phase 1, the lead and tail elements were removed from the system for autopsy (Section 4.3.1). These elements were replaced with new elements for Phase 2. Results during Phase 2 indicated reduced performance (Section 4.1.2.3); consequently, all membranes in the RO unit were replaced with new elements in Phase 3.

Table 4-4. Average Operating Conditions of UF-RO System

Parameter	Units	Phase 1	Phase 2	Phase 3
Net Operating Time	hours	5,204	3,537	3,292
Feed Flow	gpm	17.5	17.5	17.5
Permeate Flow	gpm	14.8	14.8	14.7
Recovery	%	84.7	84.4	84.3
Specific Flux	gfd	12.0	11.9	11.9
Initial Pressure	psi	171	147	167
Second Stage Pressure	psi	157	132	152
Antiscalant Dose	mg/L	5.7	7.3	6.5
Sulfuric Acid Dose	mg/L	162	97	137
Influent pH	-	6.5	6.8	6.7
Permeate pH	-	5.5	5.6	5.5
Concentrate pH	-	--	7.2	7.1

4.1.2.2 Optimization of UF-RO Operating Parameters

Phase 1 established baseline conditions for the UF-RO. Sulfuric acid was added to the RO influent to achieve a pH value of 6.5.

In Phase 2, sulfuric acid addition was reduced based upon Langelier saturation index (LSI) calculations. An analysis of the concentrate water quality indicated that the RO system could operate in a LSI range of 0-1, with the addition of 6.5 mg/L of antiscalant. Consequently, the concentrate pH was allowed to rise to a target of 7.2. This change increased the feed water pH to 6.8, and decreased sulfuric acid use by 40% (from 162 to 97 mg/L).

In Phase 3, new membranes were used, and modeling software (IMSDesign by Hydranautics) was also used to optimize the operation of the RO system. Modeling results, based on historical feed water quality and operational parameters, indicated that fouling in Stage 2 of the RO system could be reduced by decreasing the recovery in Stage 1, thereby increasing the flow rate across the membranes in Stage 2, and decreasing the salt concentration and fouling potential of the water. The proper amount of diversion was accomplished by increasing the backpressure in the Stage 1 permeate line to 34 psi. Other operating targets remained the same as in Phase 2: a flux of 12 gfd, overall recovery of 85%, 6.3 mg/L of antiscalant, and a target concentrate pH of 7.2.

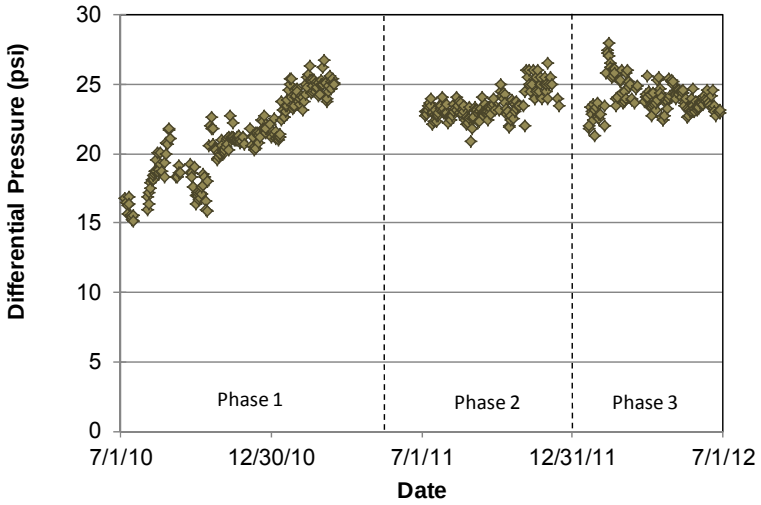
4.1.2.3 UF-RO System Performance Data

The data presented in this section are daily averages calculated from hourly data collected automatically by the system loggers. The only exception was during Phase 2, from October 27, 2011 through December 15, 2011. During this period, data from the loggers was corrupted; daily averages were calculated from values that were manually recorded twice per day, once in the morning and once in the afternoon.

Differential Pressure

Figure 4-11 presents the differential pressure data for the RO system, i.e., the drop in pressure from the RO feed to the RO concentrate, on the pressurized side of the membrane. The differential pressure increased steadily during Phase 1, which suggests deposition of materials in the feed flow path. Literature from the membrane manufacturer indicates that these materials may include metal oxides, colloids, minerals, polymerized silica, microorganisms, organics, and antiscalant (Hydranautics, 2011a). The cleaning procedures used on the RO system between Phases 1 and 2 (see details in Section 4.1.2.4) had little effect on the differential pressure, which remained close to 25 psi. The differential pressure was relatively constant during Phases 2 and 3, which indicated minimal additional deposition.

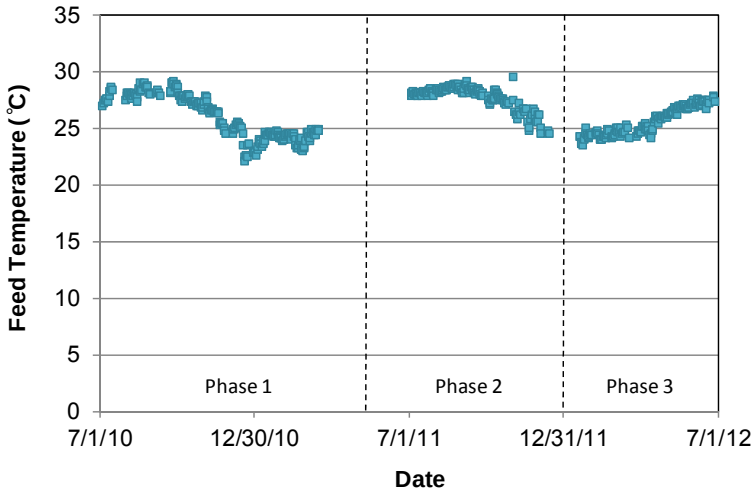
Figure 4-11. UF-RO System: Differential Pressure Data



Temperature

Figure 4-12 presents the temperature data for the RO system on the UF train. There was a clear seasonal variation, with temperatures decreasing from approximately 29°C in the summer to 22°C in the winter. Temperature is important to RO performance, because increasing temperatures increase the diffusion rate through the membrane for both water and solutes. Consequently, as temperature increases, the flux of water through the membranes increases (or the feed pressure decreases in systems operated at constant flux, such as this one). In addition, as temperatures increase, solute concentrations in the permeate generally increase as well (Kim et al., 2009).

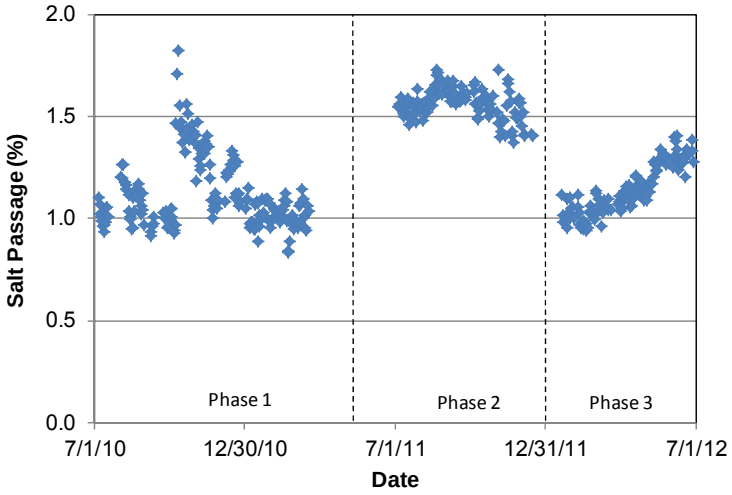
Figure 4-12. UF-RO System: Temperature Data



Salt Passage

Salt passage data for the RO system on the UF train are presented in Figure 4-13; the values were corrected for temperature and permeate flow according to the manufacturer's software. The salt passage was level at approximately 1% for the first three months of operation, increased suddenly on October 8, 2010, then decreased until the end of Phase 1. Salt passage throughout Phase 2 varied from 1.4-1.7%; these values were generally higher than those observed in Phase 1. In Phase 3, salt passage started at 1% but increased over time to approximately 1.3%.

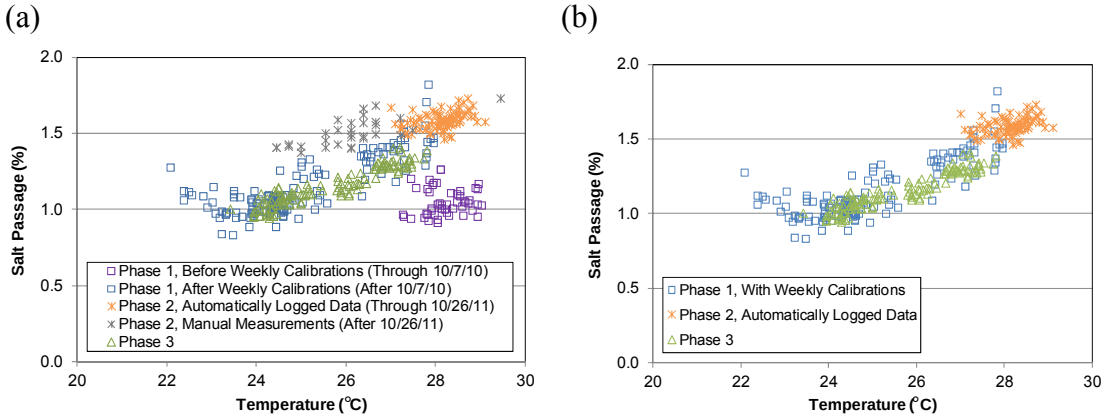
Figure 4-13. UF-RO System: Salt Passage Data Over Time



Most of these changes can be attributed to the changes in temperature, or operational conditions, as shown in Figure 4-14. Much of the data follows a linear trend of increasing salt passage with increasing temperature; this trend suggests that the correction provided by the manufacturer did not perfectly account for the water temperature. In addition to the temperature trend, several

distinct periods can be observed in Figure 4-14a. Weekly calibration of the conductivity analyzer began October 8, 2010, during Phase 1. The lower salt passage values prior to that date are likely an artifact, rather than truly low values.

Figure 4-14. UF-RO System: Salt Passage as a Function of Temperature (a) All Data, (b) Auto-logged Data, with Weekly Calibration of the Analyzer



In addition, data from the autologger was corrupted between October 26 and December 15, 2011, during Phase 2. Values during this time were averages of two manually recorded values taken once in the morning and once in the afternoon. Salt passage followed a diurnal trend, with the salt passage lowest at night under the coldest temperatures, and increasing during the day as temperatures increased. The manually recorded data excluded the low nighttime salt passage values, resulting in higher-than-normal values for that period. As show in Figure 4-14b, once the data from these two operational periods were excluded, the salt passage followed a linear trend with temperature. There were no apparent differences in performance among Phases 1, 2, and 3.

Feed Pressure and Flux

Figure 4-15 presents feed pressure data and Figure 4-16 presents normalized specific flux data for the UF-RO system; note that the specific flux is directly related to the feed pressure, and decreases as feed water pressure increases. With the new membranes in Phases 1 and 3, the feed pressure increased from an initial value of approximately 150 psi to between 160 and 170 psi after about two months. At the same time, the specific flux decreased from approximately 0.12 to 0.10 gfd/psi. These changes occurred while the temperature was relatively constant, and are likely due to minor biological and organic fouling that inevitably occurs during the conditioning of new membranes.

The membranes were thought to have reached steady state around October 2010 (Phase 1) and March 2012 (Phase 3), when the pressure and flux values stabilized. However, the steady state during Phase 1 lasted only one to two months, after which the temperature decreased, the feed pressure increased, and the specific flux decreased. By mid-March 2011, the feed pressure reached approximately 200 psi, and the specific flux had declined to 0.08 gfd/psi. Literature from the manufacturer indicates that feed pressure increases approximately 3% for every 1°C decrease in temperature (Hydranautics, 2011b). Thus the 4°C decrease during Phase 1 would be expected to increase the feed pressure by approximately 12%, or 19 psi, to approximately 180 psi. However, feed pressure increased beyond that point, presumably due to fouling. The Phase 3 data show no clear indications of fouling, beyond the initial conditioning period.

Figure 4-15. UF-RO System: Feed Pressure and Temperature

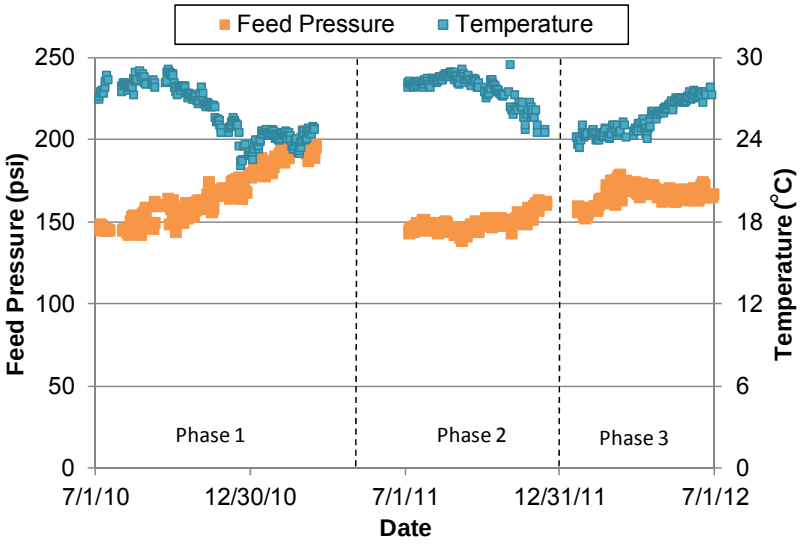
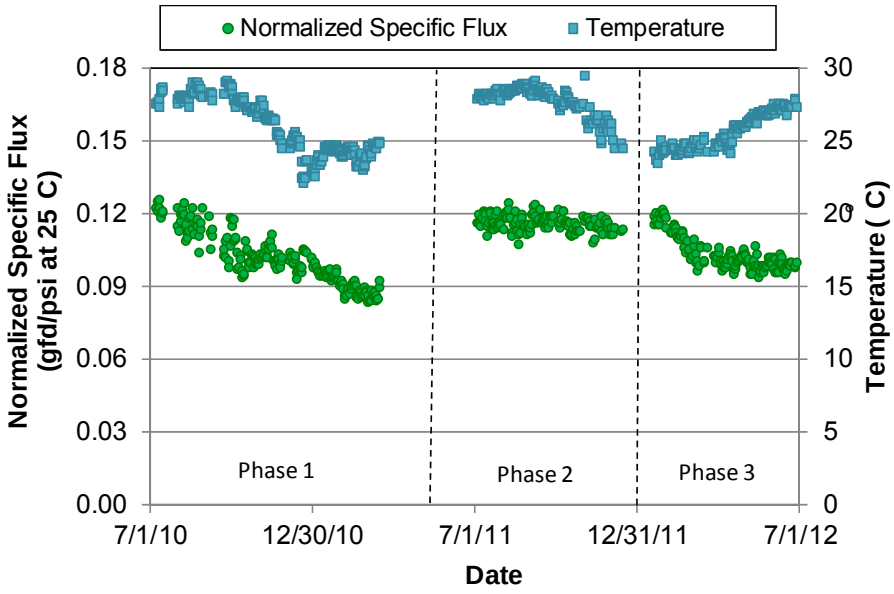


Figure 4-16. UF-RO System: Normalized Specific Flux



The specific flux is normalized for temperature; however, as shown by the salt passage data, temperature corrections are not always perfect. In this case, the steepest decrease in the specific flux occurred at the end of Phase 1, when the temperature was relatively constant, so this decline was likely due to fouling. As with the feed pressure, the Phase 3 data show no clear indications of fouling, beyond the initial conditioning period.

4.1.2.4 Cleaning of the UF-RO System

The changes in the RO operating performance at the end of Phase 1 (described in the previous section) suggested that the membranes needed to be cleaned. As a result, the RO system was taken offline in mid-March 2011. Two membrane elements were removed for autopsy: one lead element and one tail element. The elements that were removed for analysis were replaced with new ones after the RO system cleaning and prior to startup of Phase 2. The autopsy results are discussed in Section 4.3.

Following the extraction of the two membrane elements for autopsy, a cleaning of the membrane elements was performed on the RO system. The system was initially cleaned with a high pH solution containing sodium tripolyphosphate and Na-EDTA. This solution is recommended to remove fouling by calcium sulfate, organic materials, divalent and trivalent cations, and metal ions. A second cleaning solution of critic acid was used to remove inorganic scale, metal oxides and hydroxides, and inorganic-based colloidal matter. The composition of each of the solutions was specified by the manufacturer (Hydranautics, 2011a). The effects of these cleanings can be seen in the Phase 2 data in Section 4.1.2.3.

4.2 MBR TREATMENT TRAIN

4.2.1 MBR Operation

The MBR pilot-scale system was delivered to JWPCP in mid-June 2010. During preliminary startup, the MBR was supplied with JWPCP secondary effluent, and the aeration tank was seeded with water from a JWPCP odor control biotrickling filter unit that contained nitrifying bacteria. From August 12 to September 2, 2010, the MBR achieved nearly complete nitrification. Based on this preliminary work, it was determined that the entire volume of the aeration tank (originally designed for treating primary effluent) was not needed for full nitrification. As a result, the aeration tank was replaced by a smaller tank (Section 2.3.2). This change reduced the hydraulic retention time and energy requirements, both important factors in full-scale design and operation.

In addition to this structural change, the membranes underwent three restoration cleanings before the start of testing: details on these cleanings are given in Section 4.2.1.3. A clean-water membrane conditioning test performed on October 28, 2010, indicated that both membrane cassettes were in acceptable condition.

Testing of the MBR was divided into three operational phases (Section 5.1), each with a different target flux (Table 4-5). These phases do not include data taken during startup of the MBR, approximately the first month of operation. The following sections discuss the MBR operating parameters (Section 4.2.1.1), performance data (Section 4.2.1.2), and cleanings (Section 4.2.1.3) for the three phases of operation.

Table 4-5. Operational Phases of the MBR System

Phase	Start Date	End Date	Target Flux (gfd)
1	12/8/10	3/30/11	10
2	7/5/11	12/6/11	15
3	1/20/12	6/30/12	20

4.2.1.1 MBR System Operating Parameters

The operating parameters for each operational phase are summarized in Table 4-6, and membrane data are summarized in Table 4-7. The membranes used in Phases 1 and 2 were approximately eight years old at the time the project began; they were previously used to treat primary effluent at another plant operated by the Districts. It is possible that the age of the membranes affected the performance, e.g., the fiber breakage that occurred during Phase 2 (see TMP discussion in Section 4.2.1.2). The membranes used in Phase 3 were new.

Influent flow, flux, and hydraulic retention time (HRT) in the MBR pilot-scale system are plotted in Figures 4-17, 4-18, and 4-19, respectively. The values shown in these figures are daily averages calculated from data taken automatically every 5 min by system loggers; data taken during operational interruptions were excluded from these calculations.

Table 4-6. Average Operating Conditions of the MBR System

Parameter	Units	**Phase 1**	**Phase 2**	**Phase 3**
Flows and Flux				
Feed Flow	gpm	29	21	34
Flux	gfd	10	14	20
Hydraulic Retention Time (HRT)	min	73	96	74
Cyclic Backpulse				
Interval	min	11	11	11*
Duration	sec	45	45	45
Flow	gpm	51	25	27
Biological Parameters				
Membrane Tank Mixed Liquor Suspended Solids (MLSS)	mg/L	3,700	3,300	4,000
Solids Retention Time (SRT)	days	11	18	12
Mixed Liquor Recirculation Rate	gpm	120	140	140
Air Scouring Rate	scfm	130	120	130
Aeration Rate in Aeration Tank	scfm	25	25	25
Maintenance Cleaning				
Frequency	per week	1	---	1
NaOCl Concentration	mg/L	200	---	200
Manual Relaxations				
Frequency	per week	--	3	2
Duration	min	---	45	45

*In response to TMP increases (Section 4.2.1.2), the backpulse interval was decreased to as low as 6 min from February 6-29, 2012; to 10 min from March 5-12, 2012, and to as low as 6 min from May 2-7, 2012.

Table 4-7. Membrane Pack(s) in Service

Phase	Start Date	End Date	Pack(s) in Service
1	12/8/10	3/30/11	Both*
2	7/5/11	7/15/11	North
	7/15/11	10/6/11	South
	10/6/11	10/7/11	North
	10/7/11	12/6/11	South*
3	1/20/12	6/30/12	Single New Pack

*Restoration cleanings were conducted on February 24, 2011, and October 11-13, 2011; no membranes were in service during these cleanings.

Figure 4-17. MBR System: Influent Flow

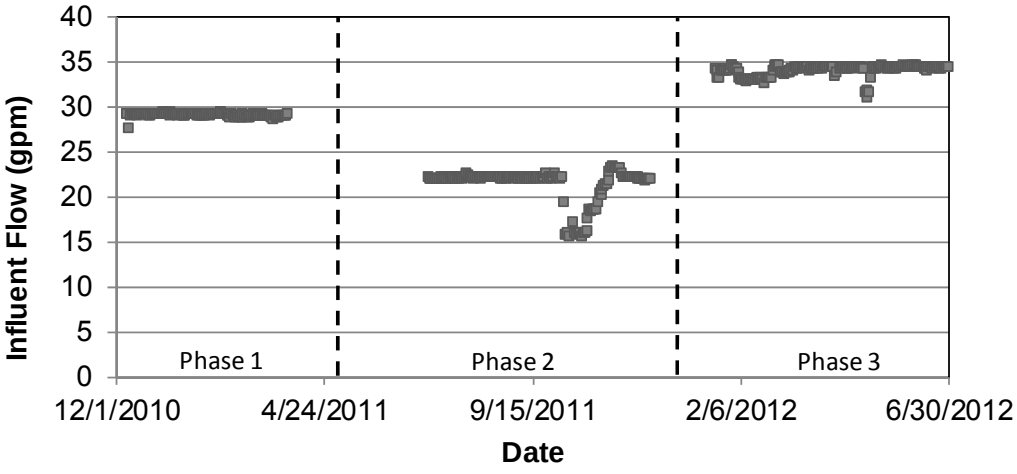


Figure 4-18. MBR System: Flux

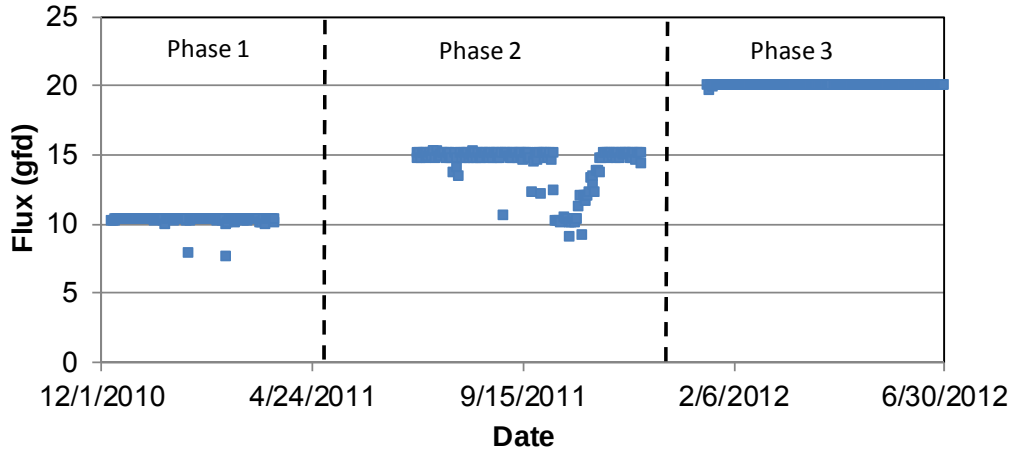
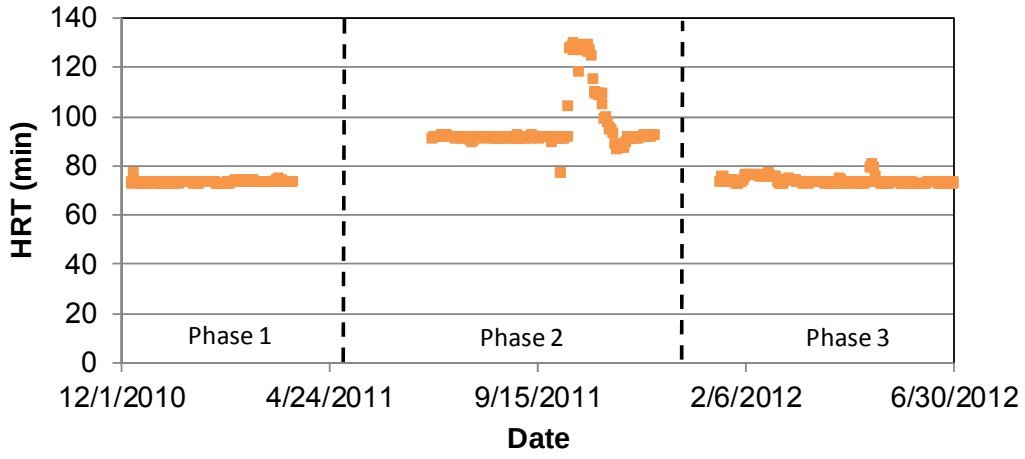


Figure 4-19. MBR System: HRT



During Phase 1, the system was operated with both membrane packs in service at a flux of 10 gfd, which is a typical flux value for MBR units that treat primary effluents. Maintenance cleans were conducted weekly; details on the cleanings can be found in Section 4.2.1.3. The influent flow and HRT were fairly constant at 29 gpm and 73 min, respectively. SRT was controlled by removing mixed liquor (i.e., solids) from the membrane tank via an overflow system.

During Phase 2, the average flux through the membranes was increased to 14 gfd. To achieve this flux, only one of the two membrane packs was used and the influent flow was decreased to an average of 21 gpm, resulting in an average HRT of 96 min. The flux, flow, and HRT were relatively constant during Phase 2, except during October 2011; this period is discussed in more detail in Section 4.2.1.2. The membrane pack in service was alternated between the two packs, which were designated the "north" and "south" packs. Pack changes were driven by operating conditions, which are described in more detail in Section 4.2.1.2. Maintenance cleanings were replaced by manual relaxations performed three times per week (see Section 4.2.1.3 for details). The cleanings were eliminated because the chlorine added during the maintenance cleanings was considered to be a possible cause for difficulties in maintaining the desired mixed liquor suspended solids (MLSS) concentrations during Phase 1. A peristaltic pump was added to the system to better control solids removal and the SRT.

For Phase 3, the flux was increased to 20 gfd, a value similar to the UF flux, and was held constant at this value throughout the period. To achieve this flux, the system was operated at an influent flow of 34 gpm and an average HRT of approximately 74 min. A new membrane cassette with new ZeeWeed® 500d membranes was installed. To accommodate the new membranes, the depth of the membrane tank was increased (see Section 2.3.3 for details on the system modification). Because the peristaltic pump installed during Phase 2 improved SRT control, weekly maintenance cleans were reinstated during Phase 3; manual relaxations were also performed twice per week (see Section 4.2.1.3 for details on the cleanings and relaxations).

4.2.1.2 MBR System Performance Data

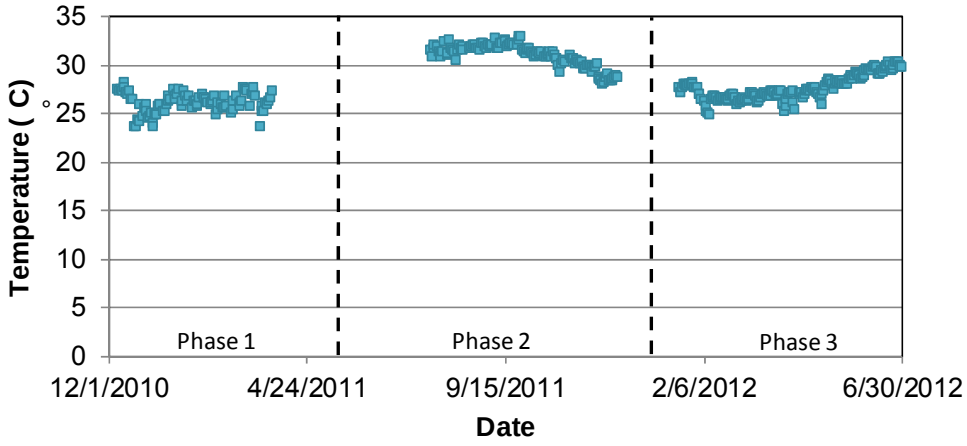
This section describes the operational performance of the MBR system. MLSS values were measured by the JWPCP Laboratory in grab samples taken from the membrane tank. The other values shown in this section are daily averages calculated from data taken automatically every

5 min by system loggers, except where noted; data taken during operational interruptions were excluded from these calculations. It is worth noting that despite some of the difficulties described in this section, the MBR consistently nitrified the JWPCP secondary effluent throughout the study, as described in Chapter 5.

Temperature

Temperature data for the MBR mixed liquor are plotted in Figure 4-20. Temperatures before September 10, 2011, are the average of manually recorded daily observations; temperatures after this date are daily averages calculated from data taken automatically every 5 min by system loggers. As with the UF and UF-RO data, there was a clear seasonal variation, with temperatures decreasing from approximately 33°C in the summer to 24°C in the winter. Temperature can affect performance, with increasing temperatures decreasing water viscosity. In systems such as this one that are operated at constant flux, a decrease in water viscosity decreases the feed pressure and TMP, and increases the flux and permeability. In addition, lower temperatures slow down biological activity.

Figure 4-20. MBR System: Temperature



SRT and MLSS

The results for MLSS and SRT are plotted in Figures 4-21 and 4-22, respectively. In general, several factors are balanced in selecting target MLSS values: higher MLSS levels allow for a more compact reactor and reduce construction costs, but can lead to membrane fouling at high concentrations. In addition, increasing MLSS requires more air for membrane scouring and for aeration, because the alpha correction factor for oxygen transfer efficiency decreases with increasing MLSS (Asano, 2007); higher air usage rates increase the energy requirements and operating costs.

MBR units usually treat primary effluent, with MLSS values of 8,000-10,000 mg/L and SRT values of 5-20 days (Tchobanoglous, 2003). For this project, the MBR was used to further oxidize the organic matter in the JWPCP secondary effluent and to nitrify the secondary effluent. Based on manufacturer recommendations, the MLSS concentrations were generally maintained between 3,000 and 4,000 mg/L. The MLSS level was controlled by the SRT; increasing the SRT increased the MLSS concentrations and vice versa, although the exact relationship is complicated due to variations in biosolids production and decay rates.

Figure 4-21. MBR System: MLSS

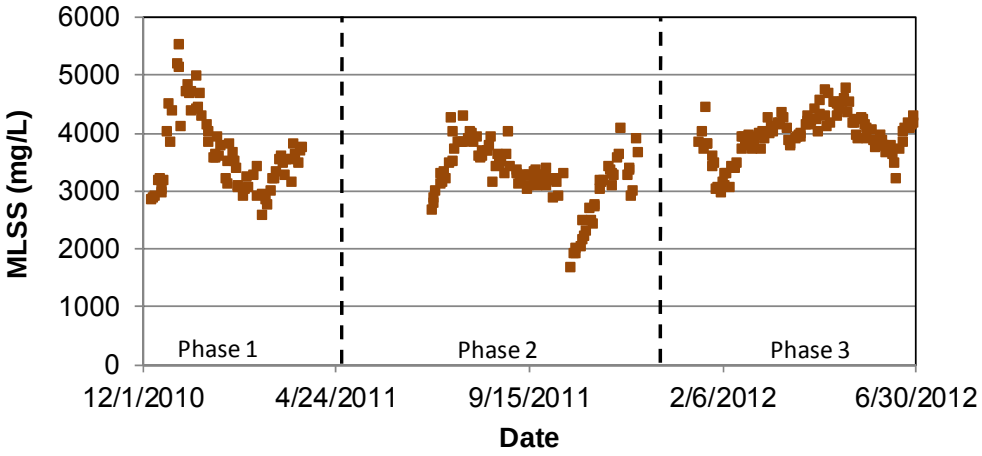
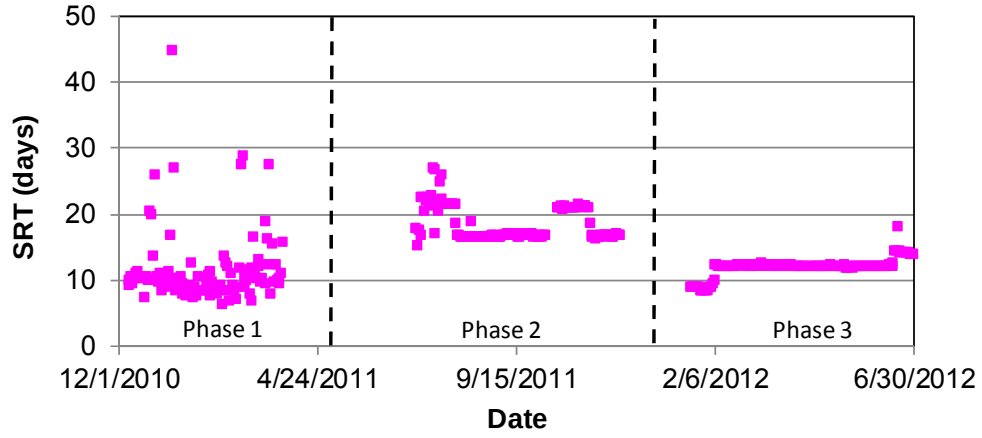


Figure 4-22. MBR System: SRT



As shown in Figure 4-22, SRT levels were most variable during Phase 1. This issue was mitigated during Phase 2 by changing the solids wasting system from an overflow system, which was prone to clogging, to a peristaltic pump. As a result, SRT values were more consistent during Phases 2 and 3, although the SRT was intentionally increased twice during each phase.

The first increase occurred at the beginning of Phase 2, in response to fouling issues (see TMP discussion below). The second increase during Phase 2 occurred in October 2011, in response to a decrease in MLSS. A restoration cleaning was performed on October 12, 2011 (details in Section 4.2.1.3) and appeared to disrupt the MLSS concentrations, which dropped to less than 1,600 mg/L after the cleaning. It is unclear why this restoration clean had a larger impact on MLSS concentrations than a similar cleaning conducted on February 24, 2011, but the SRT was increased to approximately 21 days, and the MLSS returned to pre-cleaning levels approximately three weeks later.

At the start of Phase 3, the MBR was operating at a SRT of approximately 9 days; however, this SRT value proved to be too low to maintain the target MLSS concentration of approximately 4,000 mg/L. In response, the SRT was raised to 10-12 days in early February 2012, and the MLSS recovered to the desired level. The MLSS concentration also decreased in June 2012; increasing the SRT to 14 days successfully raised the MLSS concentration back to the target levels.

TMP and Permeability

TMP and permeability data for the MBR are plotted in Figures 4-23 and 4-24, respectively. The permeability is calculated by dividing the flux by the TMP. Because the flux was relatively constant (Figure 4-18), permeability decreased when the TMP increased in an almost directly inverse relationship. For simplicity, only the TMP data are discussed below. However, the following explanations apply to the trends in both the TMP and permeability.

Figure 4-23. MBR System: TMP

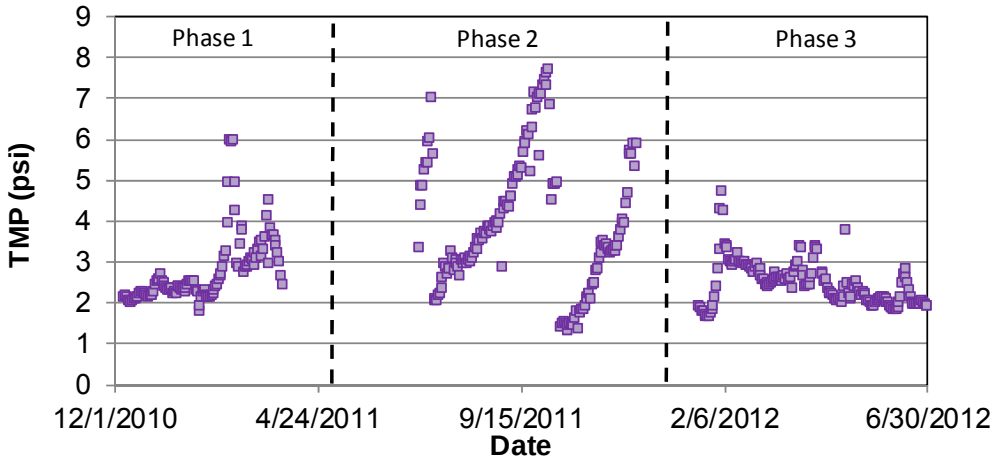


Figure 4-24. MBR System: Permeability

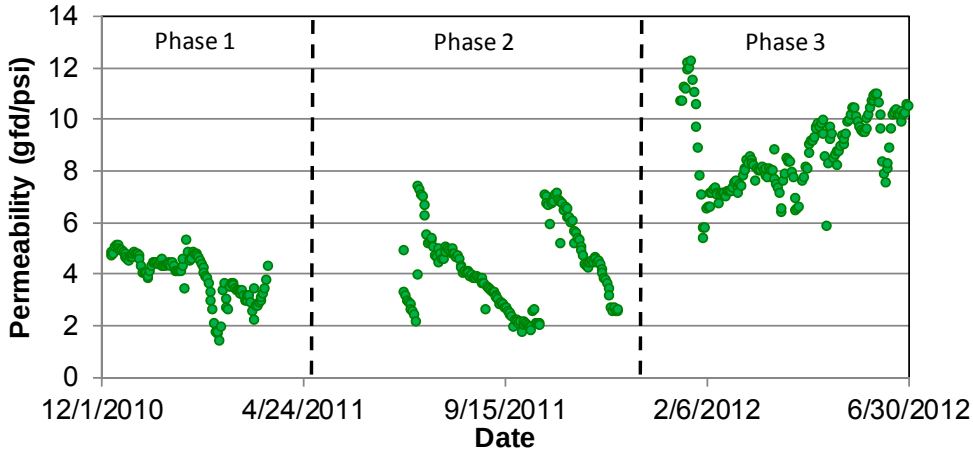
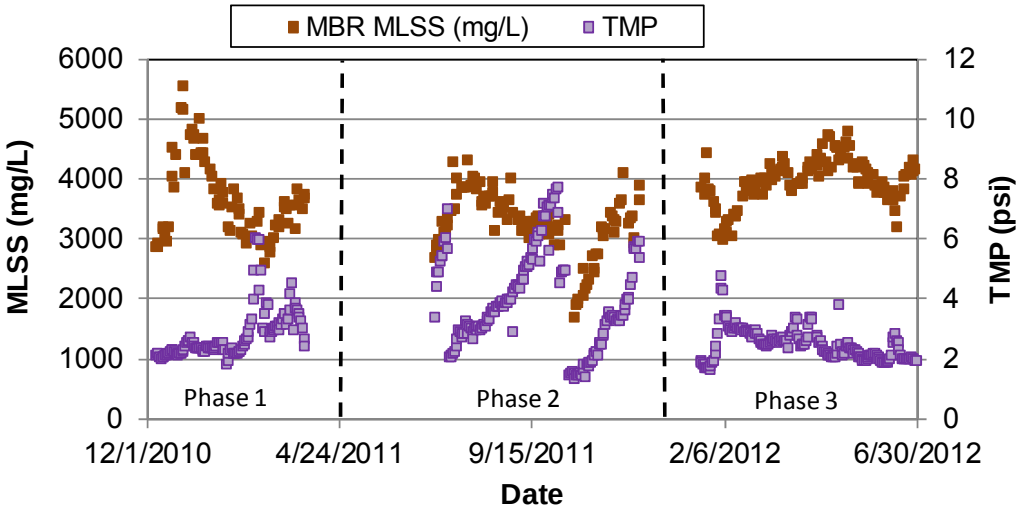


Figure 4-25 plots the TMP data with the MLSS concentration, which appeared to affect the TMP. Most of the TMP spikes coincided with a decrease in MLSS concentration below 4,000 mg/L: during Phase 1 in February and March 2011, throughout Phase 2, and during Phase 3 in February and June 2012. These spikes may have been caused by MLSS levels that were too low to remove fouling colloids or larger particles, or simply a coincidence due to an increase in the concentrations or types of foulants in the MBR feed water. The fouling was reversible, and normal TMP values were re-established for the first spike in Phase 1 by a citric acid restoration cleaning on February 24, 2011, and a decrease in the cyclic backpulse interval from 11 min to as low as 6 min from February 6 to February 29, 2012, and to 10 min from March 5 to March 12, 2012 (see Section 4.2.1.3 for details on the cleaning and backpulse methods). For the second spike in Phase 1 and both spikes in Phase 3, normal TMP values were re-established increasing MLSS level back to 4,000 mg/L.

During Phase 2, the increases in TMP were generally managed by changing the membrane pack that was in operation. The system was started with the north pack in service on July 5, 2011. The TMP rapidly increased to 7 psi and the permeability decreased to 2 gfd/psi over the following week. On July 15, 2011, the north membrane pack was replaced with the south membrane pack. Over the next three months, the TMP on the south pack increased to almost 8 psi and the permeability decreased to approximately 2 gfd/psi. On October 6, 2011, the south membrane pack was replaced by the north membrane pack, which had been out of service for almost three months, effectively providing a very long relaxation period; no other cleanings were performed. The turbidity in the permeate increased more than ten-fold, from 0.08 NTU to > 1 NTU. High turbidity values are an indication of damage to the membrane fibers; the age of the membranes (approximately nine years old at the time) may have been a factor in the damage. This abrupt decline in water quality adversely affected the downstream RO unit, as discussed in Section 4.2.2. The south membrane pack was placed back in service on October 7, 2011, but at a reduced influent flow and flux (Figure 4-17 and 4-19), due to the membrane fouling.

Figure 4-25. MBR System: TMP and MLSS



A restoration cleaning was performed on October 12, 2011, after which the influent flow and flux were slowly ramped up to the target values of 23 gpm and 15 gfd over the following month, as the MLSS concentration recovered. The restoration cleaning restored the TMP to below 2 psi, and the permeability to approximately 7 gfd/psi. From that point until the end of Phase 2, the TMP slowly increased and the flux slowly decreased. These trends were similar to the behavior during August and September, and were probably due to fouling of the membranes.

A few smaller increases in TMP occurred when the MLSS concentrations were > 4,000 mg/L: during Phase 1 in late December 2010, and during Phase 3 at the end of March, middle of April, and beginning of May 2012. Although the causes of these TMP increases were not definitively identified, they could be caused by changes in the secondary effluent water quality (Chapter 5), similar to the UF (Section 4.1.1.3). However, the TMP increases were temporary and generally did not require any change in operations. The only exception was the fouling event at the beginning of May 2012; for this event, the backpulse interval was decreased to as low as six minutes, and the foulant washed out or was degraded by the mixed liquor. On May 7, 2012, the system was returned to the normal backpulse interval of 11 minutes, and remained at that value through the end of the project.

The last observed trend TMP was a slow decrease over most of Phase 3 (with the exception of the fouling effects described above). This decrease may be due to increasing temperature and decreasing water viscosity.

4.2.1.3 Cleaning of the MBR System and Relaxation of the Membranes

Cleanings and relaxations were used to reduce fouling of the MBR membranes. There were three types of cleanings (cyclic backpulses, automated maintenance cleanings, and restoration cleanings), and two types of relaxations (cyclic and manual). Table 4-6 summarizes the frequency of the three kinds of regularly scheduled maintenance: cyclic backpulses, automated maintenance cleanings, and manual relaxations.

The MBR system could be operated in either cyclic backpulse or cyclic relaxation mode. Cyclic backpulse mode was almost always used, except during the system check and for short periods after major system upsets. Cyclic backpulses were performed at 11 min intervals throughout most of the study. For each cycle, permeate production was stopped by turning off the permeate pump and closing the product line valves. Permeate was then pumped back through only the membrane pack(s) in service, at 15 gfd for 45 seconds. Production was then resumed. Aerobic recirculation and air scouring were maintained throughout the cycle. Cyclic relaxations were similar to cyclic backpulses, but the backpulses were eliminated and permeate production was simply stopped for that period of time.

Automated maintenance cleanings were conducted weekly during Phases 1 and 3. Sodium hypochlorite was added to a target dose of 200 mg/L to the MBR permeate line; the permeate flow was then pumped back through the membranes in backpulses at a flux of 15 gfd. The first backpulse was 2 min long, followed by a total of six 45-second backpulses at 2-min intervals. During the backpulsing cycle, the aerobic recirculation pump and the air scour in the membrane tank were turned off. Because the recirculation pump was the only source of influent water into the membrane tank, the system aerated the mixed liquor and recirculated the flow for 10 min after the backpulsing cycle, to ensure that the membranes were fully submerged before beginning permeate production.

Manual relaxations replaced the automated maintenance cleanings in Phase 2, and were used in addition to the automated maintenance cleanings in Phase 3. During the manual relaxations, permeate production was stopped for 45 minutes, but recirculation and air scour were maintained.

Restoration cleanings are analogous to the CIPs for the UF unit, and were conducted as needed, with sodium hypochlorite and/or citric acid. The recirculation and air scour were turned off for the duration of each cleaning. The membrane tank was emptied, and the membranes were rinsed off with a hose. The backwash permeate tank was dosed with the cleaning agent, and the entire 800-gal volume was backwashed through the membranes at a flux of approximately 12 gfd. The membrane tank was then topped with potable water (for a total volume of 1,600 gal during Phases 1 and 2, and 2,000 gal during Phase 3), and the membranes were soaked for a duration of three hours to overnight. Sodium hypochlorite was dosed into the permeate tank to provide a target concentration of 1,000 mg/L during this soak, with no pH adjustment; citric acid was dosed to a target concentration of 2,000 mg/L, and muriatic acid was added to the membrane tank to adjust the pH to 2-2.5. After the soak, the tank was drained, rinsed, and refilled with mixed liquor that had been stored in the aeration tank. The restoration cleanings performed on the MBR during this study are summarized in Table 4-8.

Table 4-8. Restoration Cleanings for the MBR

Phase	Date	Cleaning Agent	Target Soak Dose (mg/L)	Duration
Prelim	9/2/10	NaOCl[1]	1,000	3 hours
Startup	9/26/10	Citric acid[2]	2,000	Overnight
	10/27-28/10	NaOCl	1,000	Overnight
1	2/24/11	Citric acid[2]	2,000	3 hours
Interim	6/6-7/11	Citric acid[2]/NaOCl[3]	2,000/1,000	Overnight/4 hours
2	10/11-13/11	Citric acid[2]/NaOCl[3]	2,000/1,000	Overnight/Overnight

[1] This restoration cleaning did not use a backwash; instead, sodium hypochlorite was added to the membrane tank as it was filled with potable water.

[2] When citric acid was used as the cleaning agent, muriatic acid was used to adjust the pH to 2-2.5 during the soak cycle of the restoration cleaning.

[3] As with the other cleanings, MBR permeate was used to make the citric acid solution. Because the citric acid cleaning used the entire volume of the backwash tank, permeate was unavailable for the NaOCl cleaning that followed. Therefore, the NaOCl solutions were made with potable water.

In Phases 1 and 2, the backwashes for the maintenance and restoration cleanings were generally flushed through both packs, even when only one pack was in service during Phase 2. The only exception was the last restoration clean in October 2011, where the backwash flow to the south pack was insufficient for cleaning (presumably due to membrane damage on the north pack), so the feed to the north pack was partially closed. Both packs were also exposed to the soaks within the membrane tank during the restoration cleanings in Phases 1 and 2. In Phase 3, the membrane tank contained only one membrane to backwash; no restoration cleanings were necessary in this operational phase.

4.2.2 RO Operation

4.2.2.1 MBR-RO Operating Parameters

The MBR-RO system was in operation for approximately 1.5 years (> 9,000 hours), from December 8, 2010 through June 30, 2012 and treated over 8.8 million gallons of MBR permeate; note that these dates reflect the total operational time, including time before the MBR and RO systems came to steady state operations, and the time between phases.

Average operating conditions for the RO system are shown in Table 4-9. Throughout the study, the flux was maintained at approximately 12 gfd, and recovery was approximately 85%. As with the UF-RO, antiscalant (Pretreat Plus™ 0100, King Lee Technologies) and sulfuric acid were used to help control inorganic precipitation and fouling. To control biofouling, approximately 0.7 mg N/L of ammonia was added to the fully nitrified MBR permeate, followed by chlorine addition to form chloramines. The target combined chlorine residual was 2 mg/L.

Table 4-9. Average Operating Conditions of MBR-RO System

Parameter	Units	Phase 1	Phase 2	Phase 3
Net Operating Time	hours	2,549	2,850	3,606
Feed Flow	gpm	17.5	17.5	17.5
Permeate Flow	gpm	14.7	14.7	14.7
Recovery	%	84.4	84.1	84.2
Specific Flux	gfd	11.9	11.9	11.9
Initial Pressure	psi	164	141	166
Second Stage Pressure	psi	148	134	152
Antiscalant Dose	mg/L	3.3	6.5	6.5
Sulfuric Acid Dose	mg/L	53	3	25
Influent pH	-	6.5	7.1	6.9
Permeate pH	-	5.6	5.8	5.7
Concentrate pH	-	--	7.3	7.2

A single set of RO membranes was used during Phase 1. At the end of Phase 1, the lead and tail elements were removed from the system for autopsy (Section 4.3.1). These elements were replaced with new elements for Phase 2. Results during Phase 2 indicated reduced performance (Section 4.2.2.3); consequently, all membranes in the RO unit were replaced with new elements in Phase 3.

4.2.2.2 Optimization of MBR-RO Operating Parameters

Phase 1 established baseline conditions for the RO system. Sulfuric acid was added to the RO influent to achieve a pH value of 6.5. Antiscalant was dosed at 3.3 mg/L, slightly lower than the manufacturer's recommended dose, due to dosing problems at the beginning of the phase.

In Phase 2, sulfuric acid addition was reduced based upon Langelier saturation index (LSI) calculations. An analysis of the concentrate water quality indicated that the RO system could operate in a LSI range of 0-1, with the addition of 6.5 mg/L of antiscalant. Consequently, the

antiscalant dose was increased, and the concentrate pH was allowed to rise to a target of 7.3. This change increased the feed water pH to 7.1, and decreased sulfuric acid use by 95% (50 mg/L).

In Phase 3, new membranes were used, and modeling software (IMSDesign by Hydranautics) was also used to optimize the operation of the RO system. Modeling results, based on historical feed water quality and operational parameters, indicated that fouling in Stage 2 of the RO system could be reduced by decreasing the recovery in Stage 1, thereby increasing the flow rate across the membranes in Stage 2, and decreasing the salt concentration and fouling potential of the water. The proper amount of diversion was accomplished by increasing the backpressure in the Stage 1 permeate line to 30 psi. Other operating targets remained the same as in Phase 2: a flux of 12 gfd, overall recovery of 85%, 6.5 mg/L of antiscalant, and a concentrate pH of 7.3.

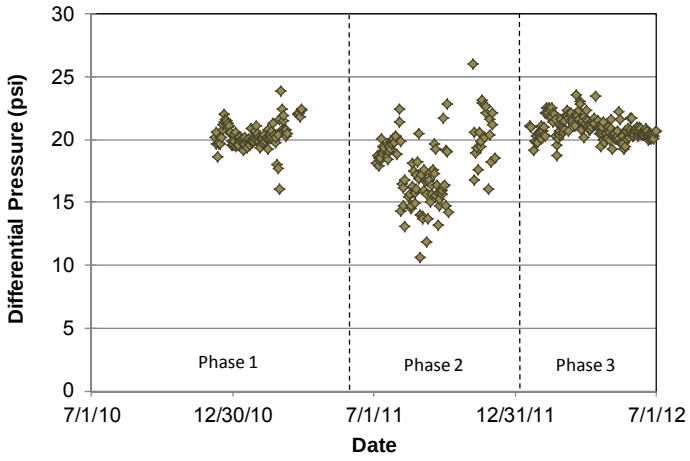
4.2.2.3 MBR-RO System Performance Data

The data presented in this section are daily averages calculated from hourly data collected automatically by the system loggers.

Differential Pressure

Figure 4-26 presents the differential pressure data for the RO system, i.e., the drop in pressure from the RO feed to the RO concentrate, on the pressurized side of the membrane. The values were relatively constant at approximately 20 psi across all three phases, but the data were more scattered during Phase 2. Overall, the results indicate that there was no deposition of materials in the feed flow path.

Figure 4-26. MBR-RO System: Differential Pressure Data

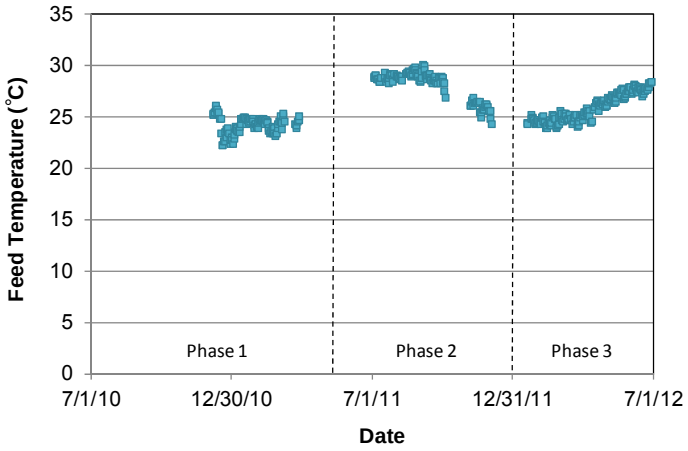


Temperature

Figure 4-27 presents the temperature data for the RO system on the MBR train. There was a clear seasonal variation, with temperatures decreasing from approximately 30°C in the summer to 24°C in the winter. Temperature is important to RO performance, because increasing temperatures increase the diffusion rate through the membrane for both water and solutes. Consequently, as temperature increases, the flux of water through the membranes increases (or the feed pressure decreases in systems operated at constant flux, such as this one). In addition, as temperatures

increase, solute concentrations in the permeate generally increase as well. Because Phase 1 on the MBR was conducted entirely during the winter months, the temperature was relatively low and constant. Temperatures were relatively high and constant during the first half of Phase 2, followed by decreasing temperatures. Conversely, Phase 3 began with low temperatures that began to increase midway through the phase.

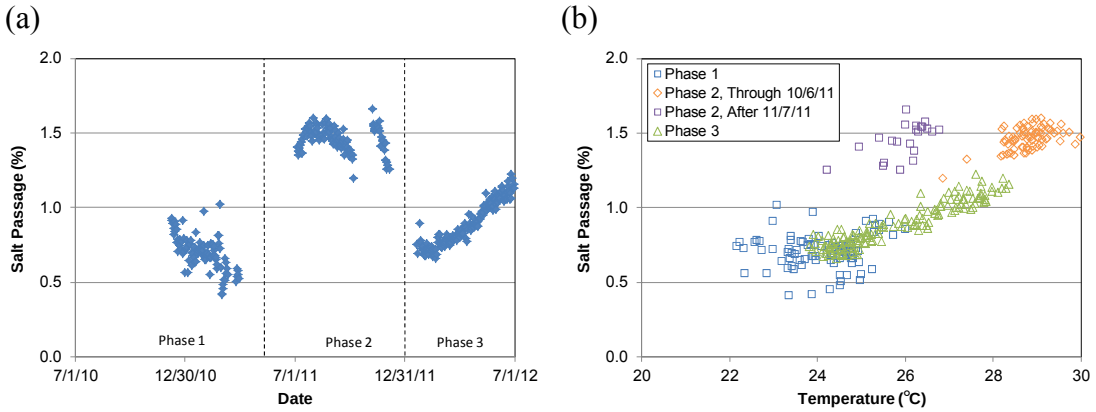
Figure 4-27. MBR-RO System: Temperature Data



Salt Passage

Figure 4-28 presents the salt passage data for the RO system on the MBR train. The salt passage decreased from 1.0 to 0.5% during Phase 1, and varied between 1.2% and 1.6% during Phase 2. In Phase 3, salt passage started at 0.7% but increased over time to approximately 1.2%. Some of these changes can be attributed to the changes in temperature, as shown by the correlation between temperature and salt passage (Figure 4-28b); the purple squares represent data taken after October 2011, when the MBR suffered membrane fiber damage and the turbidity was briefly >1 NTU in RO feed water.

Figure 4-28. MBR-RO System: Salt Passage Data as a Function of (a) Time and (b) Temperature



Feed Pressure and Specific Flux

Feed pressure data are presented in Figure 4-29, and normalized specific flux data are presented in Figure 4-30; note that the specific flux is directly related to the feed pressure, and decreases as feed water pressure increases. With the new membranes in Phases 1 and 3, the feed pressure increased from an initial value of approximately 140 psi to between 160 and 170 psi within the first two months of operation. At the same time, the specific flux decreased from approximately 0.12 to 0.09 to 0.10 gfd/psi. These trends are likely due to minor biological and organic fouling that inevitably occurs during the conditioning of the new membranes.

Figure 4-29. MBR-RO System Feed Pressure and Temperature

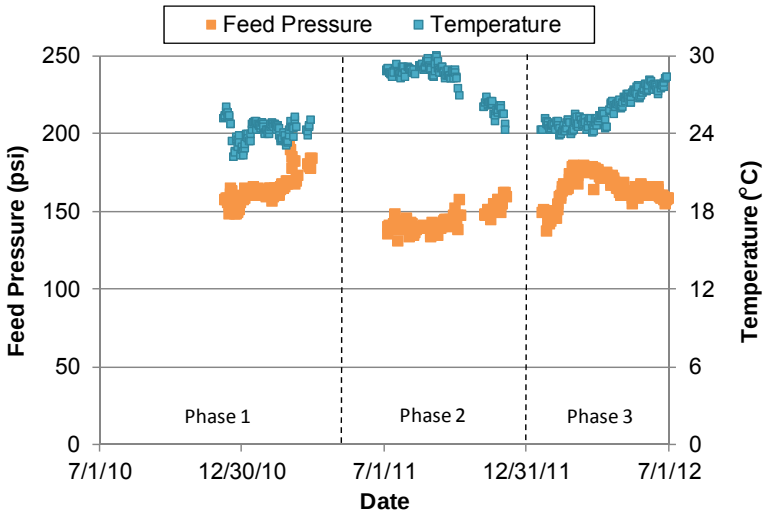
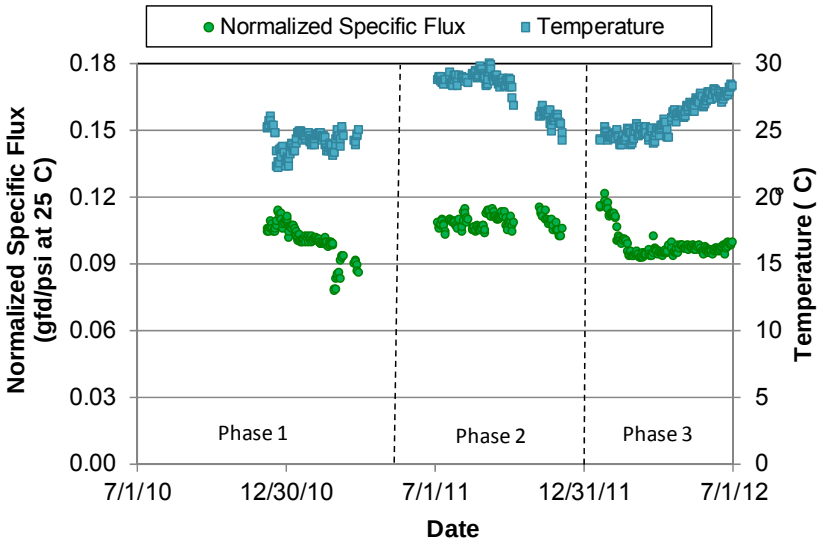


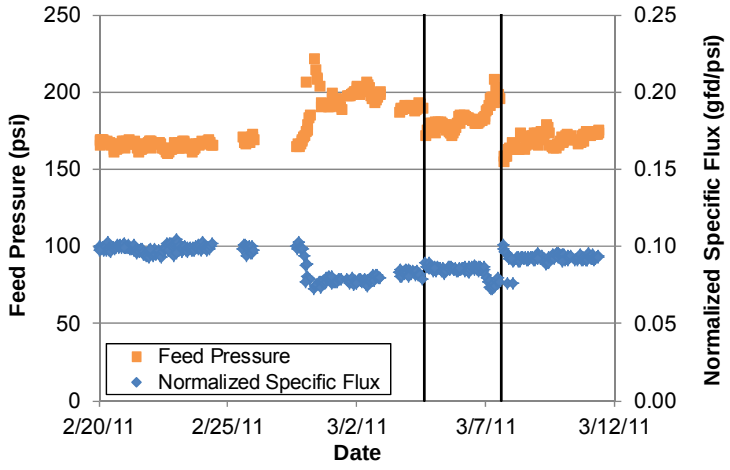
Figure 4-30. MBR-RO System Normalized Specific Flux



The membranes were thought to have reached steady state around January 2011 (Phase 1) and March 2012 (Phase 3). The system was generally stable during the steady-state periods of Phases 1 and 3, and during Phase 2, once temperature fluctuations are taken into account. Literature from the manufacturer indicates that feed pressure increases approximately 3% for every 1°C decrease in temperature (Hydranautics, 2011b). Thus the 5°C decrease during Phase 2 would be expected to increase the feed pressure by approximately 15%, or 21 psi, from 140 to 161 psi, while the 3°C increase during Phase 3 would be expected to decrease the feed pressure by approximately 9%, or 15 psi, from 170 to 155 psi. These predictions match the observed feed pressures well.

The only interruption to the steady state conditions occurred in February 2011 (Phase 1). Figure 4-31 presents hourly data for the feed pressure and normalized specific flux during this period; the temperature was relatively constant at approximately 24°C. The issues started just after midnight on February 26, 2011, when the MBR went into standby mode and stopped supplying water to the RO, which caused the RO unit to shut down as well. On February 27, 2011, both the MBR and RO were re-started. The feed pressure to the RO increased, and the specific flux decreased, which is typical at start-up; however, the values did not return to normal levels.

Figure 4-31. MBR-RO System: Feed Pressure and Normalized Specific Flux After MBR Shutdown on February 26, 2011. Vertical Lines on Graph Indicate Cleanings.



Consequently, a high pH cleaning was performed on March 4, 2011; details are provided in the next section. Immediately afterward, the feed pressure decreased slightly, from approximately 190 to 180 psi, and the specific flux increased slightly, from approximately 0.083 gfd/psi to 0.087 gfd/psi. However, on March 6, 2011, the feed pressure increased and the flux decreased again, so a second cleaning was performed the next day with an even higher pH solution (details provided in the next section). The second cleaning restored the feed pressure to the steady-state value of approximately 170 psi, and the specific flux to 0.09 gfd/psi, near the steady-state level.

4.2.2.4 Cleaning of the MBR-RO System

Three cleanings were performed on the MBR-RO system. The first two were prompted by problems following a shutdown of the RO unit, and the third was conducted between Phases 1 and 2. The first cleaning, on March 4, 2011, was based on manufacturer information (Hydranautics, 2011a) and used a sodium hydroxide solution, with a target pH of 9.5 in the feed water. Sodium hydroxide was dosed at 65 mg/L for 30 minutes. The feed to the RO unit was reduced to an average of 10.1 gpm, resulting in a feed pressure of 50 psi. The recovery throttle valve was opened all the way to promote flow across the membranes and scour the surfaces rather than pushing the flow through the membranes, which could force fouling material deeper into the membrane. Sulfuric acid and antiscalant were not dosed to the feed water during the cleaning.

The second cleaning was conducted on March 7, 2011, and was based on recommendations from King Lee Technologies. A sodium hydroxide solution was used, with a target pH of 11.5 in the feed water. Sodium hydroxide was dosed at 256 mg/L for approximately one hour. Similar to the previous cleaning, the feed to the RO unit was reduced, to an average of 10.7 gpm, and sulfuric acid and antiscalant were not dosed to the feed water.

The MBR-RO system was taken offline at the end of March 2011, in parallel with the UF-RO system. Similar to the UF-RO, two membrane elements were removed for autopsy: one lead element and one tail element. The elements that were removed for analysis were replaced with new ones after the RO system cleaning and prior to startup of Phase 2. The autopsy results are discussed in Section 4.3.

Following the extraction of the two membrane elements for autopsy, a cleaning of the membrane elements was performed on the RO system. The cleaning protocol and solutions were the same for the UF-RO and MBR-RO units. The RO system was initially cleaned with a high pH solution containing sodium tripolyphosphate and Na-EDTA. This solution was recommended to remove fouling by calcium sulfate, organic materials, divalent and trivalent cations, and metal ions. A second cleaning solution of citric acid was used to remove inorganic scale, metal oxides and hydroxides, and inorganic-based colloidal matter. The composition of each of the solutions was specified by the manufacturer (Hydranautics, 2011a).

4.3 AUTOPSY RESULTS FROM RO MEMBRANE ELEMENTS

Membrane autopsies were conducted on the lead and tail RO elements on both the UF and MBR trains at the end of Phase 1 (March 30, 2011), and on the lead and tail RO elements on the MBR train at the end of Phase 3 (June 30, 2011). The Phase 1 autopsy results are discussed in Section 4.3.1, and the Phase 3 autopsy results are discussed in Section 4.3.2. A summary of the findings are presented here; the full reports are provided in Appendix D.

4.3.1 Phase 1 Autopsies

The April 2011 autopsy found no visually-observable evidence of physical damage to the overall structure of the membranes. However, the productivity and permeability of the membranes were below manufacturer specifications, with the tail RO element from the UF train having the worst performance (66% and 43% below manufacturer specifications for productivity and permeability, respectively). In performance tests on the membrane elements and membrane sample coupons, salt rejection was 0.2-0.7 percentage points below the manufacturer specification.

Analyses of the membranes suggested both biological and inorganic fouling. Visual examinations, optical imaging, light microscope analysis, FTIR analysis, and SEM-EDS analysis indicated the presence of a thin layer of brown foulant material on the membrane surfaces of all membrane elements, with the tail RO element from the UF-RO system appearing to be most fouled. The foulant layers were composed of both organic and inorganic materials (with silicon, calcium, iron, and possibly sulfur as primary inorganic constituents). Biological examination revealed trace gram-positive bacteria in the lead RO element of the UF-RO system and possible fungi in the lead RO element of the MBR-RO system. Fujiwara test results indicated membrane halogenation (due to chlorine exposure) of all RO membrane elements, except for the tail element from the UF-RO system.

The foulant materials were removed through cleaning, and the RO membrane permeability was recovered to within or above manufacturer's specifications. However, salt passage (i.e., salt transport coefficient) was significantly elevated (by up to 527-741% and 148-601% above manufacturer specifications for the membrane samples from the UF-RO and MBR-RO systems, respectively. These results were consistent with the hypothesis of membrane fouling, along with halogen degradation of the membrane: when the foulant materials were removed, the permeability increased, but the damaged membrane allowed passage of salts. The autopsy results were also consistent with the observation that the specific fluxes increased after the membranes were cleaned; this trend was more apparent on the UF-RO membranes, which the autopsy showed to be more heavily fouled.

Damage to polyamide RO membrane is known to occur with exposure to free chlorine, while chloramines have minimal reactivity with the membranes (Causserand et al. 2008; Shemer and Semiat, 2011). However, research has shown that concentrations of ferrous iron as low as 0.05 mg/L, in combination with chloramines, can lead to enhanced oxidation and damage of polyamide RO membranes (Gabelich et al., 2004; Gabelich et al., 2005; Knoell, 2006). Total iron concentrations in the UF and MBR permeates were approximately 0.1 to 0.4 mg/L, and analysis of an MBR-RO permeate sample indicated that dominant species was ferrous iron. Because chloramines were applied to the effluent upstream of both RO units, this mechanism may have led to the observed degradation of the RO membranes in this project.

4.3.2 Phase 3 Autopsies

The June 2012 autopsy found no visually-observable evidence of physical damage to the overall structure of the membranes. The productivities of the lead RO elements from the UF-RO and MBR-RO systems were slightly lower than normal by 8% and 15%, respectively. However, performance testing of the lead element membrane sample coupons revealed normal water productivity levels, suggesting that fouling in the lead elements was localized and in the early stages. Tail element productivities were significantly below normal for both the UF-RO (by 41%) and MBR-RO (by 25%) systems. The performance of the tail elements was consistent with results from sample coupon performance testing. Performance testing also revealed normal or near normal levels of salt rejection (i.e., within 0.1% of expected normal performance).

Analyses of the membranes suggested both biological and inorganic fouling. Internal visual examinations, optical imaging, light microscope analysis, FTIR analysis, SEM-EDS, and CEI analysis indicated the presence of a thin layer of brown foulant material on the membrane surfaces of all membrane elements, with the tail RO element from the UF-RO system appearing to be most fouled. The foulant layers were primarily composed of metal silicates, clay, and iron-bearing granular material, as well as gram negative bacteria and amorphous organic material.

Fujiwara test results were negative for samples taken from the lead and tail RO elements of the UF-RO system, but were positive for membrane samples taken from the lead and tail RO elements of the MBR-RO system.

The foulant materials were removed through cleaning, and the RO membrane permeability was recovered to within or above manufacturer's specifications. Cleaning resulted in a slight elevation of the salt passage, however the levels remained within the manufacturer's specifications.

4.4 COMPARISON OF THE UF AND MBR TREATMENT TRAINS

4.4.1 UF vs MBR

Both the UF and MBR successfully treated secondary effluent from the JWPCP prior to RO treatment, and both were operated successfully at a flux of approximately 20 gfd. The UF had the advantage of simplicity over the MBR: it had a smaller footprint, and because it lacked biological treatment, it required fewer components, and less process air and energy. The UF also recovered from process upsets more quickly; days or weeks were sometimes required to bring the MLSS concentration in the MBR back to the desired value after an upset.

However, the UF was prone to fouling and was more sensitive than the MBR to changes in the JWPCP secondary effluent water quality due to events such as rain storms. The greater resistance to fouling by the MBR membranes may be due to biological activity, which may attenuate and degrade some organic foulants in the secondary effluent, or could be due to the operation and cleaning cycles on the MBR, in which the membranes are designed to operate in the concentrated environment of mixed liquor. As a practical implication of this difference, the MBR may require less cleaning maintenance than the UF, particularly toward the end of the membrane life. In addition, the membrane life may be significantly longer for the MBR; in this study, the UF membrane life was only two years, much less than the expected lifetime of five years. More work is needed to ensure that the MBR membranes continue to perform effectively over the long term.

4.4.2 RO Units

The most striking difference in operations between the two RO units was in the use of chemicals. The sulfuric acid doses for the UF treatment train were between 97 and 162 mg/L, whereas the doses used for the MBR treatment train were between 3 and 53 mg/L. These differences are due to the nitrification reaction that occurs in the MBR, which produces acid and consumes alkalinity in the water, thereby reducing the buffering capacity and the scaling potential of the effluent. The cost savings from the reduced chemical use could be a significant advantage for the MBR-RO treatment process over the UF-RO treatment process.

With respect to the performance data, the two RO units had similar values and trends for the feed pressure and specific flux. The differential pressure increased in the UF-RO, but not the MBR-RO during Phase 1; no increases were observed in either RO unit during Phases 2 and 3. The salt passage values were slightly lower in the MBR-RO than the UF-RO. More data are needed to determine whether these observed differences in the differential pressure and salt passage are reproducible or significant.

4.5 SUMMARY

4.5.1 UF

For this project, the Siemens UF unit was equipped with PVDF membrane elements and used to treat a non-nitrified, secondary-effluent, produced by a high-purity oxygen activated sludge process operating at low SRT (< 3 days). The unit performed reliably and provided acceptable RO pretreatment for a period of approximately two years. In Phases 1 and 2 of the study, membrane cleaning intervals were acceptable with CIPs required no more frequently than about every four weeks and CEBs not needed more than weekly. In Phase 3 of the study, however, the necessary CIP frequency increased to about every two weeks, and daily CEBs were required. At the end of the two-year study period, the PVDF membranes appear to be permanently fouled, with irreversible fouling becoming evident in the last six months of operation. Based on the results of this study, the tested Siemens PVDF membranes with a 0.04 micron pore size may not be appropriate for reuse applications of the JWPCP secondary effluent.

This study has clearly demonstrated the value of long-term, site-specific, comparative evaluations with membranes of various materials (polypropylene, Teflon, PVDF, etc.): some performance issues in this project were only apparent during the winter, and major fouling occurred only after approximately 1.5 years. For any future evaluation of UF membrane performance, the following are recommended:

- Strainer equipment for use upstream of the MF or UF equipment should be evaluated. The recommended 30 and 40 mesh basket strainers did not seem adequate in this project.
- Maximum cleaning intervals should be established and maintained from the beginning of the study period. In this study, the membranes were initially cleaned only when warranted by high TMP values; this mode of operation may have allowed particles to become permanently trapped in the membrane matrix. The interval can be increased as warranted by performance later.
- Particle size distributions should be routinely measured in both the feed water and the filtrate, to assist in evaluating membrane loading and performance.

4.5.2 UF-RO

The UF-RO was successfully operated for approximately two years during this project. During Phase 1, an increase in the differential pressure suggested deposition of material in the channels that connect the RO feed and concentrate; however, no further deposition occurred in Phases 2 or 3. Performance was affected by water temperature, with increasing temperature causing lower feed pressures and greater salt passage.

The autopsy results of the Phase 1 membranes indicated both fouling and chlorine degradation of the membranes. The fouling reduced the flux through the membranes, and the cleaning conducted after Phase 1 removed the foulant(s), thereby increasing both the permeability and the salt passage. Consistent with the autopsy, the specific flux increased after cleaning of the pilot-scale RO membranes. The autopsy of the Phase 3 membranes revealed fouling, but no membrane damage.

Optimization of the RO operations resulted in a 40% decrease in the use of sulfuric acid from Phase 1 to Phase 2. In Phase 3, new RO membranes were used and operations were altered to minimize fouling. The resulting sulfuric acid use was 16% lower than in Phase 1. Fouling

appeared to be controlled, but a much longer operational time would be needed to ensure that the optimized operations in Phase 3 mitigated the longer term or seasonal fouling that was observed during Phase 1.

4.5.3 MBR

The MBR was successfully operated for 1.5 years during this project, and provided good quality water for the downstream RO unit, with the exception of one fouling event. This event was most likely due to damaged membrane fibers; the age of the membranes (nine years old at the time of the event) may have been a contributing factor in the damage. In the third phase, with the newest membranes available from GE, the operating flux of the MBR was similar to that of the UF. Some fouling did occur, but in many cases, the effects were temporary. In some cases, the operation of the MBR was altered to decrease the backpulse cycle time for a short time; this change appeared to restore normal operations. The most intensive fouling occurred in Phase 2, when the flux was increased from 10 to 15 gfd, with a relatively low MLSS concentration, possibly because the MLSS was insufficient to treat the foulants in the mixed liquor and/or because the membranes were near the end of their design life.

4.5.4 MBR-RO

The MBR-RO was successfully operated for 1.5 years during this project. The differential pressure was constant for the duration, with no signs of material depositing in the channels that connect the RO feed and concentrate. Near the end of Phase 1, an unexpected MBR shutdown resulted in a RO system shutdown, and a subsequent increase in feed pressure and decrease in normalized specific flux, presumably due to fouling. Cleaning with a sodium hydroxide solution at pH 11.5 restored the membranes to near normal operations.

MBR-RO performance was affected by water temperature, with increasing temperature causing lower feed pressures and greater salt passage. During Phase 2, normalized salt passage also increased after damage of the MBR membranes increased turbidity in the feed water and caused a one-month shutdown of the RO system.

Based on the autopsy results, the membranes appeared to be both fouled and damaged during Phase 1. The fouling reduced the flux through the membranes, and the cleaning conducted after Phase 1 removed the foulant(s), thereby increasing both the permeability and the salt passage. The membrane damage on the MBR-RO membrane appeared to be less severe than on the UF-RO membrane, based on appearance and the increase in salt passage during the autopsy, and the increase in flux in the pilot-scale unit after cleaning was also smaller than for the UF-RO system.

Optimization of the RO operations resulted in a 95% decrease in the use of sulfuric acid from Phase 1 to Phase 2. In Phase 3, new RO membranes were used and operations were altered to minimize fouling. The resulting sulfuric acid use was 53% lower than in Phase 1. Fouling appeared to be controlled, but a much longer operational time would be needed to ensure that the optimized operations in Phase 3 mitigated the fouling effects that were observed during the occasional MBR shutdowns in Phases 1 and 2.

5. WATER QUALITY RESULTS: GENERAL PARAMETERS

This chapter covers results for the general water quality parameters, excluding the nitrosamines, 1,4-dioxane, and Title 22+ samples, which are covered in Chapters 6 and 7. Tables 5-1 and 5-2 present a summary of the water quality data for the UF and MBR trains, respectively. Each of these analytes is discussed in more detail in the following sections, which are grouped by removal mechanisms. Section 5.1 discusses compounds removed with solids, Section 5.2 discusses compounds affected by biological activity in the MBR, and Section 5.3 discusses compounds removed only by RO. Section 5.4 covers pH, temperature, and TSS.

For all graphs in this chapter, the three operational phases are divided by dashed vertical lines in the graphs, concentration data are plotted on a logarithmic scale unless otherwise noted, percent removals are plotted on a linear scale, and the following shorthand notations are used:

- Sec Eff: secondary effluent,
- UF-RO: RO unit on the UF train
- UF: UF filtrate,
- UF Removal: removal across the UF unit,
- RO (UF): RO permeate on the UF train,
- RO (UF) Removal: removal by the RO unit alone on the UF train,
- UF+RO Removal: removal by the combination of the UF and RO units,
- MBR-RO: RO unit on the MBR train
- MBR: MBR permeate,
- MBR Removal: removal across the MBR unit,
- RO (MBR): RO permeate on the MBR train,
- MBR (RO) Removal: removal by the RO unit alone on the MBR train, and
- MBR+RO Removal: removal by the combination of the MBR and RO units.

For all analyses, each sample with a concentration below the reporting limit was conservatively assigned the reporting limit as a concentration, e.g., concentrations < 0.01 mg/L were assumed to be 0.01 mg/L. Removals could not be calculated accurately for samples where the effluent concentration was below the reporting limit. For example, a concentration decrease from 2 mg/L to 1 mg/L would be interpreted as 50% removal on a graph or in statistical calculations, but the "true" removal could be anywhere from 50-100%. Because these values are susceptible to misinterpretation, they were omitted from the statistical analyses and from the graphs presented in this chapter. Note that using this method under-predicts removals, because the lowest effluent concentrations (corresponding to the highest removal values) were excluded from the analyses. Statistical tests in this chapter were conducted with a significance level of 0.01, i.e., tests with p-values <0.01 were interpreted as being statistically significant.

Appendix E contains additional water quality data and analysis, including tables with detailed statistics for each of the water quality parameters. In addition, selected parameters were measured in AOP experiments; the effects of AOP on these analytes were minor and are therefore not included within this chapter, but are instead discussed in Appendix E. In some of these AOP experiments, pharmaceuticals, personal care products, endocrine disrupting compounds, and other wastewater indicators were also measured; these compounds were seldom detected in the RO permeate and are discussed in Appendix E. Finally, differences in RO performance over time were observed for most parameters. Although the differences were statistically significant, they were generally too small to be of practical importance, and are instead presented in Appendix E; only larger differences are discussed within this chapter.

Table 5-1. Water Quality Data for the UF Train: Minimum, Median, and Maximum Values

		Secondary Effluent*			UF Filtrate			RO Permeate			RO Concentrate		
Parameter	**Unit**	**Min**	**Med.**	**Max**	**Min**	**Med.**	**Max**	**Min**	**Med.**	**Max**	**Min**	**Med.**	**Max**
Alkalinity, Total	mg/L $CaCO_3$	337	**373**	401	334	**372**	395	14	**20**	25	1130	**1545**	1680
Aluminum	µg/L	18	**24**	35	<10	**<10**	18	<10	**<10**	11	43	**50**	68
Ammonia	mg N/L	22	**37**	49	25	**36**	49	1.0	**1.9**	2.6	209	**217**	264
Barium	µg/L	87	**130**	199	77	**112**	172	<0.5	**<0.5**	2.8	535	**718**	783
Boron	mg/L	0.74	**0.87**	1.1	0.75	**0.86**	1.1	0.50	**0.64**	0.77	1.7	**2.1**	2.5
Calcium	mg/L	63	**72**	82	63	**72**	82	<0.02	**0.04**	0.07	404	**462**	489
Chloride	mg/L	398	**465**	554	414	**482**	564	5.3	**8.7**	17	2710	**2,940**	3130
COD, Soluble	mg/L	20	**45**	73	--	--	--	--	--	--	--	--	--
COD, Total	mg/L	29	**53**	82	--	--	--	--	--	--	118	**235**	326
Fluoride	mg/L	0.9	**1.2**	3.0	0.9	**1.2**	3.1	<0.10	**0.14**	0.34	<0.10	**6.5**	18
Iron	mg/L	0.1	**1.3**	2.6	0.1	**0.1**	0.4	<0.02	**<0.02**	<0.02	0.62	**0.69**	1.1
Magnesium	mg/L	20	**23**	29	20	**24**	28	<0.02	**<0.02**	<0.02	141	**154**	167
Nitrate	mg N/L	<0.10	**<0.10**	<0.10	<0.10	**<0.10**	<0.10	<0.10	**<0.10**	<0.10	<0.10	**0.12**	0.32
Nitrite	mg N/L	<0.01	**0.03**	0.07	<0.01	**0.04**	0.07	<0.01	**<0.01**	<0.01	0.13	**0.24**	0.37
pH	--	6.9	**7.2**	7.5	7.1	**7.3**	7.5	5.2	**5.5**	6.3	7.0	**7.1**	7.3
Phosphate	mg P/L	0.26	**0.49**	0.85	<0.13	**0.25**	0.56	<0.13	**<0.13**	<0.13	0.36	**1.52**	2.76
Potassium	mg/L	19	**21**	24	19	**21**	24	0.44	**0.69**	0.92	120	**129**	146
Silica	mg SiO_2/L	22	**25**	28	22	**25**	30	0.25	**0.51**	1.1	132	**157**	163
Sodium	mg/L	340	**407**	457	35	**415**	471	8.9	**13**	20	2,400	**2,530**	2,790
Strontium	µg/L	628	**746**	895	620	**741**	881	<0.20	**0.29**	0.66	4,000	**4,820**	5,140
Sulfate	mg/L	180	**234**	276	182	**232**	284	<0.50	**<0.50**	0.54	1,780	**2,270**	2,550
TDS	mg/L	1,170	**1,400**	1570	1,210	**1,420**	1,570	15	**36**	59	8,700	**8,830**	9,670
TKN	mg N/L	23	**39**	51	26	**38**	50	1.0	**2.0**	2.8	217	**228**	271
TOC	mg/L	13	**16**	20	11	**13**	15	<0.5	**<0.5**	0.9	74	**81**	92
TSS	mg/L	4	**10**	23	--	--	--	--	--	--	--	--	--
Turbidity	NTU	1.9	**3.2**	5.6	<0.1	**0.1**	1.4	--	--	--	--	--	--

*Minimum, median, and maximum values were calculated for the phase dates shown in Section 1.5. Because these dates for the UF and MBR trains are slightly different, the secondary effluent values in Tables 5-1 and 5-2 are also different.

Table 5-2. Water Quality Data for the MBR Train: Minimum, Median, and Maximum Values

		Secondary Effluent*			MBR Permeate			RO Permeate			RO Concentrate		
Parameter	**Unit**	**Min**	**Med.**	**Max**	**Min**	**Med.**	**Max**	**Min**	**Med.**	**Max**	**Min**	**Med.**	**Max**
Alkalinity, Total	mg/L $CaCO_3$	337	**373**	401	47	**100**	125	<5	**5**	6	335	**478**	524
Aluminum	µg/L	18	**24**	33	<10	**<10**	17	<10	**<10**	<10	29	**30**	51
Ammonia	mg N/L	22	**37**	49	<1.0	**<1.0**	1.9	<1.0	**<1.0**	<1.0	1.8	**2.4**	11
Barium	µg/L	107	**134**	199	97	**118**	182	<0.5	**<0.5**	1.7	585	**724**	777
Boron	mg/L	0.74	**0.89**	1.1	0.07	**0.88**	1.1	0.39	**0.62**	0.77	1.7	**2.4**	3.1
Calcium	mg/L	63	**73**	82	63	**72**	84	<0.02	**0.03**	0.07	377	**428**	470
Chloride	mg/L	398	**475**	554	405	**481**	559	2.6	**5.8**	14	2,730	**2,820**	3,060
COD, Soluble	mg/L	20	**47**	73	--	--	--	--	--	--	--	--	--
COD, Total	mg/L	34	**55**	82	16	**32**	66	--	--	--	79	**222**	225
Fluoride	mg/L	0.9	**1.2**	3.0	1.0	**1.2**	3.5	<0.10	**<0.10**	1.1	6.3	**7.1**	20
Iron	mg/L	0.1	**1.4**	2.6	0.1	**0.1**	0.2	<0.02	**<0.02**	<0.02	0.5	**0.6**	0.8
Magnesium	mg/L	20	**24**	29	20	**24**	28	<0.02	**<0.02**	0.03	126	**143**	163
Nitrate	mg N/L	<0.10	**<0.10**	<0.10	23	**39**	55	<0.10	**2.8**	5.2	199	**218**	231
Nitrite	mg N/L	<0.01	**0.03**	0.06	<0.01	**0.02**	0.08	<0.01	**<0.01**	<0.01	0.03	**0.12**	0.17
pH	-	6.9	**7.1**	7.4	6.6	**7.0**	7.5	5.4	**5.6**	6.6	7.0	**7.2**	7.6
Phosphate	mg P/L	0.26	**0.51**	0.86	<0.13	**0.29**	0.73	<0.13	**<0.13**	<0.13	0.23	**1.5**	2.4
Potassium	mg/L	19	**21**	24	19	**21**	23	0.27	**0.58**	0.96	118	**127**	140
Silica	mg SiO_2/L	22	**25**	28	22	**25**	27	0.13	**0.37**	1.4	138	**147**	152
Sodium	mg/L	340	**414**	457	335	**419**	476	5.7	**11**	21	2,230	**2,430**	2,520
Strontium	µg/L	628	**757**	895	608	**748**	924	<0.20	**0.23**	0.68	3,750	**4,540**	5,370
Sulfate	mg/L	180	**240**	276	180	**240**	281	<0.50	**<0.5**	0.54	1,220	**1,560**	1,740
TDS	mg/L	1,170	**1,410**	1,570	1,280	**1,510**	1,680	14	**34**	76	7,250	**8,620**	9,210
TKN	mg N/L	23	**40**	51	<1.0	**<1.0**	<1.0	<1.0	**<1.0**	<1.0	<1.0	**<1.0**	<1.0
TOC	mg/L	13	**16**	20	7.7	**9.2**	12	<0.5	**<0.5**	<0.5	55	**58**	63
TSS	mg/L	4	**11**	23	--	--	--	--	--	--	--	--	--
Turbidity	NTU	2.0	**3.4**	5.6	<0.1	**0.1**	0.8	--	--	--	--	--	--

*Minimum, median, and maximum values were calculated over all three phases shown in Section 1.5. Because the phase dates for the UF and MBR trains are slightly different, the secondary effluent values in Tables 5-1 and 5-2 are also different.

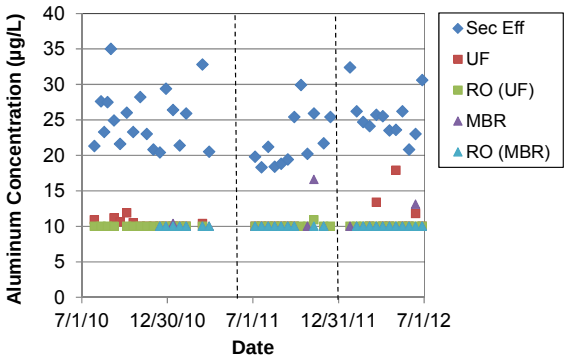
5.1 COMPOUNDS REMOVED WITH SOLIDS

Analytes that were removed with solids (turbidity, aluminum, iron, and barium) are discussed in this section. These compounds were removed to a similar degree by the UF and the MBR, which were equipped with membranes of the same nominal pore size. TOC was also partially removed by the UF, but was affected by biological activity and is discussed in Section 5.2.

5.1.1 Aluminum

Aluminum results are presented in Figure 5-1; note that the concentrations on the y-axis are on a linear scale. Concentrations were always below the target concentration of 50 µg/L, even in the secondary effluent. The UF and MBR generally removed aluminum to below the JWPCP Lab reporting limit of 10 µg/L; RO permeate concentrations were always below the reporting limit. Due to the low concentrations, removals could not be accurately calculated for any of the unit processes, and no comparisons were made between the two trains or over time.

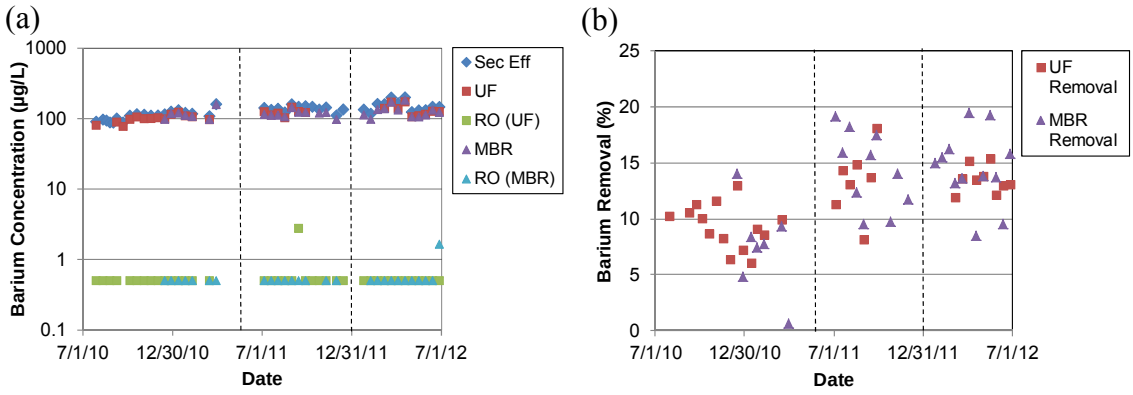
Figure 5-1. Aluminum Concentrations



5.1.2 Barium

The barium concentrations in the secondary effluent increased statistically significantly from Phase 1 to 2, but were always well below the target of 1,000 µg/L (Figure 5-2). Both the UF and MBR removed approximately 10-15% of the barium in the secondary effluent, and the RO removed it to below reporting limits. Median removals by the UF and MBR increased slightly but significantly, from 8-9% in Phase 1 to 14-15% in Phases 2 and 3. The reason for the improved removals by the UF and MBR in Phases 2 and 3 is unknown; however, the difference has no practical importance, given the high levels of removal in the RO units.

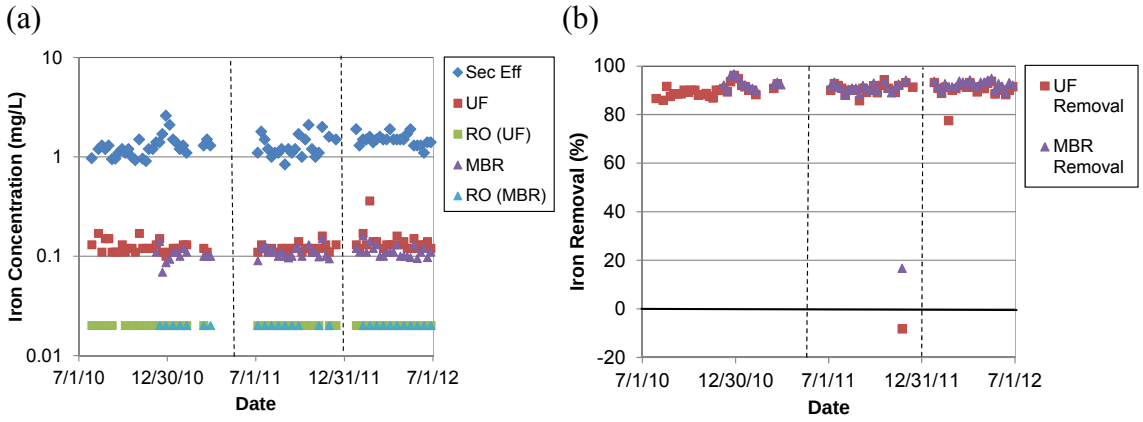
Figure 5-2. Barium Results. (a) Concentrations and (b) Removals



5.1.3 Iron

Figure 5-3 shows the results for iron. Concentrations typically ranged from 0.8 to 2.6 mg/L in the secondary effluent, and were generally below the target of 0.3 mg/L in the UF filtrate and MBR permeate. The performance of the UF and MBR were similar to each other and relatively constant over time, with median removals of 90-95%. RO removed the remaining iron to below the reporting limit of 0.02 mg/L.

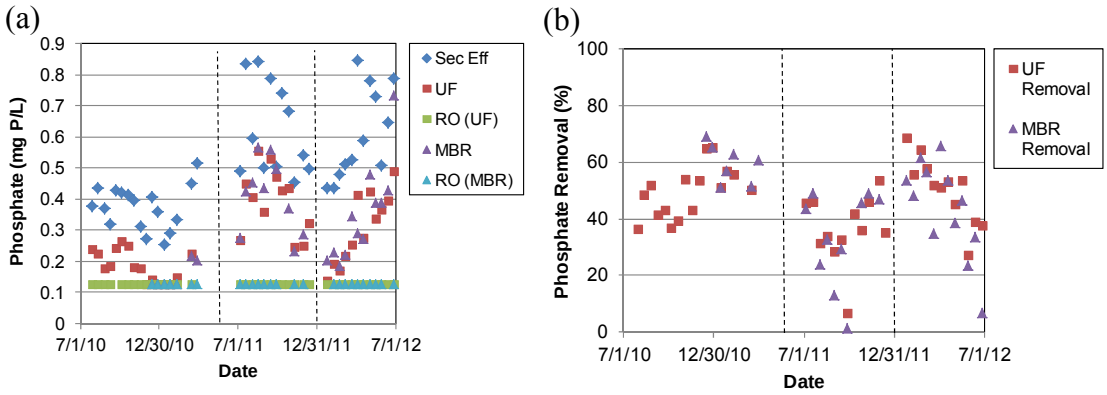
Figure 5-3. Iron Results. (a) Concentrations and (b) Removals



5.1.4 Phosphate

Figure 5-4 presents the results for phosphate; note that the concentrations on the y-axis of Figure 5-4a are on a linear scale. Concentrations in the secondary effluent ranged from approximately 0.2 to 0.9 mg P/L, and appeared to follow a seasonal trend in 2011 and 2012 but not in 2010, with higher concentrations during the summer. As a result, the secondary, UF, and MBR effluent concentrations were significantly lower in Phase 1 than in Phases 2 or 3. The UF and MBR removed approximately 50% of the phosphate in the water, and no significant differences were observed between the two units. Phosphate was removed to below reporting limits by the RO units; no target was set for effluent phosphate concentrations.

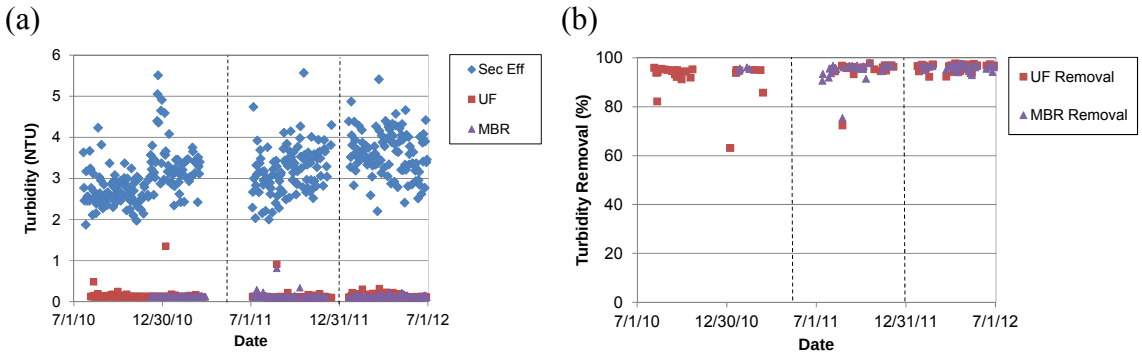
Figure 5-4. Phosphate Results. (a) Concentrations and (b) Removals



5.1.5 Turbidity

Turbidity results are presented in Figure 5-5; note that the concentrations on the y-axis in Figure 5-5a are on a linear scale. Turbidity values ranged from approximately 1.9 to 5.6 NTU in the secondary effluent, with the average values increasing statistically significantly from Phase 1 to Phase 2, and again from Phase 2 to Phase 3. The UF and MBR always removed turbidity to below the target of 2 NTU. The performance of the UF and MBR were similar to each other and relatively constant over time, with median removals of 95-97%.

Figure 5-5. Turbidity Results. (a) Concentrations and (b) Removals



5.2 BIOLOGICAL TREAMENT BY THE MBR

Biological activity in the MBR affected several constituents in the pilot-scale system: the nitrogen species (ammonia, TKN, nitrate, and nitrite), alkalinity, COD, and TOC. The MBR was operated under nitrifying conditions, so ammonia and TKN were oxidized to nitrate, with nitrite as an intermediate. Alkalinity was consumed during the nitrification process, and TOC and COD were consumed by biological activity.

5.2.1 Ammonia and TKN

Ammonia and TKN results are presented in Figures 5-6 and 5-7. Ammonia and TKN concentrations in the secondary effluent increased slightly but statistically significantly, from a median concentration of 36 mg N/L ammonia in Phases 1 and 2 (38 mg N/L TKN), to 40 mg N/L in Phase 3 (42 mg N/L TKN). The UF provided negligible removal of either analyte, while the MBR generally reduced concentrations down to the reporting limit of 1 mg N/L. Ammonia and TKN removals for MBR-RO are not shown in Figures 5-6b and 5-7b because the concentrations in the RO effluent were generally below reporting limits.

Figure 5-6. Ammonia Results. (a) Concentrations and (b) Removals

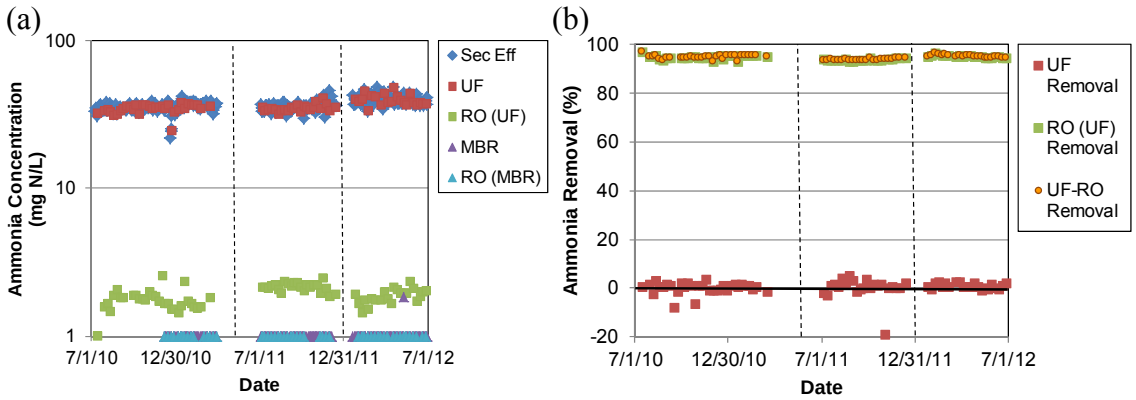
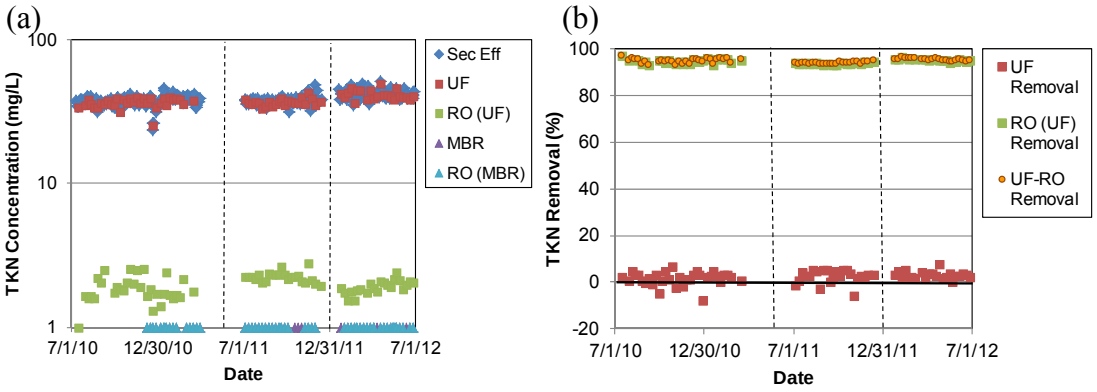


Figure 5-7. TKN Results. (a) Concentrations and (b) Removals

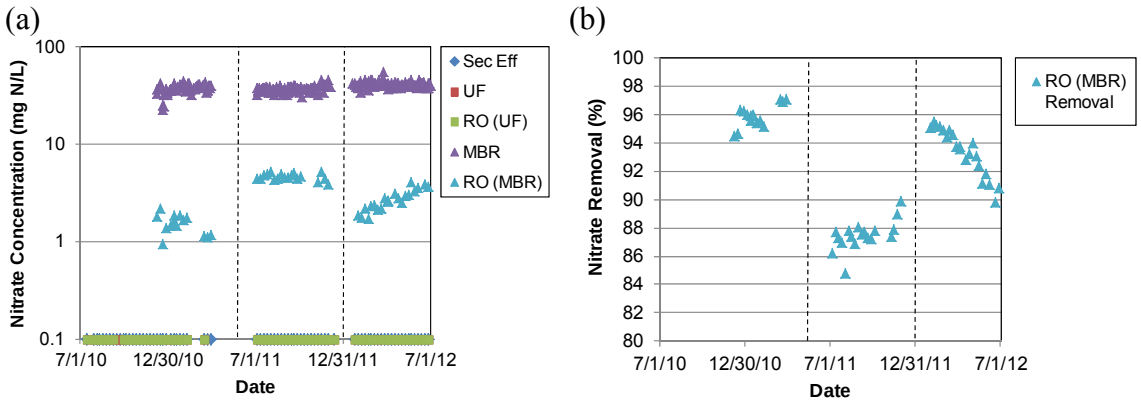


The performance of the UF-RO was significantly worse during Phase 2 (See Appendix E for details), but the effects were small: removals were approximately 95% for ammonia and TKN in all three phases, and permeate concentrations were generally between 1.0 and 2.8 mg N/L, regardless of temperature. There were no specific effluent targets for ammonia or TKN, although the total nitrogen target was 10 mg N/L. The UF-RO permeate (which had low nitrate and nitrate concentrations, as discussed in Sections 5.2.2 and 5.2.3) could meet this limit. The ability of the MBR-RO to meet this limit is discussed in the next section.

5.2.2 Nitrate

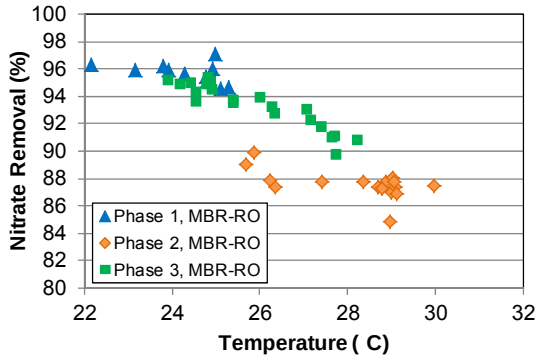
Nitrate results are shown in Figure 5-8. Nitrate levels in the secondary effluent, UF filtrate, and UF-RO permeate were consistently below the reporting limit of 0.1 mg N/L. The MBR typically nitrified most of the ammonia nitrogen to nitrate. As the median secondary ammonia levels increased from 36 mg N/L in Phases 1 and 2 to 40 mg N/L in Phase 3, median nitrate levels in the MBR permeate increased from 37 mg N/L during Phases 1 and 2 to 41 mg N/L during Phase 3.

Figure 5-8. Nitrate Results. (a) Concentrations and (b) Removals



For the RO unit on the MBR train, permeate concentrations and removals varied significantly over time. The correlation between temperature and RO removals can be seen in Figure 5-9. Nitrate removals in the MBR-RO permeate decreased from 96% in the winter to as low as 85% during the warmer months, and concentrations increased from approximately 2 to 5 mg N/L. The observed removals by the RO membranes during Phase 2 were slightly lower than expected from the temperature trend, which may reflect chlorine degradation of the RO membranes, as discussed in Section 4.3. Despite the worse performance in Phase 2, the target concentration of 10 mg N/L total nitrogen was achieved. However, the temperature effect was relatively large and could be an important factor in RO design for some facilities.

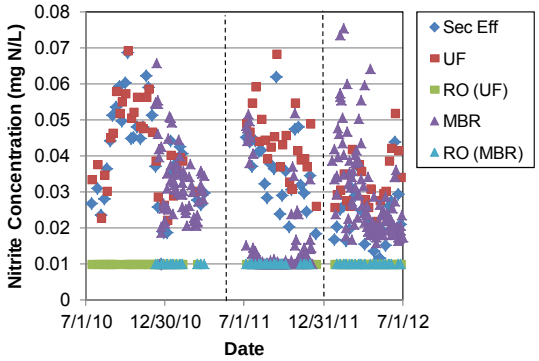
Figure 5-9. Temperature Effects on Removal of Nitrate by RO



5.2.3 Nitrite

Nitrite results are shown in Figure 5-10; note that the y-axis on Figure 5-10a is on a linear scale. Concentrations in the secondary, UF, and MBR samples varied from < 0.01 to 0.08 mg N/L, well below the target of 1 mg/L; due to the low concentrations, removals across the UF and MBR were not calculated. RO removed nitrite to below the reporting limit of 0.01 mg/L.

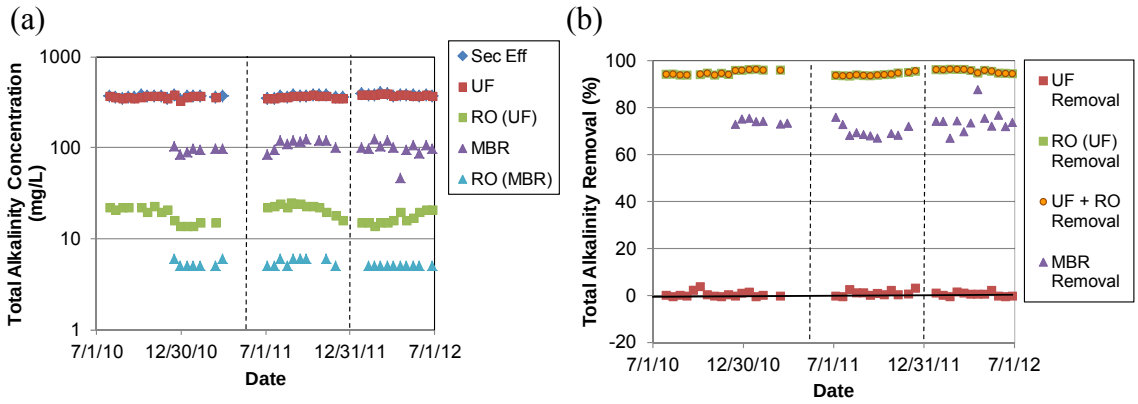
Figure 5-10. Nitrite Results.



5.2.4 Alkalinity

Results for total alkalinity are shown in Figure 5-11. Secondary effluent concentrations ranged from approximately 340 to 400 mg/L as $CaCO_3$, and increased slightly but statistically significantly in Phase 3. The UF had no effect on alkalinity, but the MBR decreased alkalinity levels by approximately 70-75%. This decrease in alkalinity corresponded to a theoretical ammonia consumption of 38 mg N/L of ammonia (Tchobanoglous et *al.*, 2003), which matched the observed decrease in ammonia (Section 5.2.1). The lower alkalinity levels in the MBR-RO permeate (median concentration < 5 mg/L as $CaCO_3$, compared to 20 mg/L as $CaCO_3$ in the UF-RO permeate) reduced the sulfuric acid requirements for the MBR-RO (Section 4.4.2) and may have improved the performance of the AOP, thereby reducing the hydrogen peroxide dose required to meet treatment targets (Section 6.4.3).

Figure 5-11. Total Alkalinity Results. (a) Concentrations and (b) Removals



Removals by the UF-RO correlated with temperature (Appendix C), but the effect was small: the UF-RO removed approximately 95% of the alkalinity, and permeate concentrations were approximately 20 mg/L as $CaCO_3$ throughout the study. There was no target for the alkalinity concentration.

5.2.5 COD

Results for total and soluble COD in secondary effluent samples are plotted in Figure 5-12. For the UF train, the median soluble COD level was 8 mg/L (15%) lower than the total COD level of 53 mg/L. Filtration through the UF was expected to remove particulate COD, leaving approximately 45 mg/L of COD in the UF filtrate.

Total COD results are shown in Figure 5-13; note that total COD samples were only collected for the secondary effluent and MBR permeate, and concentrations are plotted on a linear scale. The total COD concentrations in the secondary effluent ranged from 34 to 82 mg/L, and increased significantly in Phase 3. The median concentration in the secondary effluent was approximately 55 mg/L in Phases 1, 2, and 3, and the MBR removed approximately 23 mg/L (40%). Similar to the UF, the MBR was expected to remove the 8 mg/L of particulate COD from the secondary effluent. The remaining 15 mg/L was presumably removed by biological activity in the reactor, indicating that approximately 25% of the total COD (approximately one-third of the soluble COD) in the secondary effluent was biodegradable. There was no target concentration for COD.

Figure 5-12. Comparison of Total and Soluble COD

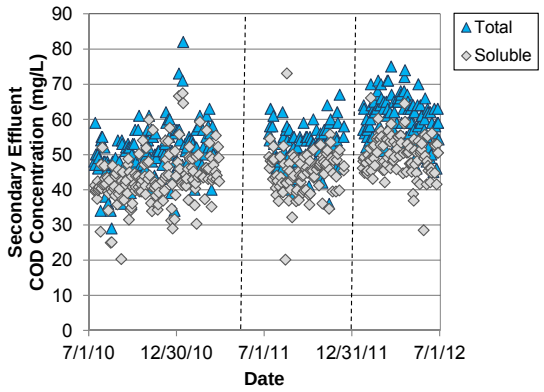
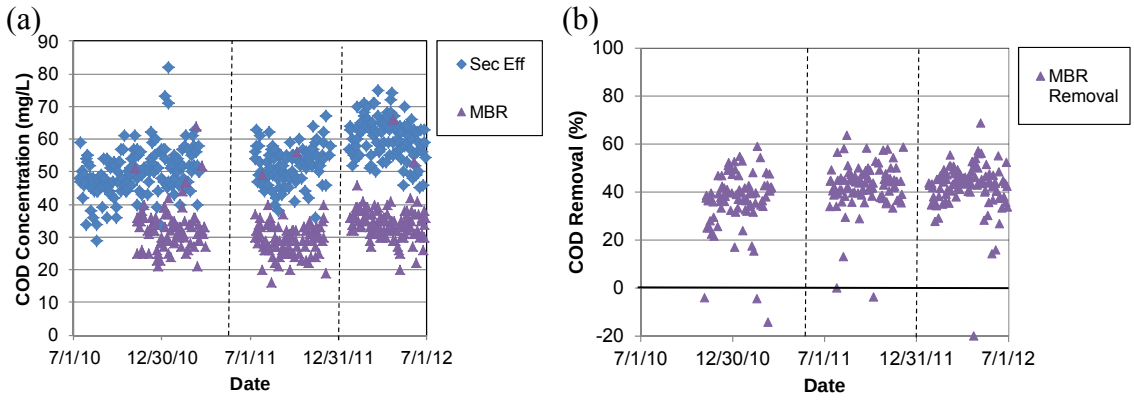


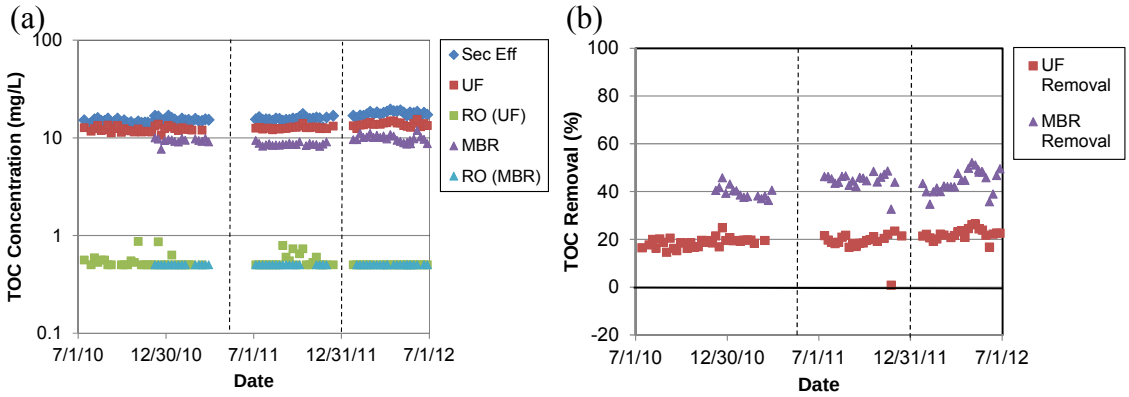
Figure 5-13. Total COD. (a) Concentrations and (b) Removals



5.2.6 TOC

TOC results are shown in Figure 5-14. Concentrations in the secondary effluent ranged from approximately 13 to 20 mg/L, and increased significantly from Phase 1 to Phase 2, and again in Phase 3. Approximately 20% of the TOC in the secondary effluent was likely associated with solids and filtered out by the UF. The MBR removed an additional 20% (total of 40% removal), due to biological activity in the reactor. The RO units generally removed TOC down to the reporting limit of 0.5 mg/L, which was also the target concentration. However, the UF-RO permeate concentrations were occasionally greater than the target concentration of 0.5 mg/L during Phases 1 and 2; the MBR-RO permeate consistently met the TOC target.

Figure 5-14. TOC. (a) Concentrations and (b) Removals



5.3 CONSTITUENTS REMOVED ONLY BY RO

This section discusses the analytes that were removed only by the RO units. Because the UF or MBR was ineffective for removal of these parameters, only the RO performance is discussed in the following sections. The constituents are organized in alphabetical order: boron, calcium, chloride, fluoride, magnesium, potassium, silica, sodium, strontium, sulfate, and TDS.

5.3.1 Boron

Boron results are plotted in Figure 5-15; the y-axis on Figure 5-15a is on a linear scale. Secondary effluent concentrations ranged from approximately 0.7 to 1.1 mg/L, and increased significantly between Phases 1 and 2.

Median removals by the RO units in the three operational phases varied from 17 to 44%, with significantly worse performance in Phase 2 (Figure 5-16a). As shown in Figure 5-16b, removals correlated with temperature, and decreased from approximately 45% at 24°C to 15% at 29°C; concentrations increased from as low as 0.4 mg/L in the early months of 2011 to 0.8 mg/L in the summers of 2011 and 2012. The target concentration for boron was 0.5 mg/L, and was only achieved in Phase 1 for the MBR-RO (operated during the winter months, December 2010 to March 2011). During the winter of 2011-2012, the increased removals in the colder weather were offset by an increase in boron concentrations in the RO influent stream. Thus, both temperature and influent composition impacted the boron concentrations in the RO permeate.

Figure 5-15. Boron Results. (a) Concentrations and (b) Removals

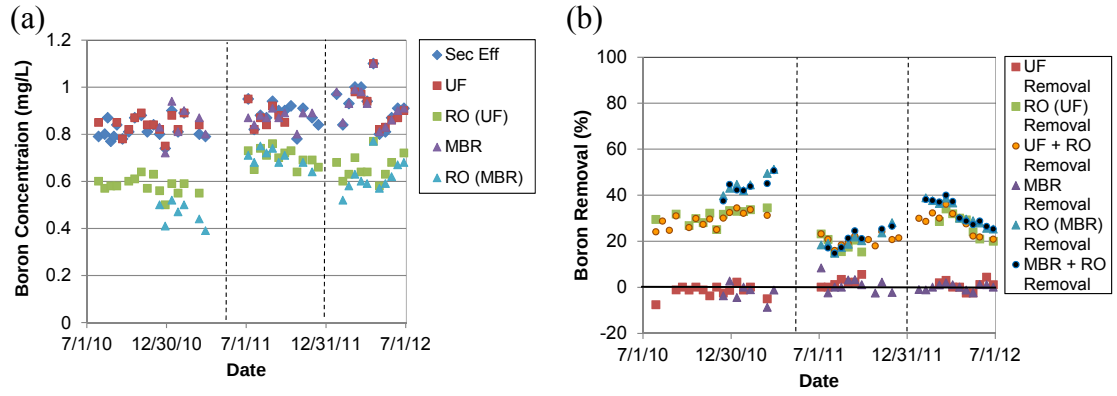
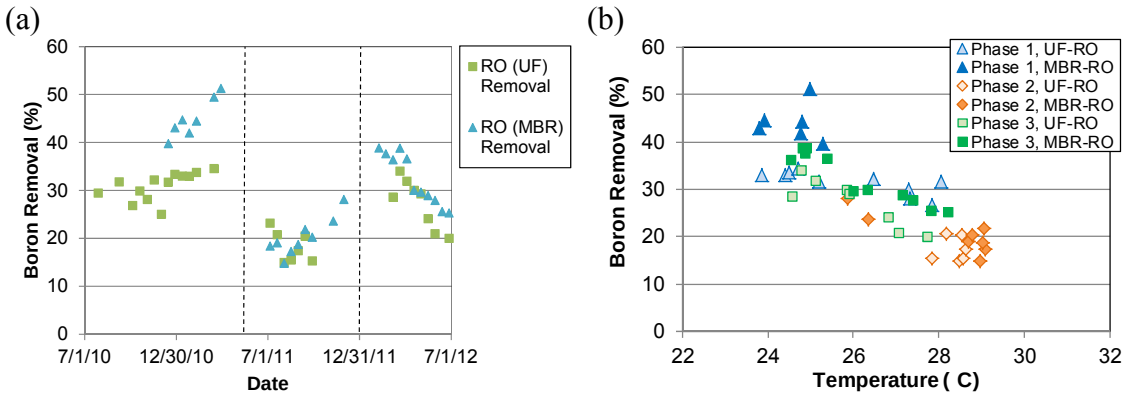


Figure 5-16. Boron Removals by RO Alone as a Function of (a) Time and (b) Temperature

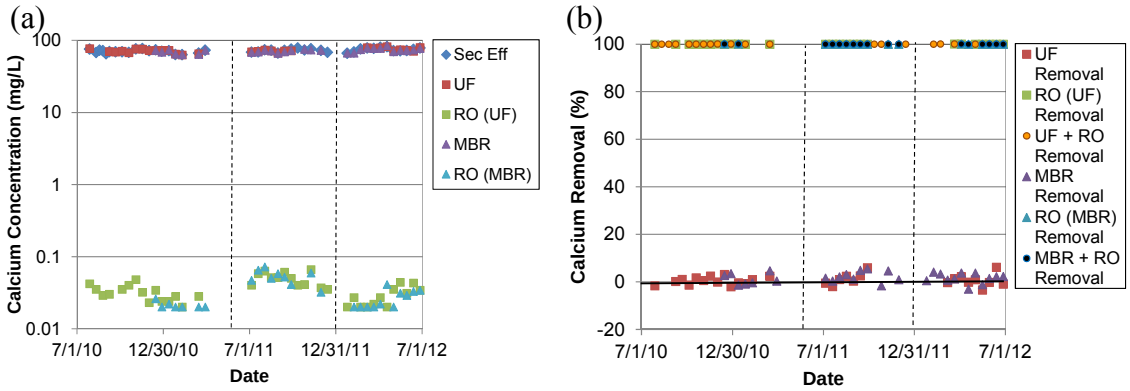


Boron is notoriously difficult to remove from water, and the target concentration of 0.5 mg/L was exceeded frequently. Meeting the boron target of 0.5 mg/L may necessitate the use of ion exchange or RO membranes that are specific for boron removal; further research on boron removal technologies continues to be conducted (Ferreira et *al*., 2006; Hilal et *al*., 2010; Dydo et *al*., 2012). Alternatively, boron source control could be considered, to reduce the levels entering the JWPCP. Boron in the JWPCP effluent likely originates from laundry and cleaning products, and from industries such as fiberglass manufacturing, ceramic material production and semiconductor manufacturing.

5.3.2 Calcium

Calcium results are plotted in Figure 5-17. Secondary effluent concentrations varied from approximately 63 to 82 mg/L, with no significant differences over time. The RO units on both trains provided median removals of > 99% in Phases 1, 2, and 3. RO removals correlated with temperature (Appendix C), but the effect was small: permeate concentrations were generally near the reporting limit of 0.02 mg/L throughout the study. There was no target concentration for calcium.

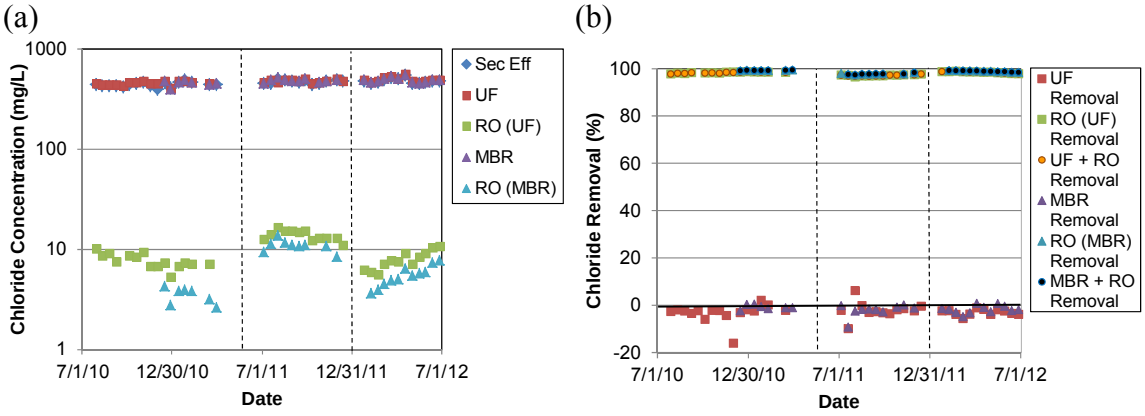
Figure 5-17. Calcium Results. (a) Concentrations and (b) Removals



5.3.3 Chloride

Chloride results are plotted in Figure 5-18. Secondary effluent concentrations ranged from approximately 400 to 550 mg/L, and increased significantly from Phase 1 to Phase 2. The RO units on both trains provided median removals of approximately 98% across all three phases of operation. RO removals correlated with temperature (Appendix C), but had no practical implications on water quality: permeate concentrations varied between 2 and 17 mg/L, and were always well below the target concentration of 100 mg/L.

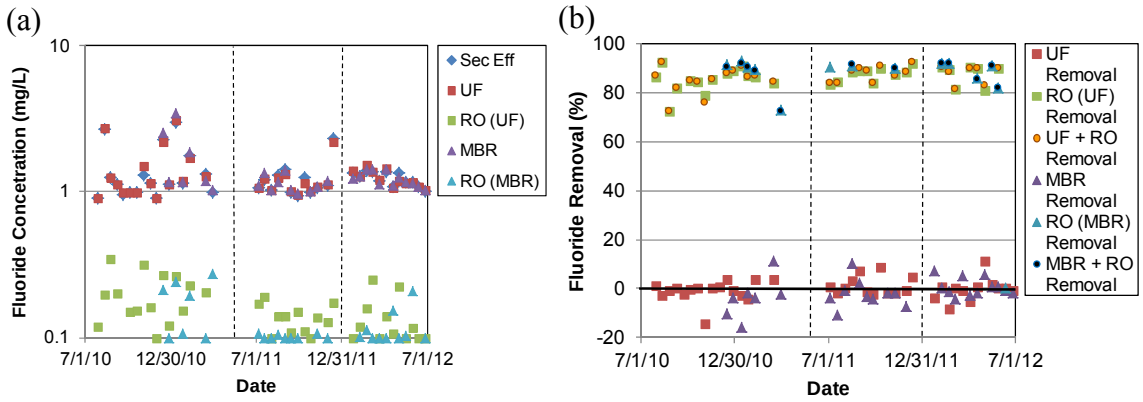
Figure 5-18. Chloride Results. (a) Concentrations and (b) Removals



5.3.4 Fluoride

Fluoride results are plotted in Figure 5-19. Secondary effluent concentrations ranged between approximately 0.9 and 3.0 mg/L, with no difference among the three phases. The RO units on both trains provided median removals of 86-91% across all three phases of operation. There was no statistically significant difference in performance among the three phases, and removals did not correlate with temperature (Appendix E). Permeate concentrations ranged from 0.1 to 0.4 mg/L, and were always less than the target concentration of 2 mg/L.

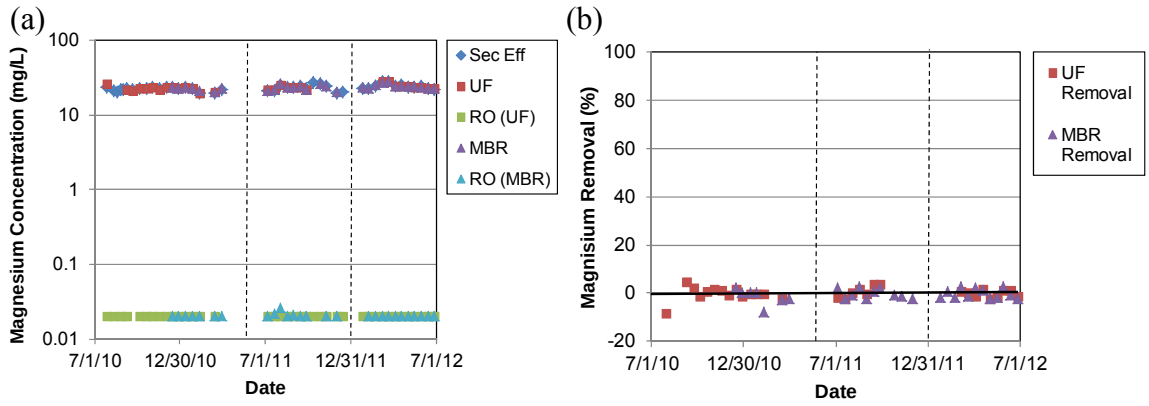
Figure 5-19. Fluoride Results. (a) Concentrations and (b) Removals



5.3.5 Magnesium

Magnesium results are plotted in Figure 5-20. Secondary effluent concentrations varied from approximately 20 to 29 mg/L, with no significant differences among the phases. The RO units on both trains provided median removals of > 99% across all three phases of operation. RO permeate concentrations were generally below the reporting limit of 0.02 mg/L during all three phases. Because the RO permeate levels were low, removals across the RO were not calculated. There was no target concentration for magnesium.

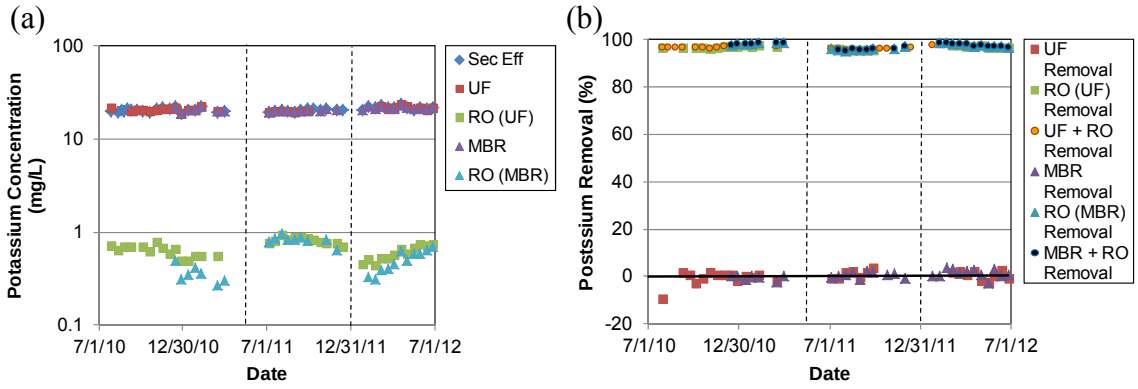
Figure 5-20. Magnesium Results. (a) Concentrations and (b) Removals



5.3.6 Potassium

Potassium results are plotted in Figure 5-21. Secondary effluent concentrations varied from approximately 19 to 24 mg/L, with a small but statistically significant increase in average concentrations from Phase 2 to Phase 3. The RO units on both trains provided median removals of 96-98% in Phases 1, 2, and 3. RO removals correlated with temperature (Appendix C), but the effect was small: permeate concentrations ranged from 0.2 to 1.0 mg/L throughout the study. There was no target concentration for potassium.

Figure 5-21. Potassium Results. (a) Concentrations and (b) Removals



5.3.7 Silica

Silica results are plotted in Figure 5-22. Secondary effluent concentrations varied from approximately 22 to 28 mg SiO_2/L, with no differences across the three phases. The RO units on both trains provided median removals of 96-99% across all three phases of operation. RO removals correlated with temperature, but the removals in Phase 2 were lower than expected from the temperature trend (Figure 5-23), which may reflect chlorine degradation of the RO membranes, as discussed in Section 4.3. The resulting RO permeate concentrations increase from as low 0.13 mg SiO_2/L at the end of Phase 1, to as high as 1.4 mg SiO_2/L near the beginning of Phase 2. There was no target concentration for silica.

Figure 5-22. Silica Results. (a) Concentrations and (b) Removals

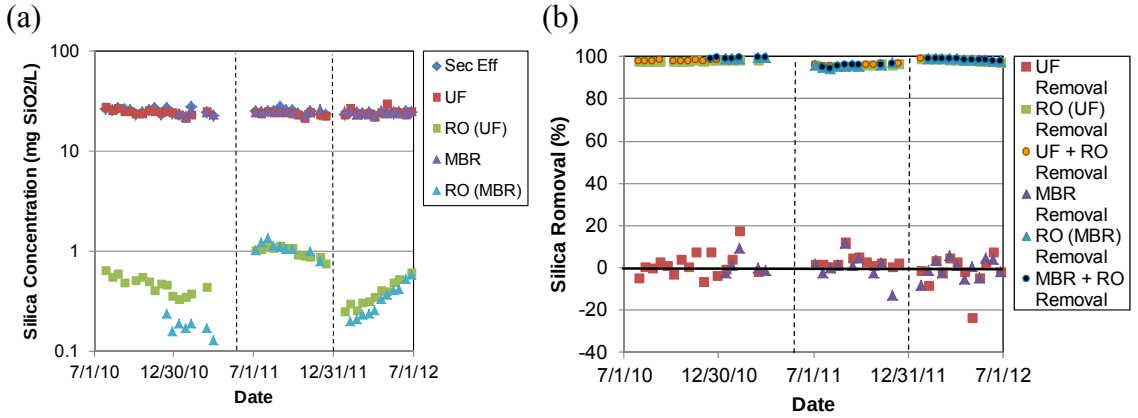
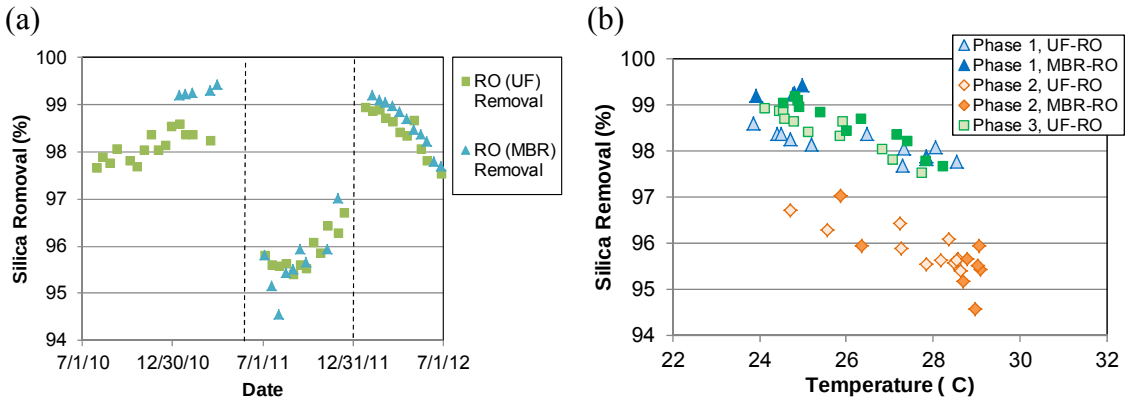


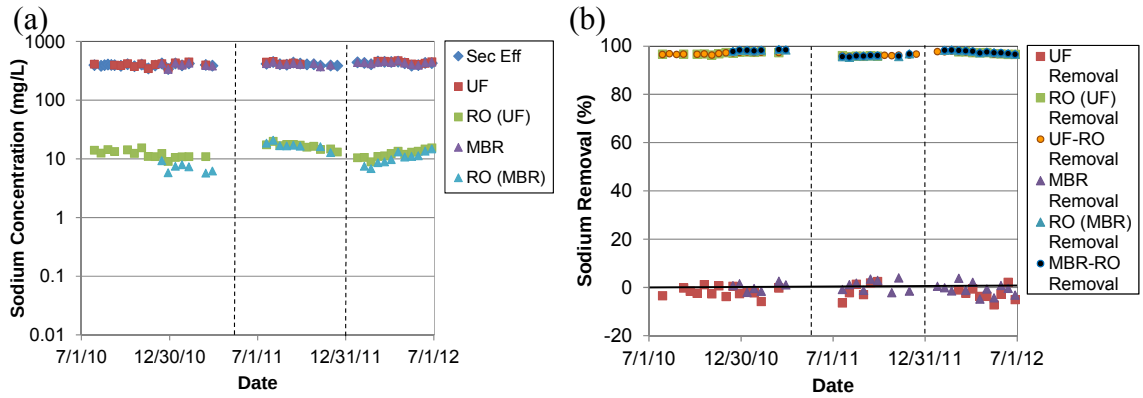
Figure 5-23. Silica Removals by RO Alone as a Function of (a) Time and (b) Temperature



5.3.8 Sodium

Sodium results are plotted in Figure 5-24. Secondary effluent concentrations varied from approximately 340 to 460 mg/L, with no changes in concentrations across the phases. The RO units on both trains provided median removals of 96-98% in Phases 1, 2, and 3. RO removals correlated with temperature (Appendix C), but the effect was small: permeate concentrations ranged between 5 and 21 mg/L throughout the study. There was no target concentration for sodium.

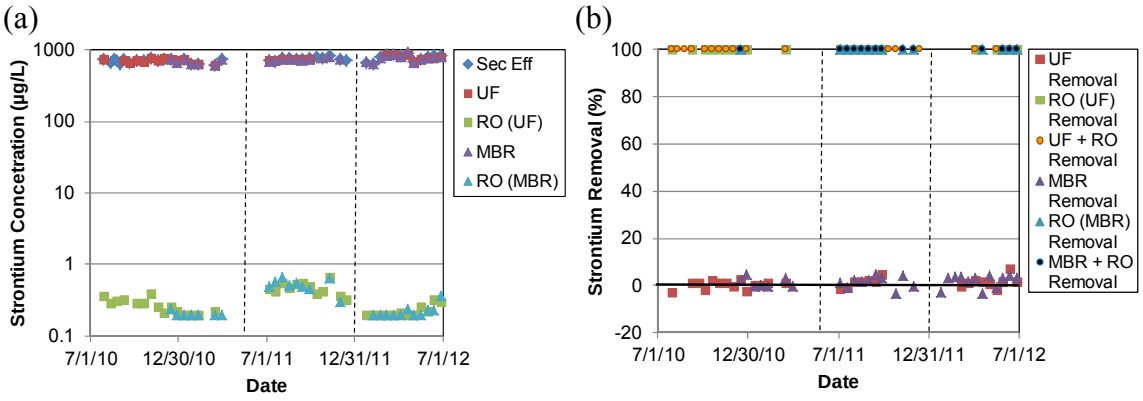
Figure 5-24. Sodium Results. (a) Concentrations and (b) Removals



5.3.9 Strontium

Strontium results are plotted in Figure 5-25. Secondary effluent concentrations varied from approximately 630 to 900 µg/L, and increased significantly from Phase 1 to Phase 2. The RO units on both trains provided median removals of > 99% in Phases 1, 2, and 3. RO removals correlated with temperature (Appendix C), but the effect was small: permeate concentrations ranged from < 0.2 to 0.7 µg/L throughout the study. There was no target concentration for strontium.

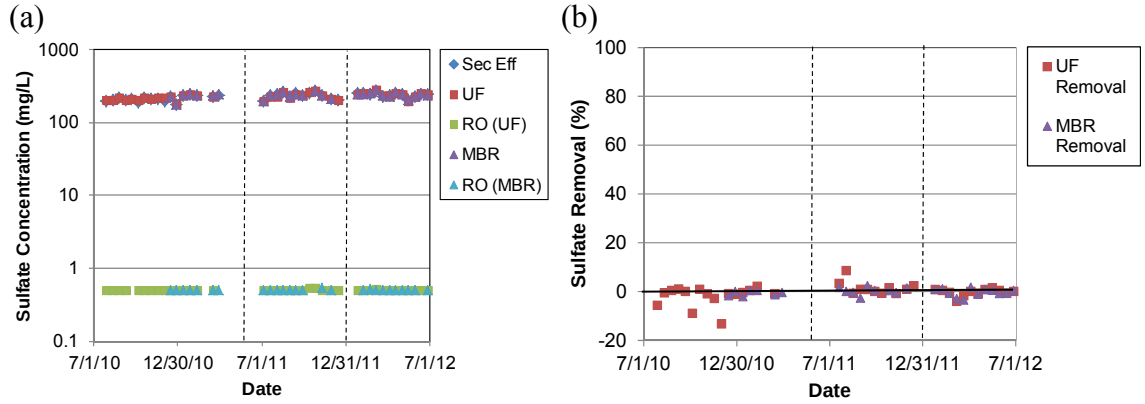
Figure 5-25. Strontium Results. (a) Concentrations and (b) Removals



5.3.10 Sulfate

Sulfate results are plotted in Figure 5-26. Secondary effluent concentrations ranged from approximately 180 to 280 mg/L, and increased significantly from Phase 1 to Phase 2. Median RO permeate concentrations in both trains were below both the target concentration of 100 mg/L and the reporting limit of 0.5 mg/L in Phases 1, 2, and 3.

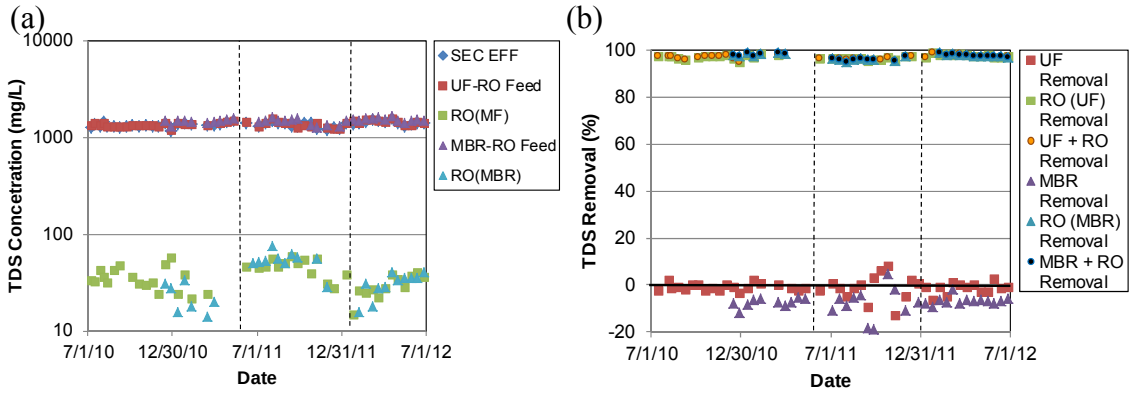
Figure 5-26. Sulfate Results. (a) Concentrations and (b) Removals



5.3.11 TDS

TDS results are plotted in Figure 5-27. Secondary effluent concentrations varied from approximately 1,100 to 1,600 mg/L, with no consistent differences over time. The RO units on both trains provided median removals of 96-98% in Phases 1, 2, and 3. RO removals correlated with temperature (Appendix C), but had no practical implications on water quality. Permeate concentrations varied from 14 to 76 mg/L throughout the study, well below the target of 450 mg/L.

Figure 5-27. TDS Results. (a) Concentrations and (b) Removals



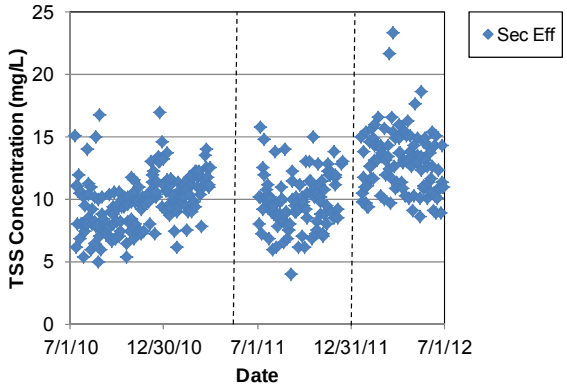
5.4 OTHER CONSTITUENTS

This section discusses several other constituents: TSS, which was measured only in the secondary effluent, and pH and temperature (for which removals are meaningless).

5.4.1 TSS

TSS was measured in secondary effluent only. Results are presented in Figure 5-28; note that the concentrations are on a linear scale. TSS values were relatively low, indicating good sludge settling in the full-scale JWPCP facility.

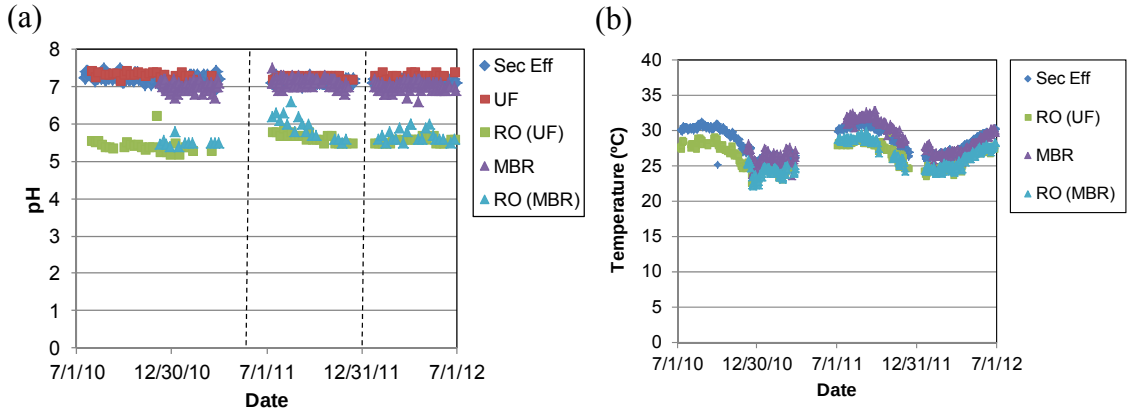
Figure 5-28. TSS Concentrations



5.4.2 pH and Temperature

Results for pH and temperature are plotted in Figure 5-29; note that the y-axes are on a linear scale. The pH was close to neutral for the secondary, UF, and MBR effluents. As described in Chapter 4, sulfuric acid was added upstream of the RO units, and decreased the pH in the RO permeates to approximately 5.5. Because this value was lower than the target of 6.5-8.5, the RO permeate would likely need to be treated (e.g., with decarbonation and lime) to raise the pH, as is typical for AWT systems.

Figure 5-29. Results for (a) pH and (b) Temperature



In Figure 5-29b, the temperature of the UF filtrate is not included because the probe supplied with the unit was unreliable. The temperatures in the secondary effluent, MBR permeate, and RO permeates were similar and followed a clear seasonal trend, with temperatures > 30°C during the summer months, and temperatures < 20°C during the winter months.

5.5 SUMMARY

In general, concentrations of analytes in the secondary effluent increased during the study period. The concentrations of barium, boron, chloride, phosphate, strontium, and sulfate were significantly lower in Phase 1 than in Phases 2 or 3. The concentrations of TOC and turbidity increased significantly from Phase 1 to Phase 2, and again to Phase 3. Finally, the concentrations of TSS, alkalinity, ammonia and TKN, total and soluble COD, and potassium were significantly higher in Phase 3 than in either Phase 1 or 2. These changes in secondary effluent quality may have contributed to fouling of the UF and MBR membranes, as described in Chapter 4.

The UF and MBR removed analytes that were associated with particles and could be filtered out (aluminum, barium, iron, phosphate, and turbidity); the RO then removed the measured parameters to below reporting limits. The biological activity within the MBR converted ammonia and TKN to nitrate, consumed alkalinity, and further degraded the organic matter (COD and TOC) in the secondary effluent. Consequently, concentrations of nitrate increased across the MBR, and concentrations of ammonia, TKN, alkalinity, COD, and TOC decreased. The RO systems removed 93-97% of the measured compounds, or removed them to below reporting limits.

The RO units removed the other general water quality parameters by >95%, except fluoride (80% removal) and boron (15-50% removal). Water temperature affected the RO rejection of almost all compounds except fluoride; however, the impacts were generally small and did not affect the ability of the RO to achieve the target concentrations. The compounds that exhibited the largest temperature effects were boron and nitrate. As water temperature increased from approximately 24°C to 29°C, RO removals decreased from 45% to 15% for boron and from 96% to 85% for nitrate. Outside of the temperature effect, the RO performance was relatively consistent over time; membrane conditions appeared to affect the removals of silica and nitrate during Phase 2, but did not impact the ability of the RO units to meet the target concentrations.

Ultimately, the treated water from the pilot-scale UF and MBR trains met the water quality targets for groundwater recharge, except for TOC, boron, and pH. TOC concentrations in the UF-RO permeate occasionally exceeded the 0.5 mg/L target in Phases 1 and 2, but consistently met the target in Phase 3, after the RO membranes were replaced; concentrations in the MBR-RO permeate consistently achieved the target throughout the study. Boron was present in the RO permeates of both trains at concentrations as high as 0.8 mg/L, which is greater than the target of 0.5 mg/L. Boron is difficult to remove; although technologies such as ion exchange could be used, source control should be considered a priority to reduce the concentrations entering the JWPCP. Finally, additional treatment (e.g., with decarbonation and lime) would likely be necessary to raise the pH of the RO permeate before use.

6. WATER QUALITY RESULTS: NITROSAMINES AND 1,4-DIOXANE

This chapter covers results for the seven analyzed nitrosamine species (NDMA, NDEA, NDPA, NDBA, NMEA, NPIP, and NPYR) and 1,4-dioxane. These compounds are discussed separately from the general water quality parameters in Chapter 7, because the removal requirements for these compounds typically drive the design specifications for AOP in AWT systems. Because the compounds generally behaved similarly to each other across each unit process, the sections in the chapter are organized by unit operation. Section 6.1 discusses the secondary effluent, Section 6.2 discusses the UF treatment train, Section 6.3 discusses the MBR treatment train, and Section 6.4 compares the UF and MBR treatment trains.

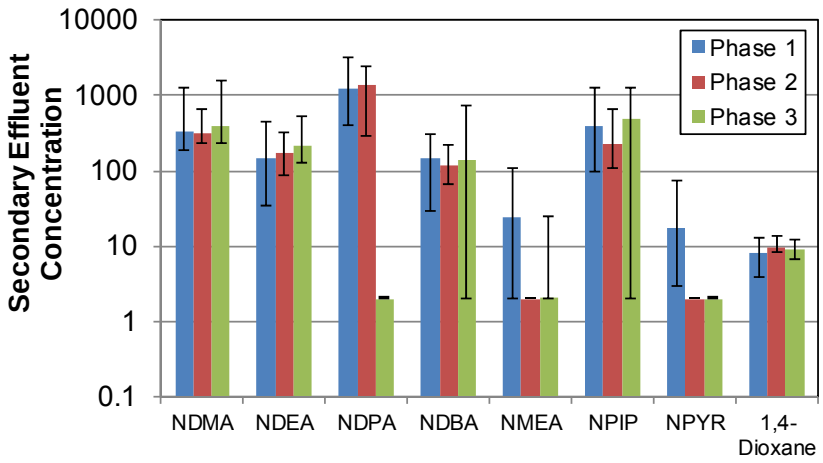
The data in this chapter are presented graphically; statistics for the data are tabulated in Appendix F. For all analyses, samples with concentrations below the reporting limit were conservatively assigned the reporting limit as a concentration, e.g., concentrations < 2 ng/L were assumed to be 2 ng/L. In many cases, the concentrations or calculated removals for a given compound varied widely. To avoid having an extreme point skew the reported values, the following analyses generally use median values, rather than average values, except where noted. Finally, the significance level for all statistical tests was set at 0.01, i.e., tests with p-values <0.01 were interpreted as being statistically significant.

6.1 JWPCP SECONDARY EFFLUENT

Figure 6-1 plots the median concentrations of the seven nitrosamine species and 1,4-dioxane in the secondary effluent. The error bars represent the minimum and maximum observed values. As can be seen in Figure 6-1, the concentrations varied widely for some compounds. NDPA concentrations decreased from thousands of ng/L in Phases 1 and 2, to below the reporting limit in Phase 3. Similarly, NMEA and NPYR concentrations were in the tens of ng/L in Phase 1, but decreased to generally below the reporting limit in Phases 2 and 3. These variations likely reflect changes in the industrial composition of the wastewater entering the JWPCP.

Figure 6-1. Median Concentrations of Nitrosamines and 1,4-Dioxane in Secondary Effluent.

Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.



6.2 UF TREATMENT TRAIN

6.2.1 UF Results

Figure 6-2 shows the median concentrations in the UF filtrate, and Figure 6-3 shows the removals by the UF. Removals were calculated for secondary and UF effluent samples that were paired (taken on the same day), and a t-test was applied to the values to determine whether the UF provided significant removal. Note that no UF samples were taken during Phase 2 for any compound, or in Phase 3 for 1,4-dioxane, so those concentrations and removals are not plotted. In addition, accurate removals could not calculated for NDPA, NMEA, and NPYR in Phase 3, because many samples had UF filtrate concentrations below the reporting limit.

Figure 6-2. Median Concentrations of Nitrosamines and 1,4-Dioxane in UF Filtrate.
Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.

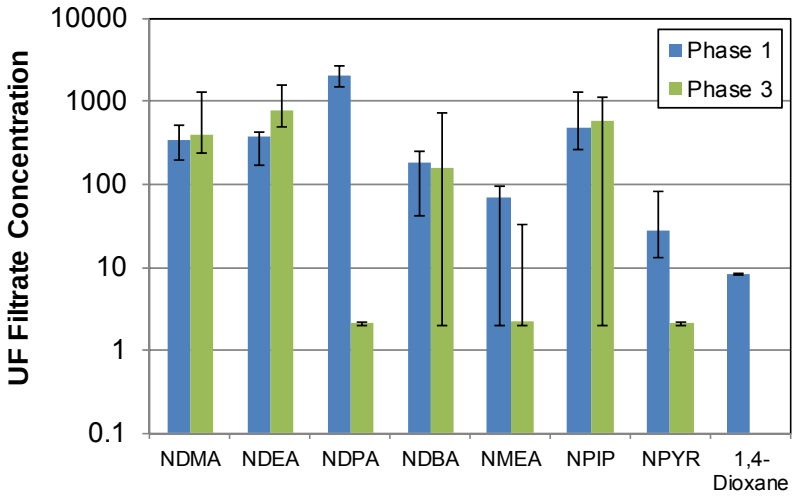
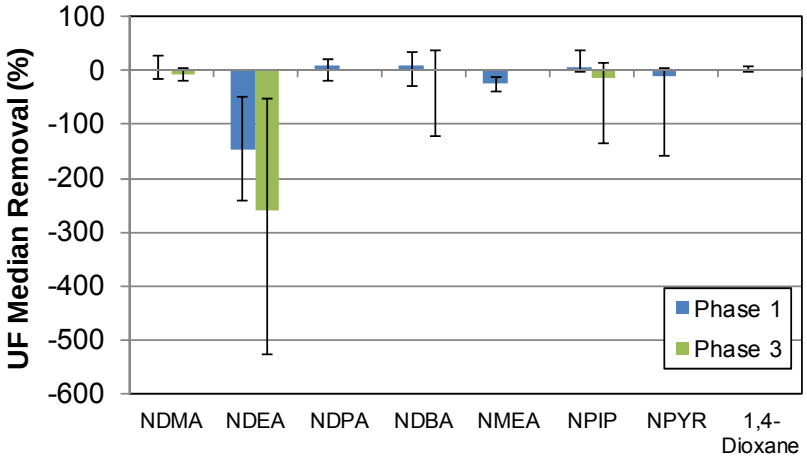


Figure 6-3. Median Removal of Nitrosamines and 1,4-Dioxane by UF.



The UF did not change the concentration of most of the compounds significantly. However, NDEA concentrations increased significantly in both Phases 1 and 3, NMEA concentrations increased significantly in Phase 1, and NDMA concentrations increased significantly during Phase 3. Formation of these compounds may be due to the addition of chlorine upstream of the UF unit. Chloramines (formed from the reaction of chlorine and ammonia) are known to form NDMA in the presence of precursor compounds (Mitch and Sedlak, 2004), and chlorine has been shown to form NDEA and NMEA in the presence of diethylamine and ammonia (Andrzejewski *et al*., 2005).

6.2.2 RO Results

Figure 6-4 shows median concentrations in the RO permeate, and Figure 6-5 shows median removals by the RO alone and the combination of the UF and RO. Percent removals were calculated for paired samples (taken on the same day), and were used in a t-test to determine whether the RO alone or the combination of UF and RO provided significant removal. Removals were calculated only when both the influent and effluent samples were taken (i.e., UF filtrate and RO permeate samples for removal by RO alone, or secondary effluent and RO permeate samples for removal by combined UF and RO), and when the RO permeate concentrations were above reporting limits.

Given these constraints, removals across the RO alone were calculated for NDMA and NDEA during Phases 1 and 3, and for NDPA during Phase 1. For the combined UF-RO, removals were calculated for NDMA and NDEA during all three phases, for NDPA during Phases 1 and 2, and for 1,4-dioxane during Phase 2.

RO alone and the combination of UF and RO provided statistically significant removal of all compounds. Removals generally increased with increasing molecular mass, with NDMA being the smallest molecule and NDPA being the largest. NDMA is known to be poorly removed by RO membranes (Steinle-Darling *et al*., 2007).

Figure 6-4. Median Concentrations of Nitrosamines and 1,4-Dioxane in UF-RO Permeate.

Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.

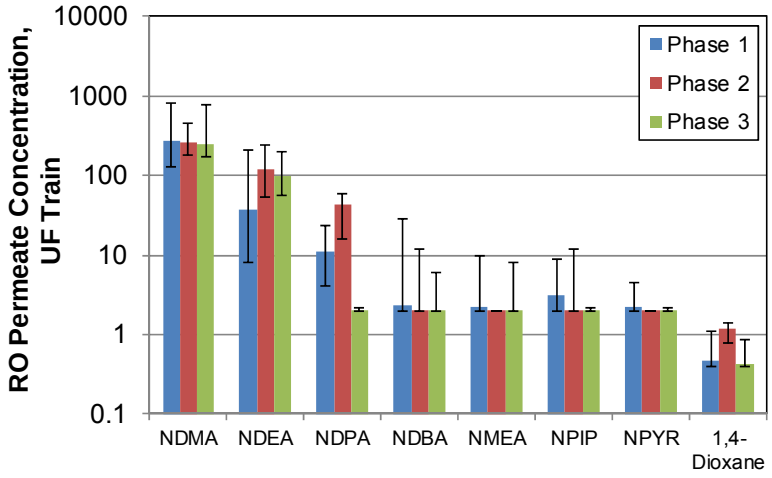
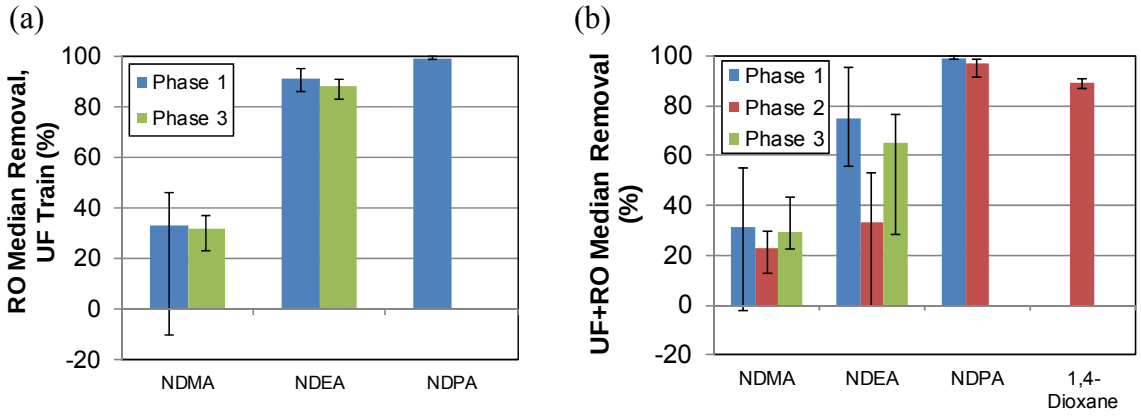


Figure 6-5. Removal of Nitrosamines and 1,4-Dioxane by (a) RO Alone and (b) Combined UF and RO.



As shown in Figure 6-4, the median concentrations of NDBA, NMEA, NPIP, and NPYR were always below the target levels (provided in Section 3.5), and generally below the reporting limit of 2 ng/L in Phases 1, 2, and 3. NDMA and NDEA concentrations were consistently above the CDPH notification level of 10 ng/L. The concentrations of NDPA and 1,4-dioxane were occasionally above their targets (10 ng/L and 1 µg/L, respectively), particularly during Phase 2. The treatment of these four compounds by advanced oxidation is discussed in Section 6.2.3.

With respect to performance over time, removals by the combination of UF and RO were significantly lower during Phase 2 for NDMA, NDEA, and NDPA. In addition, RO permeate concentrations of NDEA, NDPA, and 1,4-dioxane were significantly higher in Phase 2. The poorer performance during Phase 2 may be due to factors such as chlorine degradation of the membranes and higher average temperatures during Phase 2. Chlorine degradation of the membranes was observed during the membrane autopsy (Section 4.3), and was exposed after the deep cleaning that was performed between Phases 1 and 2. The effect of temperature on RO rejection could not be evaluated, due to the limited number of UF filtrate samples. However, temperature effects were observed for NDMA and NDEA across the MBR-RO membranes (Section 6.3.2), and for many of the general water quality parameters (Chapter 5). This effect has been documented previously (Kim *et al*., 2009), and was attributed to compounds diffusing more rapidly through the RO membranes at higher temperatures, thereby increasing their concentrations in the RO permeate.

6.2.3 AOP Results

The following sections provide more details on the experiments conducted with UV and hydrogen peroxide during Phase 1; AOP experiments were not conducted during Phases 2 or 3. Note that throughout this section, RO permeate is referred to as the "influent" for the AOP system. Also, the EED values in this study are specific to the tested reactor and should not be applied to other systems.

The objectives of the AOP testing were to meet the target concentrations, and to characterize the effects of UV EED and hydrogen peroxide on the removal of compounds of interest. Table 6-1 lists the four compounds of interest for the AOP experiments. These were the only compounds that either exceeded the target concentrations in the RO permeate or had removal requirements specified by CDPH.

Table 6-1. CDPH Treatment Requirements: UF Train

	Units	1,4-Dioxane	NDMA	NDEA	NDPA
Notification Level (NL)	ng/L	1,000	10	10	10
Max. Observed Conc., RO Permeate	ng/L	1,400	830	240	60
Log Removal Required to Meet NL	-	0.15	1.9	1.4	0.8
Log Removal Required by DGRR	-	0.5	1.2*	-	-
Controlling Log Removal	-	0.5	1.9	1.4	0.8

*The 1.2-log removal requirement was removed in the 2011 CDPH DGRR but was kept as a target for this project.

For 1,4-dioxane, the treatment goals were an effluent concentration less than 1 μg/L and 0.5-log removal. Based on the concentrations in the UF-RO permeate, the 0.5-log requirement was more difficult to meet, and was used as the target for this project. Because the natural concentrations were too low to measure 0.5-log removal, 1,4-dioxane was spiked at concentrations of 4 to 20 μg/L into the UV influent (RO permeate) for the AOP experiments.

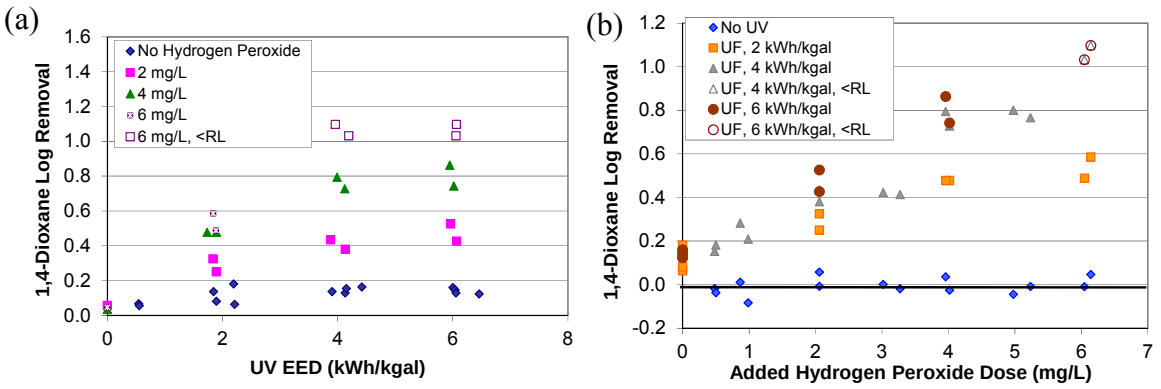
For NDMA, the treatment goals were an effluent concentration less than 10 ng/L and 1.2-log removal. Based on the maximum concentration measured in the UF-RO permeate, the 10 ng/L effluent concentration was more difficult to meet. Natural NDMA concentrations were used in most experiments, although NDMA was spiked at concentrations up to 1,400 ng/L in a few initial experiments. Because the influent NDMA concentrations were not controlled, they varied for each combination of EED and hydrogen peroxide dose, and caused similar variations in the effluent concentrations. As a result, log removal was a more reliable method for comparing doses. Based on the maximum observed concentration and the notification level, a log removal of 1.9 was chosen as the target for these AOP experiments. Note that if NDMA were concentrations decreased (e.g., through source control), a lower target log removal could be used, potentially reducing the required size and cost of the AOP system.

For NDEA and NDPA, the treatment goal was an effluent concentration less than 10 ng/L; there were no log removal requirements. Natural NDEA and NDPA concentrations were used in all experiments. Due to the uncontrolled influent concentrations, log removal was more reliable effluent concentrations in comparing UV/hydrogen peroxide doses. Based on the maximum observed concentrations in the UF-RO permeate and the notification levels, log removals of 1.4 and 0.8 were chosen as the targets for NDEA and NDPA, respectively. Similar to NDMA, if source control were implemented and the AOP influent concentrations decreased, a lower target log removal could be used, potentially reducing the required size and cost of the AOP system.

6.2.3.1 Removal of 1,4-Dioxane

Figure 6-6 shows the effects of UV EED and hydrogen peroxide dose on the removal of 1,4-dioxane. UV alone (no hydrogen peroxide) removed some 1,4-dioxane, as shown in Figure 6-6a. This result was unexpected, because literature indicates that 1,4-dioxane is not susceptible to photolysis (Asano *et al*., 2007); however, UV could form radical species from the chloramine residuals present in the water (Watts and Linden, 2007), and these radicals may react with 1,4-dioxane. As seen in Figure 6-6b, hydrogen peroxide alone (no UV) provided no removal of 1,4-dioxane. Removals increased with increasing UV EED at a constant hydrogen peroxide dose, and increased with increasing hydrogen peroxide dose at a constant UV EED.

Figure 6-6. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of 1,4-Dioxane in UF-RO Permeate.



The treatment goal of 0.5-log removal was met at a UV EED of 2 kWh/kgal and a hydrogen peroxide dose of approximately 4-6 mg/L, but could also be met at a UV EED of 6 kWh/kgal and a hydrogen peroxide dose of approximately 2 mg/L.

6.2.3.2 Removal of Nitrosamines

Figure 6-7 shows the effects of UV EED and hydrogen peroxide dose on the removal of NDMA. Removal increased with increasing EED, but hydrogen peroxide dose had no effect. The treatment goal of 1.9-log removal was achieved at a UV EED of approximately 4 kWh/kgal.

Figures 6-8 and 6-9 show the effects of UV EED and hydrogen peroxide dose on the removal of NDEA and NDPA, respectively. Hydrogen peroxide alone had no effect, but at a fixed UV EED, increasing hydrogen peroxide dose increased removals. At a fixed hydrogen peroxide dose, increasing UV EED increased removals. The NDEA target removal of 1.4-log was not met at any of the tested doses. The NDPA target removal of 0.8-log was met at a UV EED of 4 kWh/kgal and a hydrogen peroxide dose of 6 mg/L, but could also be met at a UV EED of 6 kWh/kgal and a hydrogen peroxide dose of approximately 4 mg/L.

Figure 6-7. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of NDMA in UF-RO Permeate.

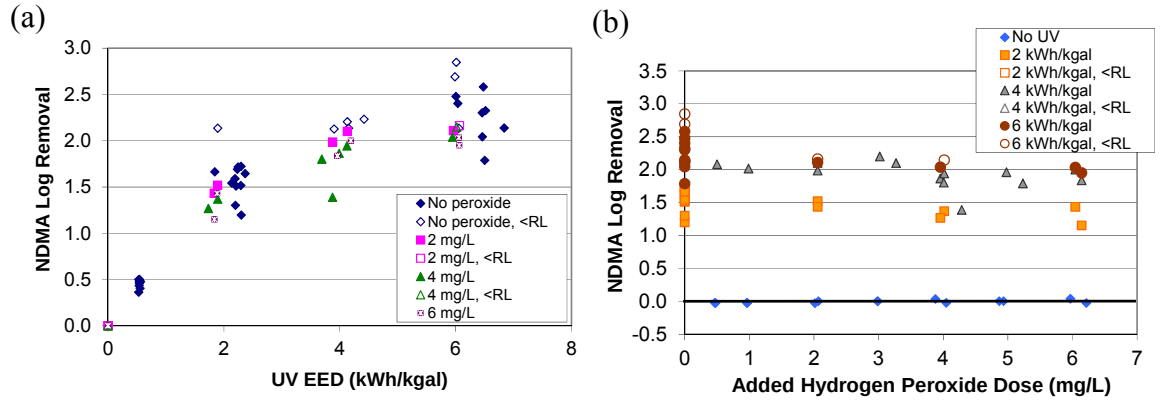


Figure 6-8. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of NDEA in UF-RO Permeate.

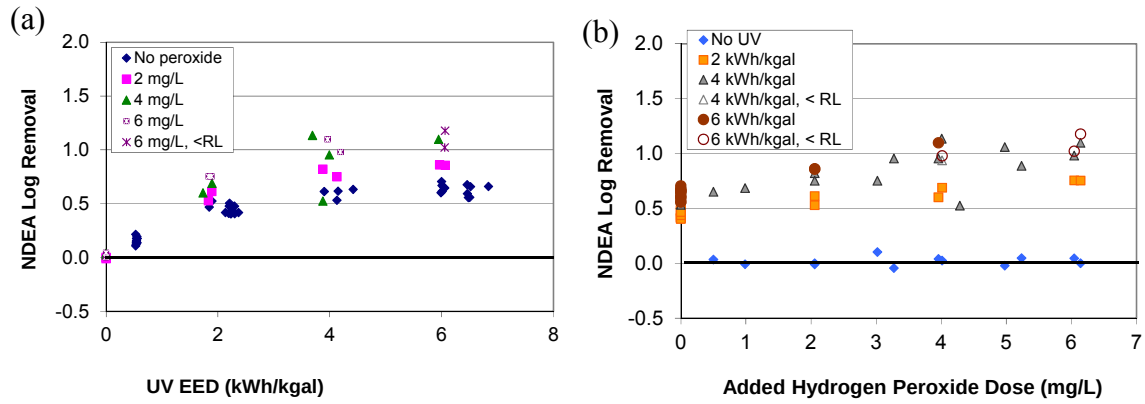
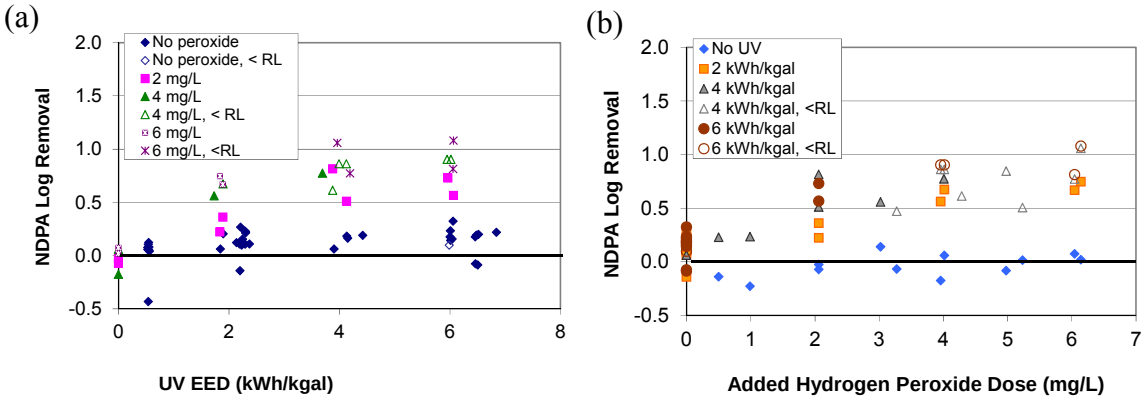


Figure 6-9. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of NDPA in UF-RO Permeate.



Of the three detected nitrosamines, NDMA was the most susceptible to UV. An EED of 6 kWh/kgal provided approximately 2.3-log removal of NDMA, followed by NDEA with approximately 0.6-log removal, then NDPA with approximately 0.2-log removal. For the combination of UV and hydrogen peroxide, NDMA continued to be the most easily removed; it was difficult to observe differences between NDEA and NDPA removal, because many NDPA samples were below the reporting limit after AOP treatment.

Table 6-2 provides the estimated hydrogen peroxide doses required to meet the targets for each of the compounds. The 0.5-log removal requirement for 1,4-dioxane was met at all three tested UV EEDs, with the required hydrogen peroxide decreasing as the EED increased. The target NDMA removal of 1.9-log was met at EED values of 4 and 6 kWh/kgal; no hydrogen peroxide was necessary.

The target NDPA removal of 0.8-log was met at an EED value of 4 kWh/kgal in combination with 6 mg/L of hydrogen peroxide, or 6 kWh/kgal with 4 mg/L of hydrogen peroxide. Note that the log removal target was based on the maximum observed concentration in the UF-RO permeate and the Notification Levels set by CPDH for drinking water wells. If the removal target were instead based on the 90th percentile value of 45 ng/L, the CDPH notification level could be

met at doses similar to those required for 1,4-dioxane. If the removal target were based on the median value of 8 ng/L, no AOP treatment would be required.

The target NDEA removal of 1.4-log was not met at the tested UV EED values and hydrogen peroxide doses. If the removal target were instead based on the 90th percentile value of 180 ng/L, the CDPH notification level might be met at UV EED values of 6 kWh/kgal in combination with a hydrogen peroxide dose of 6 mg/L. If the removal target were based on the median value of 60 ng/L, the CDPH notification level could be met at UV EED values of 4 kWh/kgal in combination with approximately 3 mg/L of hydrogen peroxide, or 6 kWh/kgal in combination with 2 mg/L of hydrogen peroxide. Reducing the influent concentrations (e.g., through source control) would provide the same benefit of reducing the doses required to meet the treatment target.

Table 6-2. Approximate Hydrogen Peroxide Doses (mg/L) Required to Meet Treatment Goals: UF Train

	UV EED (kWh/kgal)		
Compound	2	4	6
1,4-dioxane	4-6	~3	2
NDMA	x	0	0
NDEA	x	x	x
NDPA	x	6	4

x: Did not meet treatment goals at tested hydrogen peroxide doses.

6.3 MBR TREATMENT TRAIN

6.3.1 MBR Results

Figure 6-10 shows the median concentrations in the MBR permeate, and Figure 6-11 shows the removals by the MBR. Removals were calculated for secondary and MBR effluent samples that were paired (taken on the same day), and a t-test was applied to the values to determine whether the MBR provided significant removal, to a significance level of 0.01. Accurate removal values could not calculated for NDPA in Phase 3, and NMEA and NPYR in Phases 2 and 3, because MBR permeate concentrations were below the reporting limit.

The MBR affected all detected compounds except for 1,4-dioxane; the fact that several nitrosamines were removed by the MBR but not the UF suggests biological activity or sorption to the biological solids in the MBR. NDPA, NPIP, and NPYR were significantly removed in all operational phases in which they were measured. Median NDPA removals were >90%, while median NPIP removals varied from 57 to 86%, and the median NPYR removal in Phase 1 was 67%. Removals of NDMA and NDBA were lower, and removals were not consistently significant. Median NDMA removals varied from 9 to 29% and were significant in Phases 2 and 3, and median NDBA removals varied from 25 to 63% and were significant in Phases 1 and 2. These results are consistent with literature reports that these nitrosamines can be biodegraded under aerobic conditions (Drewes et *al*., 2006; Krauss et *al*., 2009).

Figure 6-10. Median Concentrations of Nitrosamines and 1,4-Dioxane in MBR Permeate.

Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.

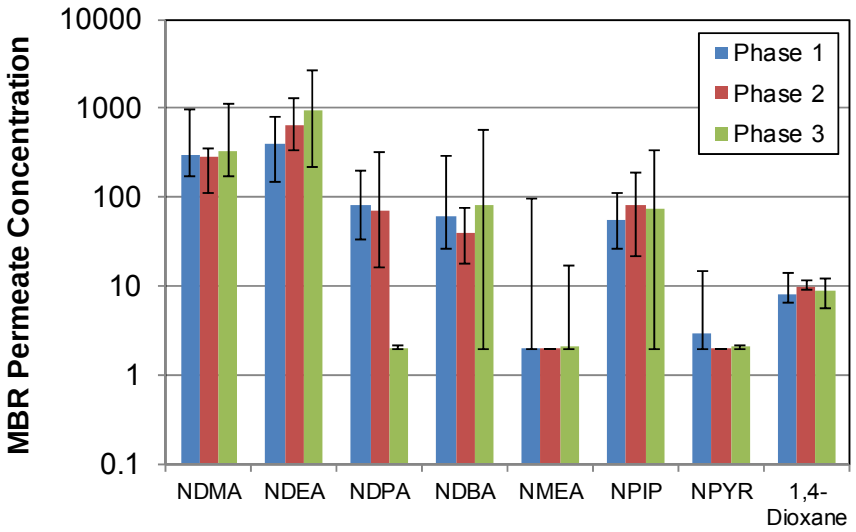
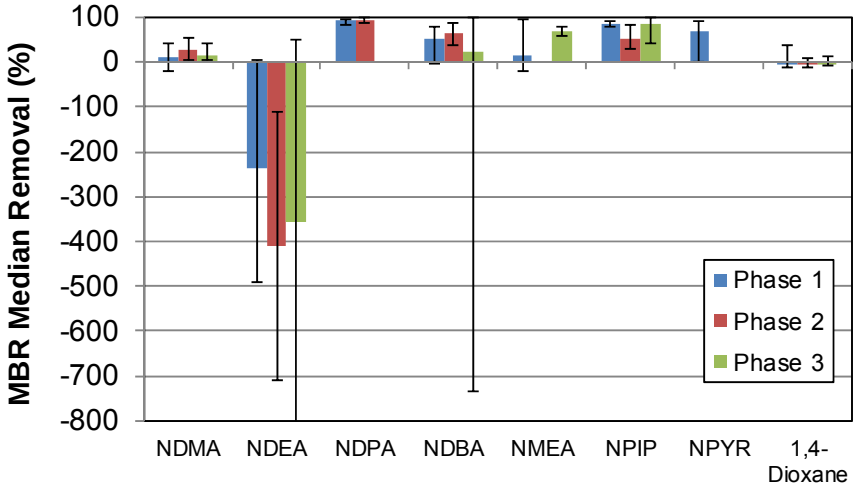


Figure 6-11. Median Removals of Nitrosamines and 1,4-Dioxane by the MBR.



NDEA concentrations increased significantly across the MBR, by approximately 200-400%. Because the MBR permeate samples were taken upstream of any chlorine addition, this increase in concentrations cannot be attributed to chlorine. NDEA could be formed by the reaction of precursor compounds with nitrate generated during the nitrification process; bacteria such as *E. coli*, *Enterococci, clostridia, bacteriodes* and *bijidobacteria* have been shown to catalyze the formation of nitrosamines in the presence of secondary amines, with nitrate reduction to nitrite as the first step (Foreman and Goodhead, 1975). However, further study is needed to identify the cause(s) of the increases in NDEA concentrations across the MBR.

6.3.2 RO Results

Figure 6-12 shows median concentrations in the RO permeate, and Figure 6-13 shows median removals by the RO alone and the combination of the MBR and RO. Percent removals were calculated for paired samples (taken on the same day), and were used in a t-test to determine whether the RO alone or the combination of MBR and RO provided significant removal. Removals were calculated only when both influent and effluent samples were taken, and when the RO permeate concentrations were above reporting limits. Given these constraints, removals were calculated for NDMA and NDEA during all three phases, and for 1,4-dioxane during Phase 2.

Figure 6-12. Median Concentrations of Nitrosamines and 1,4-Dioxane in MBR-RO Permeate.

Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.

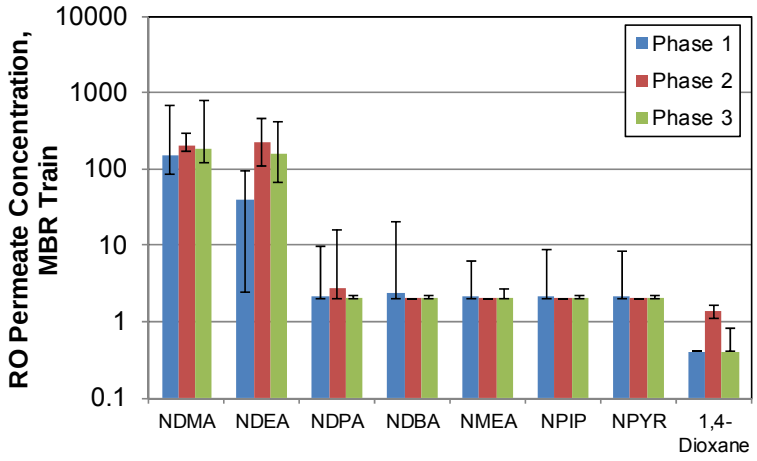
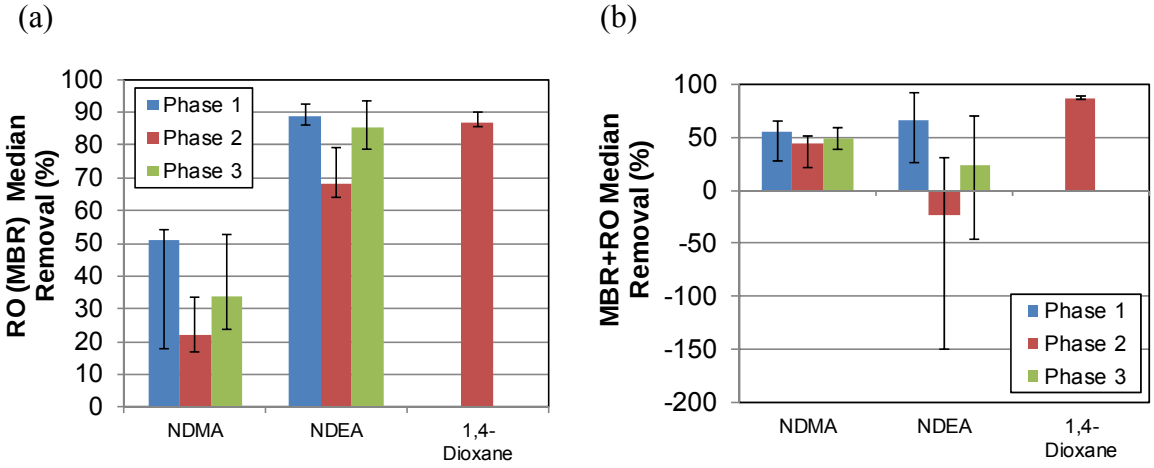


Figure 6-13. Removal of Nitrosamines and 1,4-Dioxane by (a) RO Alone and (b) the Combination of MBR and RO.

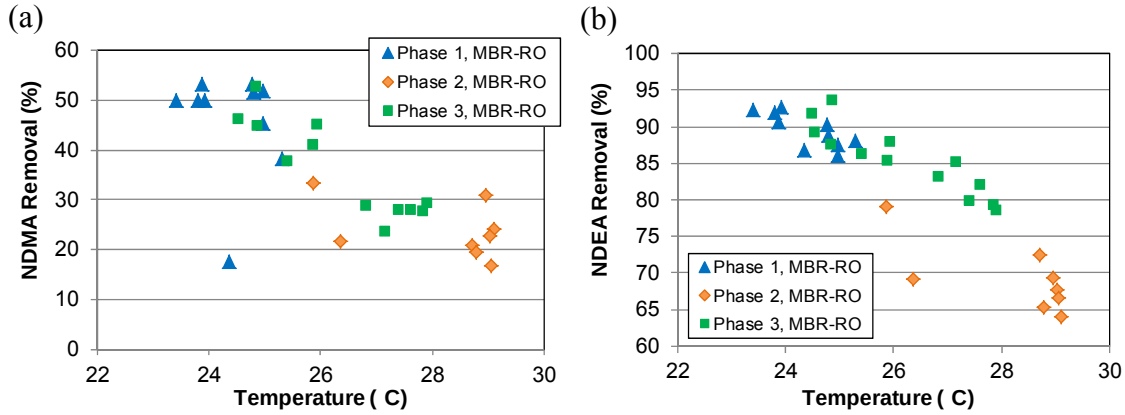


As shown in Figure 6-12, the median concentrations of NDPA, NDBA, NMEA, NPIP, and NPYR were generally below the target levels (provided in Section 3.5) and the reporting limit of 2 ng/L in Phases 1, 2, and 3. Concentrations of NDMA and NDEA were consistently above the CDPH notification level of 10 ng/L, and 1,4-dioxane concentrations were occasionally above the target of 1 µg/L during Phase 2. Treatment of these three compounds by advanced oxidation is discussed in Section 6.3.3.

In almost all cases, removal was statistically significant for RO alone and the combination of MBR and RO. The only exception was NDEA, with the combination of MBR and RO during Phases 2 and 3, due to the formation of NDEA across the MBR. As with the UF-RO, the MBR-RO removed NDEA better than NDMA.

With respect to performance over time, removals by the combination of MBR and RO were significantly lower during Phase 2 for NDMA and NDEA. Removal of 1,4-dioxane could not be compared over time, because the RO permeate concentrations in Phases 1 and 3 were below the reporting limit; however a comparison of the concentrations indicates that 1,4-dioxane levels were significantly higher in Phase 2. The poorer performance during Phase 2 may be due to factors such as chlorine degradation of the membranes and higher average temperatures during Phase 2. Chlorine degradation of the membranes was observed during the membrane autopsy (Section 4.3), and was exposed after the deep cleaning that was performed between Phases 1 and 2. Temperature effects were observed for NDMA (Figure 6-14a) and NDEA (Figure 6-14b), as well as many of the general water quality parameters (Chapter 5 and Appendix E). This effect has been documented previously (Kim *et al*., 2009), and was attributed to compounds diffusing more rapidly through the RO membranes at higher temperatures, thereby increasing their concentrations in the RO permeate.

Figure 6-14. Effect of Temperature on RO Removals of (a) NDMA and (b) NDEA.



6.3.3 AOP Results

The following sections provide more details on the experiments conducted with UV and hydrogen peroxide during Phase 1; AOP experiments were not conducted during Phases 2 or 3. Note that throughout this section, RO permeate is referred to as the "influent" for the AOP system. Also, the EED values in this study are specific to the tested reactor and should not be applied to other systems.

The objectives of the AOP testing were to meet the target concentrations, and to characterize the effects of UV EED and hydrogen peroxide on the removal of compounds of interest. Table 6-3 lists the three compounds of interest for the AOP experiments. These were the only compounds in the RO permeate that either exceeded the target concentrations or had removal requirements specified by CDPH. The target log removals were similar to those set for the AOP experiments on the UF train; see Section 6.2.3 for details on the explanation of the target removals.

Table 6-3. CDPH Treatment Requirements: MBR Train

	Units	1,4-Dioxane	NDMA	NDEA
Notification Level (NL)	ng/L	1,000	10	10
Max. Observed Conc., RO Permeate	ng/L	1,600	790	450
Log Removal Required to Meet NL	-	0.2	1.9	1.7
Log Removal Required by DGRR	-	0.5	1.2*	-
Controlling Log Removal	-	0.5	1.9	1.7

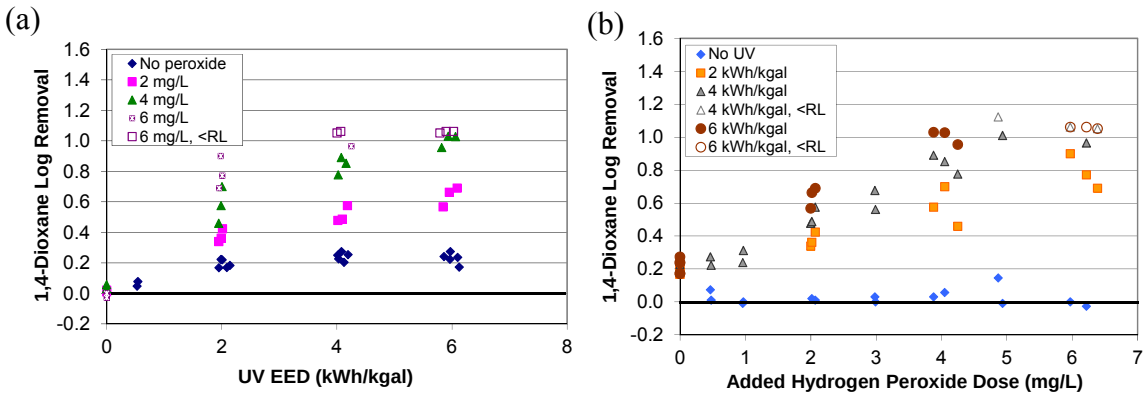
*The 1.2-log removal requirement was removed in the 2011 CDPH DGRR but was kept as a target for this project.

6.3.3.1 Removal of 1,4-Dioxane

Figure 6-15 shows the effects of UV EED and hydrogen peroxide dose on the removal of 1,4-dioxane. UV alone (no hydrogen peroxide) removed some 1,4-dioxane, as shown in Figure 6-15a. This result was unexpected, because literature indicates that 1,4-dioxane is not susceptible to photolysis (Asano *et al.*, 2007); however, UV could form radical species from the chloramine residuals present in the water (Watts and Linden, 2007), and these radicals may react with 1,4-dioxane. As seen in Figure 6-15b, hydrogen peroxide alone (no UV) provided no removal of 1,4-dioxane. Removals increased with increasing UV EED at a constant hydrogen peroxide dose, and with increasing hydrogen peroxide dose at a constant UV EED.

The treatment goal of 0.5-log removal was met at a UV EED of 2 kWh/kgal and a hydrogen peroxide dose of approximately 4 mg/L, but could also be met at a UV EED of 4 kWh/kgal and a hydrogen peroxide dose of approximately 2 mg/L.

Figure 6-15. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of 1,4-Dioxane in MBR-RO Permeate.



6.3.3.2 Removal of Nitrosamines

Figures 6-16 and 6-17 show the effects of UV EED and hydrogen peroxide dose on the removal of NDMA and NDEA, respectively. NDMA removal increased with increasing EED, but hydrogen peroxide dose had no effect. The NDMA treatment goal of 1.9-log removal was achieved at a UV EED of 4 kWh/kgal.

Figure 6-16. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of NDMA in MBR-RO Permeate.

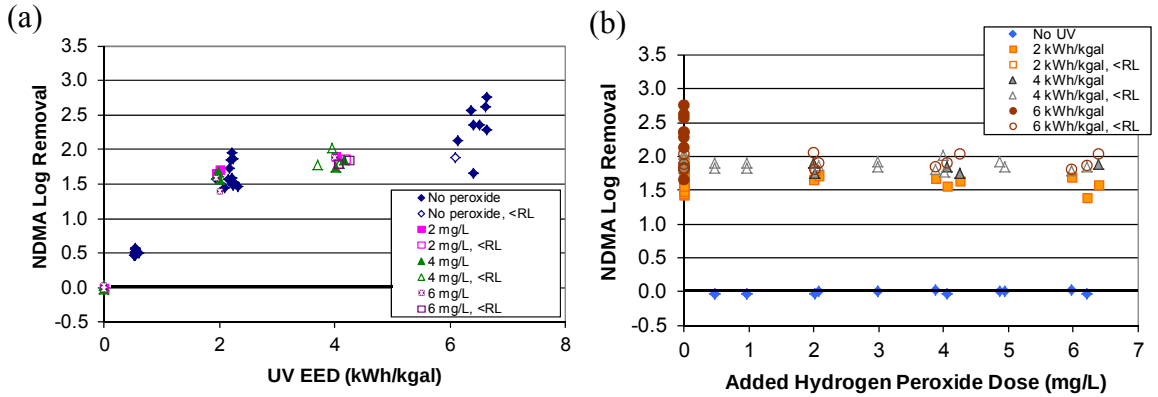
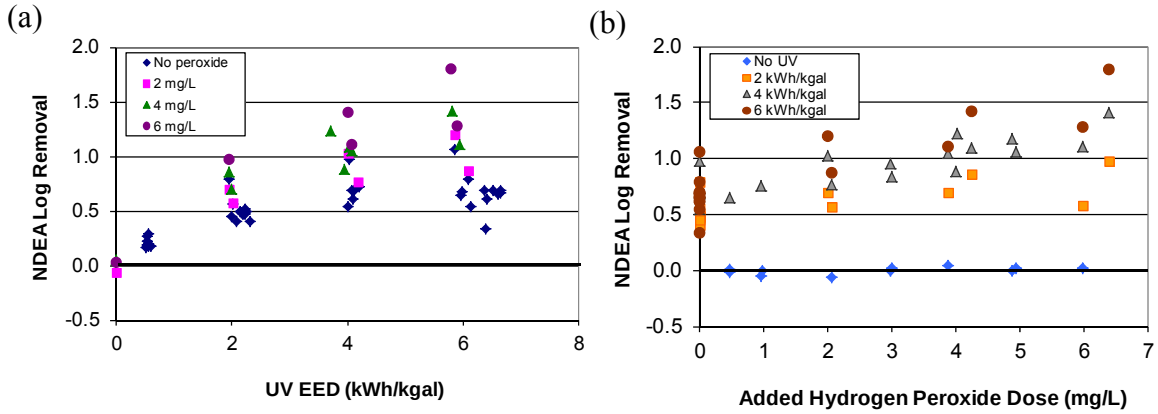


Figure 6-17. Effects of (a) UV EED and (b) Hydrogen Peroxide Dose on the Removal of NDEA in MBR-RO Permeate.



For NDEA, hydrogen peroxide alone had no effect, but at a fixed UV EED, increasing hydrogen peroxide dose increased removals. At a fixed hydrogen peroxide dose, increasing UV EED increased removals. The NDEA target removal of 1.7-log was inconsistently achieved at the highest tested doses of 6 kWh/kgal and 6 mg/L of hydrogen peroxide.

NDMA was more susceptible than NDEA to treatment by UV alone, or by the combination of UV and hydrogen peroxide. For example, an EED of 6 kWh/kgal provided approximately 2.3-log removal of NDMA, but an EED of 6 kWh/kgal in combination with hydrogen peroxide doses of 0-6 mg/L provided only 0.5 to 1.7-log removal of NDEA.

Table 6-4 provides the estimated hydrogen peroxide doses required to meet the targets for each of the compounds. The 0.5-log removal requirement for 1,4-dioxane was met at all three tested UV EEDs, with the required hydrogen peroxide decreasing as the EED increased. The target NDMA removal of 1.9-log was met at EEDs of 4 and 6 kWh/kgal; hydrogen peroxide was not needed.

The target NDEA removal of 1.7-log was inconsistently achieved at the highest tested doses of 6 kWh/kgal and 6 mg/L of hydrogen peroxide. Note that the log removal target was based on the maximum observed concentration in the MBR-RO permeate and the Notification Levels set by CPDH for drinking water wells. If the removal target were instead based on the 90th percentile value of 250 ng/L, the CDPH notification level might be consistently achieved at the highest doses tested. If the removal target were based on the median value of 80 ng/L, the CDPH notification level would be met at a UV EED of 4 kWh/kgal in combination with 6 mg/L of hydrogen peroxide, or 6 kWh/kgal in combination with 4 mg/L of hydrogen peroxide. Reducing the influent concentrations (e.g., through source control) would provide the same benefit of reducing the doses required to meet the treatment target.

Table 6-4. Approximate Hydrogen Peroxide Doses (mg/L) Required to Meet Treatment Goals: MBR Train

	UV EED (kWh/kgal)		
Compound	2	4	6
1,4-dioxane	~4	2	< 2
NDMA	x	0	0
NDEA	x	x	x

x: Did not meet treatment goals at tested hydrogen peroxide doses.

6.3.3.3 Comparison of Low Pressure (LP) and Medium Pressure (MP) UV

During the Title 22+ events in Phase 3, samples were taken across the MBR train for nitrosamines and 1,4-dioxane. Most of the data from these events are included in the analysis in the previous sections; however, the AOP testing was conducted with a different UV reactor, and the results are discussed separately in this section. The Title 22+ AOP tests in Phase 3 used a Calgon Rayox batch UV reactor to compare LP and MP UV. Both samples were dosed with 4 mg/L of hydrogen peroxide. LP UV was dosed at 0.9 kWh/kgal and MP UV was dosed at 1.5 kWh/kgal. Note that these EEDs are reactor-specific and do not apply to other reactors; however, the results can be compared against each other, because both lamps were used in the same reactor.

On the two Title 22+ sampling days in Phase 3, only NDMA and NDEA were detected in the MBR-RO permeate; all other nitrosamines and 1,4-dioxane were at concentrations below reporting limits. Results for NDMA and NDEA are summarized in Table 6-5. The NDMA target concentration of 10 ng/L was achieved with the LP lamp on both days, but not with the MP lamp. Consistent with the results from the Trojan LP UV reactors, NDEA was more difficult to remove, and the NDEA target concentration of 10 ng/L was not achieved with either lamp. The LP lamp provided a clear benefit over the MP lamp, with better removal of both NDMA and NDEA at lower EED values (i.e., lower energy use).

Table 6-5. Comparison of LP and MP UV for Treatment of NDMA and NDEA

Compound	Effluent	UV EED (kWh/kgal)	5/15/2012 Conc. (ng/L)	5/15/2012 Log Removal	5/22/2012 Conc. (ng/L)	5/22/2012 Log Removal
NDMA	MBR-RO	--	220	--	790	--
	LP	0.9	4.3	1.7	4.4	2.3
	MP	1.5	14	1.2	20	1.6
NDEA	MBR-RO	--	200	--	130	--
	LP	0.9	19	1.0	16	0.9
	MP	1.5	54	0.6	24	0.7

6.4 COMPARISON OF THE UF AND MBR TRAINS

This section compares the UF and MBR trains for treatment of nitrosamines and 1,4-dioxane. Section 6.4.1 compares the UF and MBR, Section 6.4.2 compares the RO units on the two trains, and Section 6.4.3 compares AOP on the two trains.

6.4.1 Comparison of the UF and MBR

Figure 6-18 compares the concentrations of the nitrosamines and 1,4-dioxane in the UF filtrate and MBR permeate. Figure 6-19 compares the median removals across the UF and MBR; error bars represent the minimum and maximum observed removals. Concentrations were compared for Phases 1 and 3, because no UF samples were taken during Phase 2. Removals were compared only where valid values could be calculated for both the UF and MBR; see Sections 6.2.1 and 6.3.1 for details on the determination of valid removals.

Figure 6-18. Comparison of UF and MBR Effluents.
Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.

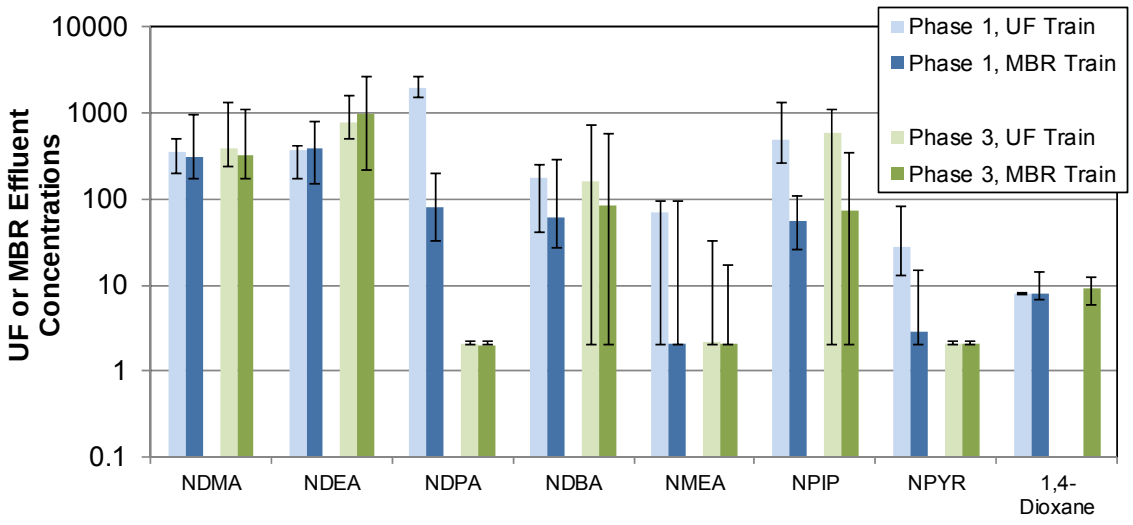
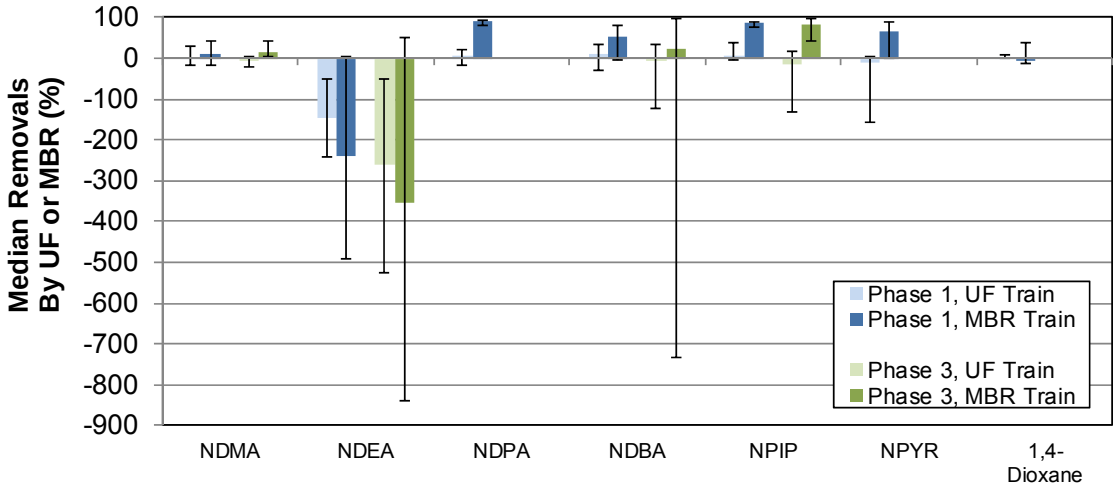


Figure 6-19. Comparison of Median Removals of Nitrosamines and 1,4-Dioxane by UF and MBR.



The MBR removed significantly more NDPA, NPIP, and NPYR than the UF for all compared operational phases. Median concentrations of these three compounds were also lower in the MBR permeate than in the UF filtrate, though the differences were significant only for NDPA and NPIP in Phase 1. The median removal by the MBR was higher than by the UF for NDMA and NDBA, although the differences were statistically significant only in Phase 1 for NDBA and only in Phase 3 for NDMA. The median concentrations in MBR permeate were lower than in the UF filtrate for both compounds, but the differences were not statistically significant. For NDEA, concentrations and percent formation were higher for the MBR, but the differences were not significant.

Overall, these results indicate that the MBR provided better treatment of five nitrosamine compounds (NDMA, NDPA, NDBA, NPIP, and NPYR) than the UF did. These differences are likely due to the biological activity under the in the MBR, where aerobic degradation can occur. The differences in NDEA concentrations, although not statistically significant, may reflect differences in the underlying sources of the NDEA. NDEA formation could be attributed to the addition of chloramines for the UF, but not for the MBR; formation across the MBR may have been due to biological activity, but more research is needed to definitively identify the cause(s).

6.4.2 Comparison of the RO Permeates from the UF and MBR Trains

Figure 6-20 compares the concentrations of the nitrosamines and 1,4-dioxane in the RO permeates from the UF and MBR trains. Figure 6-21 compares the median removals for the two trains, across the RO units and the combination of the UF-RO or MBR-RO; error bars represent the minimum and maximum observed removals. Removals were compared only where valid values could be calculated for both RO units; see Sections 6.2.2 and 6.3.2 for details on the determination of valid removals.

Figure 6-20. Comparison of RO Permeates from the UF and MBR Trains For Nitrosamines and 1,4-Dioxane.

Concentrations in ng/L, except for 1,4-Dioxane, which has units of µg/L.

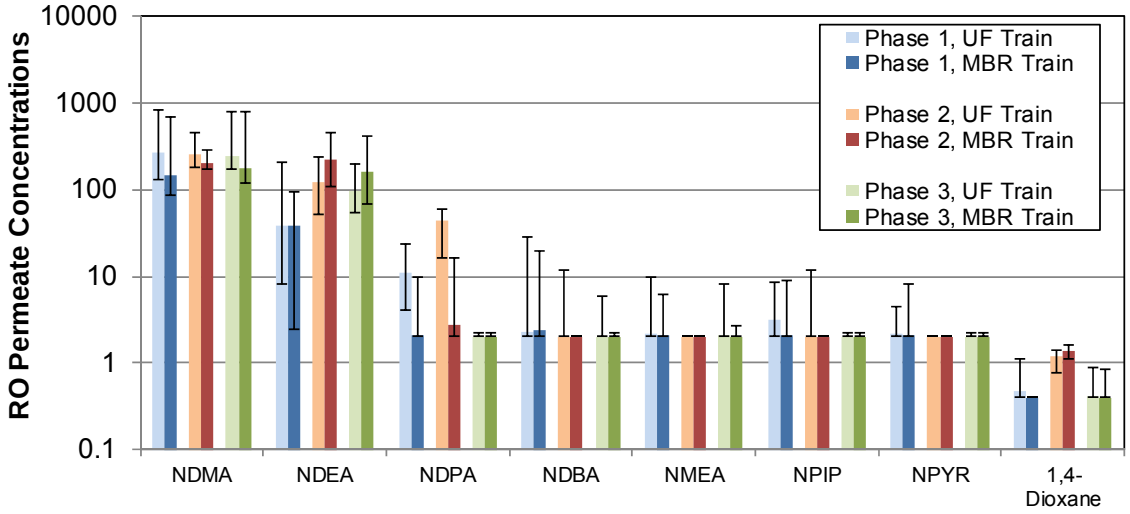
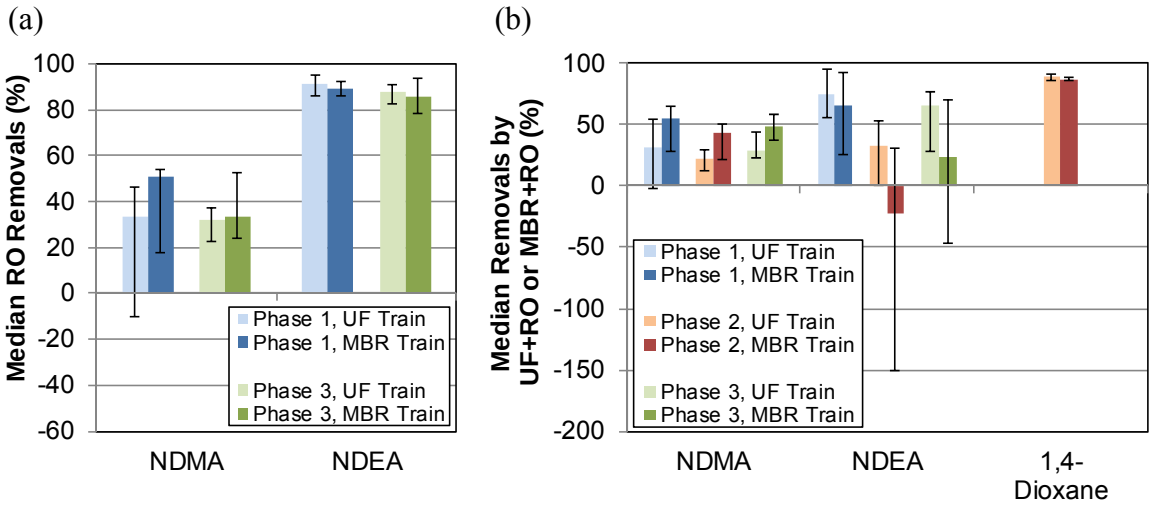


Figure 6-21. Comparison of Median Removals of Nitrosamines and 1,4-Dioxane on the UF and MBR Trains by (a) RO Alone and (b) the Combination of UF-RO or MBR-RO.



During Phase 1, NDMA removal by RO was significantly better on the MBR train than on the UF train, and MBR-RO permeate concentrations were significantly lower. The cause of this difference is unknown; however, organic fouling could play a role. Literature reports that fouling by biological organic material can decrease rejection of NDMA by RO membranes (Steinle-Darling *et al*., 2007), and the membrane autopsy after Phase 1 indicated that the RO membranes on the UF train were more heavily fouled (Section 4.3).

NDMA removals by the combination of MBR and RO were also significantly greater than removals by the combination of UF and RO during all three phases. This result is not surprising, because for all operational phases where removals could be calculated, median removals were greater in the MBR than in the UF, and were greater for the RO on the MBR train than for the RO on the UF train. Although the differences were not always significant for each individual unit, it appears that the combination of units produced a statistically observable benefit for the MBR-RO system.

There was no statistically significant difference between the RO units on the UF and MBR trains for the removal of NDEA or 1,4-dioxane, and the median removals of 1,4-dioxane for the combination of UF-RO and MBR-RO were similar (89 and 86%, respectively). However, the removal of NDEA by the combination of MBR and RO was worse than by the combination of UF and RO during all three phases, and the difference was statistically significant during Phases 2 and 3. This result was likely due to a greater production of NDEA across the MBR than across the UF.

6.4.3 Comparison of the AOP Effluents

Figures 6-22 to 6-24 compare the UF-RO or MBR-RO effluents for removal of 1,4-dioxane, NDMA, and NDEA, respectively, at each of the tested UV EED values. A statistical ANOVA test was performed to determine whether the effluent source (UF-RO or MBR-RO permeate) had a significant effect; concentrations below reporting limits were not included in the analysis. The results are summarized at the end of Appendix F

For 1,4-dioxane, there was no removal from either effluent when the UV EED was zero, and the effluent source had no significant effect. However, when UV was dosed at 2, 4, or 6 kWh/kgal, removal of 1,4-dioxane was significantly higher in the MBR-RO effluent. This result is reflected in the fact that the estimated hydrogen peroxide doses required for treatment were lower for MBR-RO effluent than for UF-RO effluent. For example, at an EED of 4 kWh/kgal, the doses required to achieve the target 0.5-log removal were ~2 mg/L for MBR-RO effluent vs. ~3 mg/L for UF-RO effluent.

For NDMA and NDEA, there was also no removal from either effluent when the UV EED was zero, and the effluent source had no significant effect. A statistically significant effect of effluent source was observed only at an EED of 2 kWh/kgal for NDMA and 4 kWh/kgal for NDEA. In both cases, removal was significantly higher in the MBR-RO effluent, similar to 1,4-dioxane. No statistically significant effect of effluent source was observed at 6 kWh/kgal, possibly because many of the data points were below the reporting limit; for these points, the true removal value is unknown (e.g., “>1-log” could be 1.1-log, 4-log, or another value altogether) and could not be included in the comparison.

Overall, the comparison of the UF-RO and MBR-RO effluents suggests that removals may be slightly better in MBR-RO effluent than in UF-RO effluent. This trend is likely caused by differences in the water quality, such as the higher UVT in the MBR-RO effluent (which would allow higher levels of radiation to pass through the effluent), or lower alkalinity (which is a scavenger for peroxide radicals). Although the magnitude of the effect was only ~0.1 to 0.2-log, these differences could result in hydrogen peroxide doses that are 1 to 2 mg/L lower for the MBR-RO effluent than the UF-RO effluent.

Figure 6-22. Comparison of UF-RO and MBR-RO Effluents for Removal of 1,4-Dioxane at UV EED Values of (a) 0, (b) 2, (c) 4, and (d) 6 kWh/kgal.

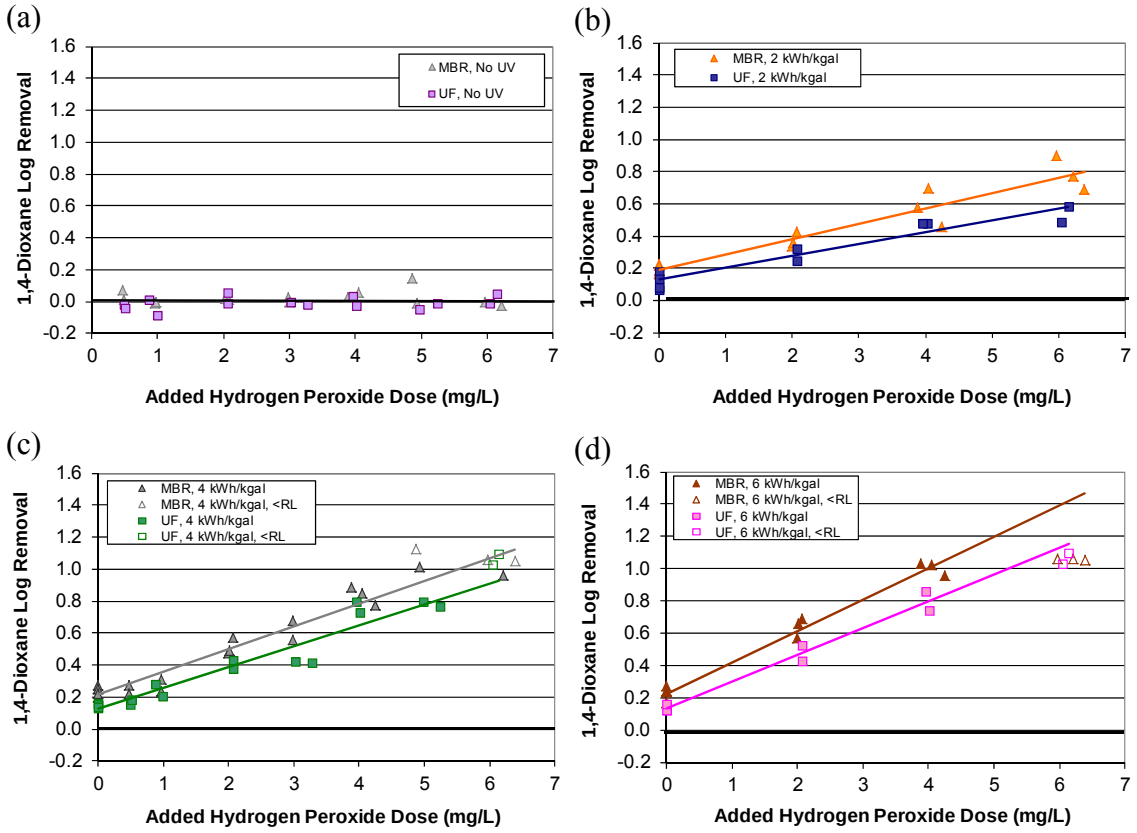
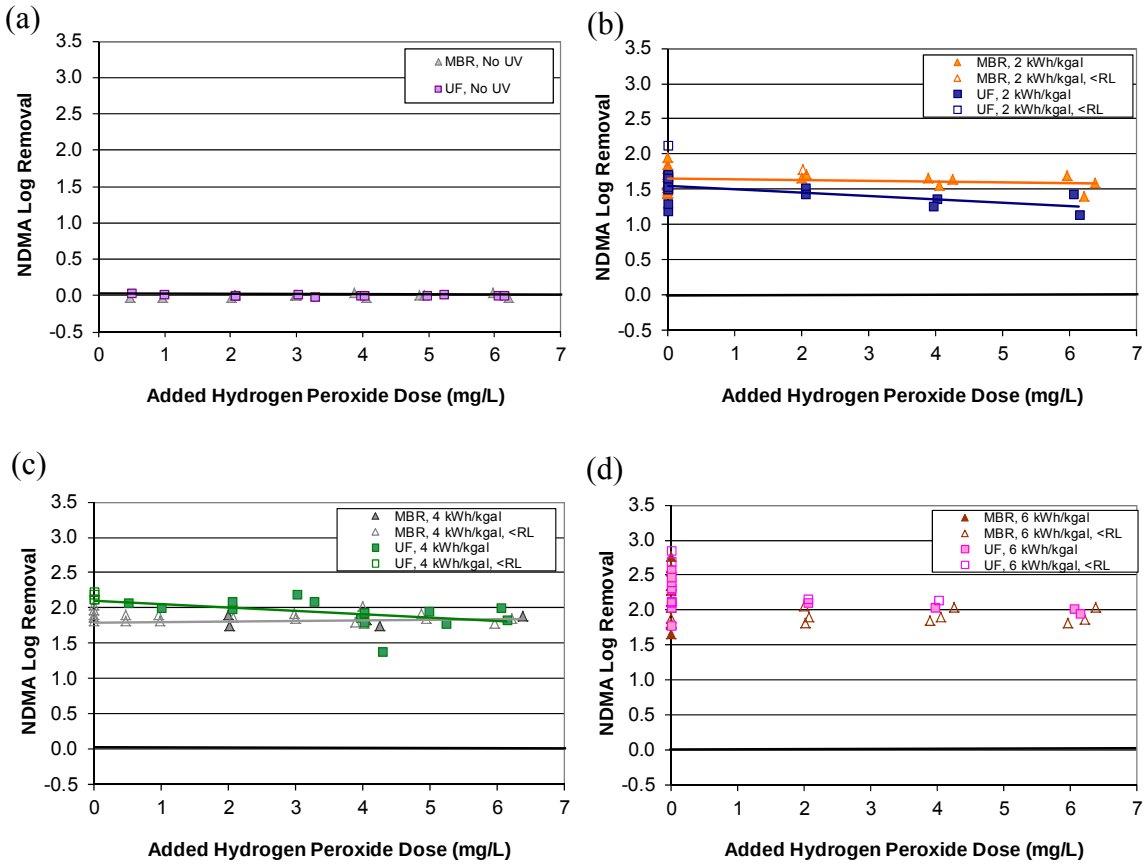
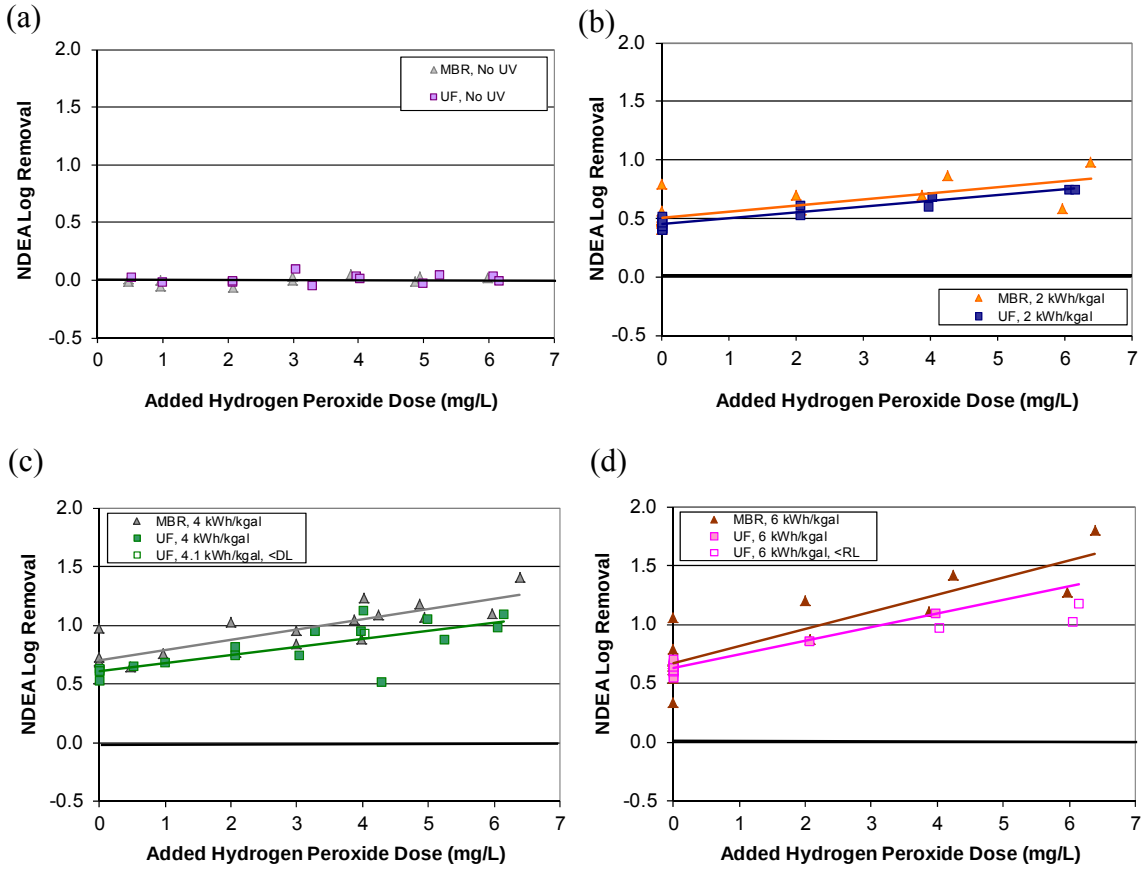


Figure 6-23. Comparison of UF-RO and MBR-RO Effluents for Removal of NDMA at UV EED Values of (a) 0, (b) 2, (c) 4, and (d) 6 kWh/kgal*.



*Note: In Figure 6-23d, there were not enough samples with concentrations above the reporting limits to provide a regression line.

Figure 6-24. Comparison of UF-RO and MBR-RO Effluents for Removal of NDEA at UV EED Values of (a) 0, (b) 2, (c) 4, and (d) 6 kWh/kgal.



6.5 SUMMARY

In pilot-scale system, the UF had very little effect on most of the nitrosamines and 1,4-dioxane. The exception was NDEA, which increased in concentration across the UF. The MBR affected all compounds except 1,4-dioxane. MBR removals of NDPA, NPIP, and NPYR were statistically significant in all operational phases where the MBR influent and effluent concentrations were above reporting limits. NDMA and NDBA were removed to a lesser degree, and the removals were not consistently significant. Similar to the UF, the concentrations of NDEA increased across the MBR. Further research is needed to determine the cause(s) of this increase. Overall, the results indicate that MBR provides better removal of NDMA, NDPA, NDBA, NPIP, and NPYR than the UF does.

The RO membranes were effective at removing most of the nitrosamines to below the target concentrations. The exceptions were NDMA and NDEA, with concentrations consistently above target levels, and NDPA and 1,4-dioxane, with concentrations occasionally above target levels.

The AOP successfully achieved target removals of 1,4-dioxane, NDMA, and NDPA. NDEA targets based on the maximum observed RO permeate concentrations were not achieved at the tested doses; however, the targets could likely be met by increasing the doses, by reducing the influent concentrations through source control, and/or by choosing a different influent concentration (e.g., the 90th percentile, rather than the maximum value).

None of the compounds were affected by hydrogen peroxide alone. NDMA removal increased with increasing UV dose, but hydrogen peroxide had no effect on removal. Removals of NDEA, NDPA, and 1,4-dioxane increased with increasing doses of either UV or hydrogen peroxide. Removals were generally slightly better in the MBR-RO effluent, which could result in lower hydrogen peroxide doses (by 1-2 mg/L) to meet regulatory removal requirements. Finally, the LP lamps provided a clear benefit over the MP lamps, with better removal of both NDMA and NDEA at lower EED values (i.e., lower energy use).

7. WATER QUALITY RESULTS: TITLE 22+ PARAMETERS

In this chapter, results from the Title 22+ sampling events are discussed, excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6. A total of 291 parameters were analyzed for this chapter; a full list of parameters and their reporting limits is provided in Appendix C. The Title 22+ parameters were grouped into fourteen categories: general physical parameters such as turbidity, general mineral parameters such as chloride, trace metals, radiological analytes, microbes, hormones, industrial endocrine-disrupting compounds (EDCs), pharmaceuticals and personal care products (PPCPs), other wastewater indicators such as caffeine, volatile organic compounds, semi-volatile organic compounds, carbamate pesticides, State Water Resources Control Board (SWRCB) surrogates, and other chemicals. Throughout this chapter, hormones, EDCs, PPCPs, and other wastewater indicators are sometimes collectively referred to as "trace organic constituents."

There were a total of six sampling events, which were conducted in three sets: from the UF train during Phase 1 (February 16 and 23, 2011), from the MBR train during Phase 1 (March 2 and 9, 2011), and from the MBR train during Phase 3 (May 15 and 22, 2011). In some cases, parameters were detected on only one of the two sampling days in a set. Because the compounds were inconsistently detected and the detected concentrations were generally very low, accurate removal values could not be calculated. Therefore, the data for these compounds are not discussed in this chapter. Complete data for all detected compounds (including those inconsistently detected) at all locations are provided in Appendix G.

This chapter is organized by sampling location: secondary effluent (Section 7.1), UF train (Section 7.2), and MBR train (Section 7.3). The two trains are compared in Section 7.4, and results are summarized in Section 7.5. For the UF and MBR units, only parameters whose concentrations changed significantly across the unit are discussed; a change of > 25% in the average concentration was considered significant. In all tables in this chapter, "↑" denotes an increase and "↓" denotes a decrease in concentration; if the concentration decreased to below reporting limits, ">" is used. For example, a decrease in concentration from 5 mg/L to < 1 mg/L is a decrease of at least 80% and would be denoted in a table as "↓ >80".

7.1 JWPCP SECONDARY EFFLUENT

Of the 291 Title 22+ parameters measured, 78 were consistently detected in both samples of at least one set. In the UF train during Phase 1, 74 parameters were detected in both samples; 72 parameters in the MBR train during Phase 1 were detected in both samples, and 74 parameters in the MBR train during Phase 3 were detected in both samples. These compounds and their concentrations are listed in Tables 7-1 to 7-4.

The concentrations of most analytes were consistent across the six days of sampling. The biggest exception was the trace organic constituents (Table 7-3), which varied by an order of magnitude in some cases. For example, carbamazepine concentrations were below the reporting limit of 20 ng/L) in the four Phase 1 samples, but were approximately 230 ng/L in the two Phase 3 samples. Octylphenol concentrations decreased from 588 ng/L on May 15, 2012, to 42 ng/L on May 22, 2012. Another exception was MTBE, which ranged from a concentration of 17 µg/L on February 16, 2011, to as low as 0.5 µg/L on March 9, 2011. The reason for the variability in the secondary effluent is mostly likely due to variations in the plant influent water quality.

Table 7-1. Title 22+ Analytes Detected in Secondary Effluent: General Parameters

Category	Analyte	Units	Reporting Limit	Phase 1[1] 2/16/11	Phase 1[1] 2/23/11	Phase 1[1] 3/2/11	Phase 1[1] 3/9/11	Phase 3[1] 5/15/12	Phase 3[1] 5/22/12
General Physical Parameters	Alkalinity, Total	mg $CaCO_3$/L	2	370	360	380	370	360	390
	Ammonia	mg N/L	0.05	39	37	40	38	45	42
	Apparent Color	ACU[2]	3	50	50	60	50	60	60
	Cyanide	mg/L	0.005	0.007	0.008	0.006	ND[2]	0.008	0.006
	Odor at 60ºC	TON[2]	1	200	200	200	200	200	200
	Organic Nitrogen	mg N/L	1.0	2.8	1.7	2.6	2.3	3.1	2.5
	pH	-	0.1	7.3	7.4	7.2	7.4	8.1	7.4
	Surfactants	mg/L	0.05	0.22	0.19	0.22	0.17	0.21	0.21
	Specific Conductance, 25ºC	µmho/cm	2	2,700	2,600	2,700	2,600	2,400	2,700
	Total Dissolved Solids	mg/L	10	1,400	1,400	1,400	1,400	1,300	1,500
	Total Hardness as $CaCO_3$	mg/L	3	260	250	250	260	280	270
	Total Organic Carbon	mg/L	0.5	15	15	16	15	17	18
	Turbidity	NTU[2]	0.05	2.6	2.2	1.7	1.6	3.2	3.9
	UV Transmittance (254 nm)	%	-	46.1	45.4	40.8	40.7	41.1	39.2
General Mineral Parameters	Bromide	µg/L	5	1,600	1,500	1,600	1,600	1,600	1,600
	Boron, Total	mg/L	0.05	0.89	0.89	1.1	0.90	0.92	1.0
	Calcium Total	mg/L	1	68	65	64	65	72	69
	Chloride	mg/L	1	490	480	460	460	460	500
	Fluoride	mg/L	0.05	1.2	1.0	2.4	1.1	1.1	2.3
	Magnesium, Total	mg/L	0.1	23	21	23	23	26	24
	Phosphorus, Total	mg/L	0.02	0.44	0.47	0.40	0.39	0.75	0.79
	Potassium, Total	mg/L	1	20	19	23	22	21	22
	Sodium, Total	mg/L	1	390	370	430	390	360	430
	Sulfate	mg/L	0.5	220	240	220	210	190	250

[1]The UF train was sampled on February 16 and 23, 2011; the MBR train was sampled on four dates: March 2 and 9, 2011, and May 15 and 22, 2012.
[2]ACU = Apparent color unit; ND = not detected; NTU = nephelometric turbidity unit; TON = threshold odor number.

Table 7-2. Title 22+ Analytes Detected in Secondary Effluent: Trace Metals, Radiological Analytes, and Microbes

Category	Analyte	Units	Reporting Limit	Phase 1[1] 2/16/11	Phase 1[1] 2/23/11	Phase 1[1] 3/2/11	Phase 1[1] 3/9/11	Phase 3[1] 5/15/12	Phase 3[1] 5/22/12
Trace Metals	Aluminum, Total	µg/L	20	22	21	24	27	22	28
	Antimony, Total	µg/L	1	2.5	2.2	7.5	2.8	4.1	2.3
	Arsenic, Total	µg/L	1	3.7	2.8	1.6	1.8	2.3	5.0
	Barium, Total	µg/L	2	130	110	130	130	120	140
	Chromium	µg/L	1	1.6	1.5	1.5	ND[1]	1.1	ND[1]
	Iron, Total	mg/L	0.02	1.2	1.1	1.3	1.4	1.4	1.5
	Manganese	µg/L	2	96	90	110	92	120	100
	Nickel, Total	µg/L	5	12	11	10	9.3	8.7	9.7
	Selenium, Total	µg/L	5	14	8.6	9.7	9.9	ND[1]	9.2
Radiological	Gross Beta	pCi/L	1.7-3.4	11	7.6	12	10	15	12
	Uranium	pCi/L	0.7	1.4	1.2	1.6	1.2	1.1	1.6
Microbes	Cryptosporidium	Oocysts/10L	1	2	2	2	1	NS[2]	NS[2]
	Giardia	Cysts/10L	1	1,680	1,330	1,530	1,920	NS[2]	NS[2]
	Heterotrophic Plate Count	cfu/mL	1	>5,700	>5,700	>5,700	>5,700	<1[3]	>5,700
	Total Coliform	MPN/100 mL	1.1	>23	>23	>23	>23	>2,400[4]	>23
	Fecal Coliform	MPN/100 mL	1.1	>23	>23	>23	>23	>2,400[4]	>23
	E. Coli	MPN/100 mL	2	>23	>23	>23	>23	>2,400[4]	>23[4]

[1]The UF train was sampled on February 16 and 23, 2011; the MBR train was sampled on four dates: March 2 and 9, 2011, and May 15 and 22, 2012.

[2]ND = not detected, NS = not sampled

[3]This sample had an unusually low HPC value; the laboratory likely switched this sample with the LP UV sample, which was expected to be < 10 cfu/mL but was > 5,700 cfu/mL on this date.

[4]Method SM 9223B was used to analyze total coliform and fecal coliform on May 15, 2012, and E. coli on May 15 and 22, 2012. This method had a different measurement range (on May 15, 2012) from SM 9221B, which was used for all other total coliform, fecal coliform, and E. coli samples.

Table 7-3. Title 22+ Analytes Detected in Secondary Effluent: Trace Organic Constituents

Category	Analyte	Units	Reporting Limit	Phase 1[1] 2/16/11	Phase 1[1] 2/23/11	Phase 1[1] 3/2/11	Phase 1[1] 3/9/11	Phase 3[1] 5/15/12	Phase 3[1] 5/22/12
Hormones	17β-Estradiol	ng/L	1.2-2.0	7.3	ND[3]	ND[3]	ND[3]	6.7	10
	Estrone	ng/L	10	26	32	19	22	23	46
Industrial	Bisphenol A	ng/L	25	165	119	403	123	616	448
EDCs	4-Nonylphenol (Tech Mix)	ng/L	25	990	1,100	1,000	1,200	2,900	618
	Nonylphenol Monoethoxylate	ng/L	125	2,360	2,630	2,670	3,280	4,820	5,120
	Nonylphenol Diethoxylate	ng/L	125	8,000	9,550	8,100	9,700	6,980	7,000
	4-tert Octylphenol	ng/L	25	630	460	630	780	588	42
	Octylphenol Monoethoxylate	ng/L	125	1,400	1,040	1,090	1,270	1,160	1,000
	Octylphenol Diethoxylate	ng/L	125	4,850	4,150	3,530	3,860	1,560	1,540
PPCPs	Azithromycin	ng/L	10	1,010	991	984	883	450	244
	Acetaminophen	ng/L	10-20[2]	24	16	ND[3]	ND[3]	39	42
	Carbamazepine	ng/L	10-20[2]	ND[3]	ND[3]	ND[3]	ND[3]	234	230
	DEET	ng/L	10	518	494	396	401	388	274
	Dilantin	ng/L	25	310	308	300	323	1,520	1,330
	Gemfibrozil	ng/L	20	1,170	1,180	1,210	1,080	410	366
	Ibuprofen	ng/L	10-20[2]	ND[3]	ND[3]	ND[3]	ND[3]	84	24
	Meprobamate	ng/L	10	394	363	414	387	772	746
	Sulfamethoxazole	ng/L	10	958	1,000	1,270	978	638	724
	Triclosan	ng/L	25	499	466	420	488	656	700
Other	Caffeine	ng/L	10	392	353	515	291	840	652
Wastewater	Iopromide	ng/L	30	1,010	871	645	759	1,280	1,140
Indicators	Sucralose	ng/L	40	20,800	19,900	21,000	19,300	30,800	33,600
	TCEP	ng/L	10	339	396	381	418	486	464

[1]The UF train was sampled on February 16 and 23, 2011; the MBR train was sampled on four dates: March 2 and 9, 2011, and May 15 and 22, 2012.
[2]Reporting limit was 10 ng/L for samples taken in 2011, 20 ng/L for samples taken in 2012.
[3]ND = not detected.

Table 7-4. Other Title 22+ Analytes Detected in Secondary Effluent

Category	Analyte	Units	Reporting Limit	Phase 1[1] 2/16/11	Phase 1[1] 2/23/11	Phase 1[1] 3/2/11	Phase 1[1] 3/9/11	Phase 3[1] 5/15/12	Phase 3[1] 5/22/12
Volatile	Dibromomethane	µg/L	0.5	0.71	0.58	0.58	0.66	0.68	0.67
Organic	Bromochloromethane	µg/L	0.5	0.66	0.62	0.54	0.66	0.94	0.78
Compounds	Dichloromethane	µg/L	0.5	2.3	3.4	5.3	2.5	2.7	3.2
	Chloroform	µg/L	0.5	11	10	11	12	12	8.8
	Total THM	µg/L	0.5	11	11	11	13	13	8.8
	Methyl Tert-butyl Ether (MTBE)	µg/L	0.5	17	3.0	0.7	0.5	1.0	0.71
SVOCs	Di(2-Ethylhexyl) Phthalate	µg/L	0.6	ND[2]	ND[2]	1.7	2.0	ND[2]	ND[2]
Carbamate	3-Hydroxycarbofuran	µg/L	0.5	1.6	1.3	1.9	2.2	2.1	1.3
Pesticides	Aldicarb Sulfone	µg/L	0.5	1.8	1.9	2.5	2.1	1.6	1.5
SWRCB Surrogates	Dissolved Organic Carbon	mg/L	0.5	12.0	12.5	13.6	12.6	13.6	14.6
Other	t-Butyl Alcohol	µg/L	2	8.0	7.9	10	7.5	8.4	6.5
Chemicals	Carbon Disulfide	µg/L	0.5	1.5	0.52	0.68	2.2	2.3	1.8
	Chlorate	µg/L	10	50	30	24	29	33	ND[2]
	Formaldehyde	µg/L	5	19	18	15	22	24	20
	Phenol	µg/L	0.2	0.29	0.28	0.48	0.25	0.27	ND[2]

[1]The UF train was sampled on February 16 and 23, 2011; the MBR train was sampled on four dates: March 2 and 9, 2011, and May 15 and 22, 2012.
[2]ND = not detected.

7.2 TREATMENT TRAIN #1: UF-RO-AOP

7.2.1 UF Results

Of the 74 analytes that were consistently detected in the secondary effluent (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6), UF had a clear effect on 21 analytes. These analytes are listed in Table 7-5, along with the total chlorine residual, which increased across the UF to consistently detected levels. The values listed in Table 7-5 are the average of the two values for the sample sets taken on February 16 and 23, 2011.

Table 7-5. Results for the UF

Category	Analyte	Units	Secondary Effluent	UF filtrate	% Change
General	Cyanide	mg/L	0.007	0.021	↑ 182
Parameters	Organic Nitrogen	mg N/L	2.3	1.3	↓ 44
	Total Phosphorus	mg P/L	0.46	0.15	↓ 67
	Turbidity	NTU*	2.4	0.13	↓ 95
	UV Transmittance (254 nm)	%	45.8	57.4	↑ 25
Trace Metals	Iron	mg/L	1.2	0.11	↓ 90
Microbes	Cryptosporidium	Oocysts/10L	2	<1	↓ >50
	Giardia	Cysts/10L	1,510	0.5	↓ 100
	Heterotrophic Plate Count	cfu/mL	>5,700	66	↓ > 98
	Total Coliform	MPN/100 mL	>23	<1.1	↓ > 95
	Fecal Coliform	MPN/100 mL	>23	<1.1	↓ > 95
	E. Coli	MPN/100 mL	>23	<2	↓ > 91
Hormones	Estrone	ng/L	29	14	↓ 53
Industrial EDCs	Bisphenol A	ng/L	142	35	↓ 76
	4-Nonylphenol (Tech Mix)	ng/L	1,050	475	↓ 55
	Nonylphenol Monoethoxylate	ng/L	2,490	1,850	↓ 26
	4-tert Octylphenol	ng/L	545	305	↓ 44
PPCPs	Sulfamethoxazole	ng/L	979	712	↓ 27
	Triclosan	ng/L	483	348	↓ 28
SWRCB Surrogates	Total Chlorine Residual	mg/L	<0.05	4.4	↑ >8,600
Other Chemicals	Chlorate	µg/L	40	615	↑ 1,438
	Formaldehyde	µg/L	19	40	↑ 116

*NTU = nephelometric turbidity unit

The UF removed solids from the effluent, which probably accounts for the observed increase in UV transmittance and the removal of the turbidity, phosphorus, organic nitrogen, iron, and microorganisms. Several trace organic constituents were also removed by the UF, most likely due to sorption to solids that were then removed by the UF membranes (Snyder *et al*., 2007; Coleman *et al*., 2009; Cirja *et al*., 2006). Additional removal may have occurred through reaction with the chlorine that was added to the UF influent to form chloramines, which helped control biofouling of the membranes (Tang et al., 2010).

Chlorine addition increased the total chlorine residual, and may have also caused the observed increases in cyanide and formaldehyde, which are known disinfection byproducts (DBPs) of chlorination (USEPA, 1999; Kavanaugh et al., 2003; Na and Olson, 2006; Krasner et al., 1989), and chlorate, which is formed in hypochlorite solutions due to the decomposition of hypochlorite (Bolyard *et al*., 1992).

In summary, 74 analytes were detected in the UF influent. Four types of microorganisms were removed to below detection: Cryptosporidium, total coliform, fecal coliform, and E. coli. The concentrations of an additional four compounds (aluminum, vanadium, radium 228, and carbon disulfide) also decreased to below the reporting limit; these compounds were not listed in Table 7-5, because the level in the UF filtrate were generally very close to the reporting limit, so the change across the UF was small. The total chlorine residual increased to consistently detected levels. Overall, a total of 67 analytes were detected in the UF filtrate.

7.2.2 RO Results

RO effectively removed most of the Title 22+ parameters. Of the 67 analytes that were detected in the UF filtrate (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6), 19 were consistently detected in the RO effluent. These analytes are listed in Table 7-6.

The pH decreased across RO, because sulfuric acid was added to the RO influent to reduce precipitation and inorganic fouling of the membranes. The UV transmittance increased across RO, likely due to the additional removal of particles and organics. Of the other detected analytes, most were removed by > 90%. The exceptions were boron, which was removed by 33%; formaldehyde, which was reduced by 83%; chloroform and total THMs (which consisted primarily of chloroform), which were reduced by < 50%; and the dihalomethanes and total chlorine residual, which showed very little removal by RO. All of these compounds are small molecules, which are difficult to remove by RO.

In summary, 67 analytes were detected in the RO influent. Most were effectively removed by RO to below detection. A total of 19 analytes were detected in the UF-RO effluent. As shown in Table 7-6, the target concentrations were met for all parameters except boron, which is discussed in more detail in Section 5.3.1, and pH. The RO permeate would likely require treatment (e.g., decarbonation and lime addition) to raise the pH before use.

Table 7-6. Results for the UF-RO

Category	Analyte	Units	UF Filtrate	RO Permeate	% Change	Target Conc.
General Parameters	Alkalinity, Total	mg $CaCO_3$/L	360	19	↓ 95	NA*
	Ammonia	mg N/L	38	1.3	↓ 97	NA*
	Boron	mg/L	0.89	0.59	↓ 33	0.5
	Bromide	µg/L	1,550	32	↓ 98	NA*
	Chloride	mg/L	490	6.8	↓ 99	100
	Fluoride	mg/L	1.1	0.09	↓ 91	2
	pH	-	7.5	5.7	↓ 23	6.5-8.5
	Sodium	mg/L	375	10	↓ 97	NA*
	Specific Conductance, 25ºC	µmho/cm	2,700	71	↓ 97	1,600
	Total Dissolved Solids	mg/L	1,400	26	↓ 98	450
	UV Transmittance (254 nm)	%	57.4	96.6	↑ 68	NA*
Volatile Organic Compounds	Dibromomethane	µg/L	0.65	0.59	↓ 9	NA*
	Bromochloromethane	µg/L	0.62	0.64	↑ 3	NA*
	Dichloromethane	µg/L	2.7	2.5	↓ 8	5
	Chloroform	µg/L	10	5.7	↓ 46	NA*
	Total THM	µg/L	11	5.7	↓ 46	80
SWRCB Surrogates	Total Chlorine Residual	mg/L	4.4	4.1	↓ 6	NA*
Other Chemicals	Chlorate	µg/L	615	13	↓ 98	800
	Formaldehyde	µg/L	40	6.8	↓ 83	100

*NA = Not applicable.

7.2.3 AOP Results

The full suite of Title 22+ parameters was sampled on February 16, 2011; only the polybrominated diphenyl ether compounds and trace organic constituents were measured on February 23, 2011. Nineteen analytes (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6) were detected in the UF-RO effluent, and the concentrations of an additional six compounds rose to detectable levels in the AOP effluent. Table 7-7 presents the results for these 25 analytes. For Phase 1, only data from February 16, 2011, were considered, because no AOP samples were taken on February 23, 2012; consequently, the RO permeate concentrations do not necessarily match the values in Table 7-6.

Alkalinity decreased slightly, possibly due to the reaction of bicarbonate ions with hydroxyl radicals (Wang *et al.*, 2000). UV photolysis of chloramines (Watts and Linden, 2007) likely caused the observed decrease in the total chlorine residual, and increases in the concentrations of nitrate and chloride. Nitrate may also have been formed from the reaction of ammonia with hydroxyl radicals (Bonsen et al., 1997; Pollema et al., 1992); this reaction has been observed in photocatalytic TiO_2 systems, which also utilize hydroxyl radicals. Bromide concentrations also increased; reasons for this increase are unclear.

Table 7-7. Title 22+ Results for AOP (UF Train)

Category	Analyte	Units	RO Permeate[1]	AOP Effluent	% Change
General	Alkalinity, Total	mg $CaCO_3$/L	22	14	↓ 36
Parameters	Ammonia	mg N/L	1.3	1.3	0
	Boron	mg/L	0.57	0.60	↑ 5
	Bromide	µg/L	31	48	↑ 55
	Chloride	mg/L	6.8	9.1	↑ 34
	Fluoride	mg/L	0.09	0.11	↑ 17
	Nitrate	mg N/L	< 0.05	0.16	↑ > 220
	Nitrate + Nitrite, Total	mg N/L	< 0.1	0.16	↑ > 60
	pH	-	5.5	5.6	↑ 2
	Sodium	mg/L	10	11	↑ 10
	Specific Conductance, 25ºC	µmho/cm	74	72	↓ 3
	Total Dissolved Solids (TDS)	mg/L	26	30	↑ 15
	UV Transmittance (254 nm)	%	97.0	99.0	↑ 2
Trace	Chromium, Hexavalent	µg/L	< 0.05	0.13	↑ > 160
Metals	Copper	µg/L	< 2	27	↑ > 1,250
	Lead	µg/L	< 0.5	0.68	↑ > 36
Volatile	Dibromomethane	µg/L	0.67	< 0.5	↓ > 25
Organic	Bromochloromethane	µg/L	0.66	0.57	↓ 14
Compounds	Dichloromethane	µg/L	1.8	1.6	↓ 11
	Chloroform	µg/L	5.9	5.2	↓ 12
	Total THM	µg/L	5.9	5.2	↓ 12
SWRCB	Dissolved Organic Carbon	mg/L	<0.50	0.65	↑ > 30
Surrogates	Total Chlorine Residual	mg/L	3.7	0.4	↓ 88
Other	Chlorate	µg/L	11	< 10	↓ > 9
Chemicals	Formaldehyde	µg/L	7.3	27	↑ 270

[1]Values are from only February 16, 2011, when matching samples from the AOP were taken; these numbers may not match the average RO values in Table 7-6.

Among the organic compounds, formaldehyde concentrations increased across the AOP; this observation is consistent with published literature on UV disinfection (Awad, 1993; Malley *et al*., 1995). Despite the increase, the formaldehyde concentration in the final product water was well below the target concentration of 100 µg/L. In addition, dibromomethane concentrations decreased slightly and dissolved organic carbon concentrations increased slightly, but these changes were small, and may be within normal sampling/analytical variability.

Finally, the concentrations of hexavalent chromium, copper, and lead increased. These increases may indicate that the RO permeate leached metals from the UV reactors or fittings; care should be taken to ensure that such leaching does not occur in the full-scale system. Despite the increases, the final concentrations of all analytes except boron remained below the applicable target concentrations.

7.3 TREATMENT TRAIN #2: MBR-RO-AOP

7.3.1 MBR Results

Of the 72 analytes that were consistently detected in the secondary effluent (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6), the MBR had affected 40 analytes. These 40 analytes are listed in Tables 7-8 and 7-9, along with acetaminophen and the two nitrate analytes, which increased across the MBR to detectable levels.

The performance of the MBR was generally quite similar in Phases 1 and 3. The three exceptions were chromium, phenol, and acetaminophen. Chromium concentrations decreased by 0.3 μg/L in Phase 1, but increased by 9.8 μg/L in Phase 3. Phenol decreased by > 0.17 μg/L in Phase 1, but increased by 0.19 μg/L in Phase 3. Acetaminophen increased by 22 ng/L in Phase 1, but concentrations did not change in Phase 3. The relatively small magnitude of the changes and the inconsistent behavior suggests that the MBR has little effect on any of these compounds.

Like the UF, the MBR removed solids from the effluent, which may account for the observed increase in UV transmittance and the removal of the turbidity, phosphorus, some organic nitrogen, iron, aluminum, and microorganisms. In addition, biological nitrification within the MBR decreased concentrations of ammonia, organic nitrogen, alkalinity, and organic matter (TOC and DOC) and increased concentrations of nitrate.

Literature indicates that biological activity may also be responsible for decreases in the levels of color, formaldehyde, t-butyl alcohol, trihalomethanes, and dichloromethane (Williams and Pirbazari, 2007; Jerusutthirak *et al*., 2011; Morrison *et al*., 2002; Wahman *et al*., 2006; Wahman *et al*., 2005; IPCS, 1996). In addition, the decrease in manganese levels may be attributable to uptake and oxidation by microbes in the MBR (Nealson, *et al*., 1998). Although reduced manganese is soluble, the oxidized form is a precipitate that can be filtered out by the membranes. Abiotic oxidation by oxygen or chlorine is relatively slow at neutral pH (Crittenden *et al*., 2005), but oxidation by bacteria and other microorganisms can be faster (Nealson *et al*., 1988).

For the trace organic constituents, concentrations of sulfamethoxazole increased, while the concentrations decreased for the other 11 compounds (excluding acetaminophen, which was discussed above). The changes in the sulfamethoxazole concentrations may simply represent the natural variability in the samples or analyses. Both the UF and MBR provided removal of several trace organic constituents, but the UF generally provided more removal of the following six compounds: estrone, bisphenol A, nonylphenol, nonylphenol monoethoxylate, octylphenol, and triclosan. The extra removal of these compounds by the MBR may be due to biological activity, sorption to solids that were then removed from the effluent by the membranes, or a combination of the two mechanisms (Schröder et al., 2006; Chen et al., 2008; Coleman et al., 2009; Snyder et al., 2007). Six compounds were removed by the MBR but not the UF: nonylphenol diethoxylate, octylphenol diethoxylate, octylphenol monoethoxylate, gemfibrozil, DEET, and caffeine. These results are consistent with biological activity, which has been reported in the literature for these compounds (Snyder et al., 2007; Schröder et al., 2006; Chen et al., 2008; Coleman et al., 2009).

Table 7-8. Title 22+ Results for the MBR: General Parameters, Trace Metals, Radiological Analytes, and Microbes

Category	Analyte	Units	Phase 1 Secondary Effluent	Phase 1 MBR Permeate	Phase 1 % Change	Phase 3 Secondary Effluent	Phase 3 MBR Permeate	Phase 3 % Change
General	Alkalinity, Total	mg $CaCO_3$/L	375	110	↓ 71	375	103	↓ 73
Parameters	Ammonia	mg N/L	39	0.06	↓ 100	44	0.08	↓ 100
	Apparent Color	ACU[1]	55	40	↓ 27	60	30	↓ 50
	Cyanide	mg/L	[2]	[2]	[2]	0.007	0.009	↑ 30
	Nitrate	mg N/L	<0.05	38	↑ 75,900	<0.1	43	↑ 42,900
	Nitrate + Nitrite, Total	mg N/L	<0.1	38	↑ 37,900	<0.1	43	↑ 42,900
	Organic Nitrogen	mg N/L	2.5	<1	↓ > 60	3.1	<1	↓ > 68
	Total Organic Carbon	mg/L	15	9.6	↓ 38	18	9.0	↓ 49
	Total Phosphorus	mg P/L	0.40	0.11	↓ 72	0.77	0.32	↓ 58
	Turbidity	NTU[1]	1.7	0.14	↓ 92	3.5	0.16	↓ 96
	UV Transmittance (254 nm)	%	40.8	57.5	↑ 41	40.2	59.8	↑ 49
Trace Metals	Aluminum	µg/L	26	<20	↓ > 22	25	<20	↓ > 20
	Iron	mg/L	1.4	0.1	↓ 91	1.5	0.1	↓ 92
	Manganese	µg/L	101	51	↓ 50	110	7.2	↓ 93
Radiological	Uranium	pCi/L	1.4	2.3	↑ 64	1.4	1.8	↑ 30
Microbes	Cryptosporidium	Oocysts/10L	1.5	<1	↓ > 33	NS[1]	NS[1]	NS[1]
	Giardia	Cysts/10L	1,720	<1	↓ 100	NS[1]	NS[1]	NS[1]
	Heterotrophic Plate Count	cfu/mL	>5,700	3,350	↓ > 41	[3]	[3]	[3]
	Total Coliform	MPN/100 mL	>23	6.6	↓ > 71	>23	5.1	↓ > 78
	Fecal Coliform	MPN/100 mL	>23	1.1	↓ > 95	>23	<1	↓ > 96
	E. Coli	MPN/100 mL	>23	<2	↓ > 91	>23	<1	↓ > 96

[1]ACU = apparent color unit, NS = not sampled, NTU = nephelometric turbidity unit.
[2]Inconsistently detected.
[3]Values appeared to be unreliable, and are not included in this table. Based on samples taken on other dates, HPC values (in cfu/mL) for the secondary, MBR, and UV effluents were expected to be >5,700, approximately 3,000, and < 30, respectively. However, on May 15, 2012, the secondary effluent HPC was <1 cfu/mL and the LP UV was >5700 cfu/mL. On May 22, 2012 the MBR permeate HPC was <1 and LP UV HPC was 2,500 cfu/mL. It is likely that these two sets of samples were switched.

Table 7-9. Title 22+ Results for the MBR: Other Analytes

Category	Analyte	Units	Phase 1			Phase 3		
			Secondary Effluent	MBR Permeate	% Change	Secondary Effluent	MBR Permeate	% Change
Hormones	Estrone	ng/L	21	<10	↓ > 51	35	<1.2	↓ > 97
Industrial EDCs	Bisphenol A	ng/L	263	34	↓ 87	532	22	↓ 96
	4-Nonylphenol (tech mix)	ng/L	1,100	170	↓ 85	2,730	210	↓ 92
	Nonylphenol Monoethoxylate	ng/L	2,970	419	↓ 86	4,970	275	↓ 94
	Nonylphenol Diethoxylate	ng/L	8,900	875	↓ 90	6,990	584	↓ 92
	4-tert Octylphenol	ng/L	705	63	↓ 91	603	32	↓ 95
	Octylphenol Monoethoxylate	ng/L	1,180	<125	↓ >89	1,080	<63	↓ > 94
	Octylphenol Diethoxylate	ng/L	3,690	191	↓ 95	1,550	<63	↓ > 96
PPCPs	Acetaminophen	ng/L	<10	22	↑ > 120	41	41	↑ 1
	DEET	ng/L	399	294	↓ 26	681	234	↓ 66
	Gemfibrozil	ng/L	1,150	353	↓ 69	1,430	128	↓ 91
	Sulfamethoxazole	ng/L	1,120	1,710	↑ 52	759	1,350	↑ 77
	Triclosan	ng/L	454	86	↓ 81	678	61	↓ 91
Other Wastewater Indicators	Caffeine	ng/L	403	231	↓ 43	746	282	↓ 62
Volatile	Dichloromethane	µg/L	3.9	*	*	3.0	< 0.5	↓ > 83
Organic	Chloroform	µg/L	12	1.5	↓ 87	10	1.2	↓ 89
Compounds	Total THM	µg/L	12	1.5	↓ 88	11	1.2	↓ 89
SWRCB Surrogates	Dissolved Organic Carbon	mg/L	13	9.4	↓ 28	14	8.8	↓ 37
Other Chemicals	t-Butyl Alcohol	µg/L	8.8	<2.0	↓ > 77	7.5	<2	↓ > 73
	Chlorate	µg/L	27	<10	↓ > 63	22	<10	↓ > 53
	Formaldehyde	µg/L	19	15	↓ 22	22	15	↓ 32
	Phenol	µg/L	0.37	<0.20	↓ > 45	0.27	0.46	↑ 70

*Inconsistently detected.

The cause of the decrease in chlorate concentration is unknown. Chlorate is not volatile, and does not sorb strongly to solids (Gonce and Voudrias, 1994). It can be biodegraded under reducing conditions (van Ginkel *et al*., 1995), but should not be reduced under the aerobic conditions within the MBR.

In summary, 72 analytes were detected in the MBR influent. Three categories of microorganisms (Cryptosporidium, Giardia, and E. Coli) and six other analytes in Tables 7-8 and 7-9 (organic nitrogen, aluminum, estrone, octylphenol monoethoxylate, t-butyl alcohol, and chlorate) were removed to below detection. The concentrations of four additional analytes (carbon disulfide, bromochloromethane, dibromomethane, and MTBE) also decreased to below the reporting limit, and total chlorine residuals were increased to the reporting limit of 0.05 mg/L; these compounds were not listed in Tables 7-8 and 7-9 because the levels were generally very close to the reporting limit, so the change across the MBR was small. Concentrations of three analytes (nitrate, total nitrate and nitrite, and acetaminophen) increased from below detection to detectable levels. Overall, a total of 63 analytes were detected in the MBR permeate.

7.3.2 RO Results

RO effectively removed most of the Title 22+ parameters. Of the 63 analytes that were detected in the MBR permeate (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6), 18 were consistently detected in the RO effluent. In addition, the concentrations of two analytes (bromodichloromethane and chlorodibromomethane) increased to consistently detected levels. These 20 analytes are listed in Table 7-10.

The performance of the MBR was generally similar in Phases 1 and 3. The only exception was chloroform, which decreased by 0.2 μg/L in Phase 1 but increased by 0.35 μg/L in Phase 3; these changes are small and suggest that the RO had little effect on chloroform. The total chlorine residuals increased and the pH decreased across RO, because chloramines and sulfuric acid were added to the RO influent to reduce fouling of the membranes. The addition of chloramines (added as ammonia, followed by chlorine) likely also caused the observed increases in the concentrations of the THMs (bromodichloromethane and chlorodibromomethane) and ammonia. The UV transmittance increased across RO, likely due to the removal of particles and organics. Of the other detected analytes, most were removed by > 90%. The exceptions were turbidity, which was removed by 37-55%; boron, which was removed by 32-54%; formaldehyde, which was reduced by 30-39%; and chloroform, which showed little removal by RO. It is unclear why turbidity remained in the RO permeate, although the concentrations were close to the reporting limit of 0.05 mg/L. The other detected compounds are small molecules that are difficult to remove by RO.

In summary, 63 analytes were detected in the RO influent. Most were effectively removed by RO to below detection. A total of 20 analytes were detected in the MBR-RO effluent. As shown in Table 7-10, the target concentrations were met for all parameters except boron, which is discussed in more detail in Section 5.3.1, and pH. The RO permeate would likely require treatment (e.g., decarbonation and lime addition) to raise the pH before use.

Table 7-10. Title 22+ Results for the MBR-RO

Category	Analyte	Units	Phase 1 MBR Permeate	Phase 1 RO Permeate	Phase 1 % Change	Phase 3 MBR Permeate	Phase 3 RO Permeate	Phase 3 % Change	Target Conc
General Parameters	Alkalinity, Total	mg $CaCO_3$/L	110	6.5	↓ 94	103	4.5	↓ 96	NA[1]
	Ammonia	mg N/L	0.06	0.48	↑ 650	0.08	0.25	↑ 213	NA[1]
	Boron	mg/L	1.00	0.46	↓ 54	0.91	0.62	↓ 32	0.5
	Bromide	µg/L	1,700	101	↓ 94	1,600	79	↓ 95	NA[1]
	Chloride	mg/L	460	2.6	↓ 99	480	5.8	↓ 99	100
	Fluoride	mg/L	1.9	0.09	↓ 95	1.7	0.07	↓ 96	2
	Nitrate	mg N/L	38	1.1	↓ 97	43	3.4	↓ 92	10
	Nitrate + Nitrite, Total	mg N/L	38	1.1	↓ 97	43	3.4	↓ 92	10
	pH	-	7.3	5.7	↓ 21	7.7	6.4	↓ 18	6.5-8.5
	Sodium	mg/L	390	6.2	↓ 98	380	12	↓ 97	NA[1]
	Specific Conductance, 25ºC	µmho/cm	2,500	37	↓ 99	2,350	62	↓ 97	1,600
	Total Dissolved Solids	mg/L	1,500	14	↓ 99	1,450	37	↓ 97	450
	Turbidity	NTU[1]	0.14	0.06	↓ 55	0.16	0.10	↓ 37	2
	UV Transmittance (254 nm)	%	57.5	95.4	↑ 66	59.8	98.0	↑ 64	NA[1]
Volatile Organic Compounds	Chlorodibromomethane	µg/L	< 0.5	1.5	↑ > 190	<0.5	0.96	↑ >92	NA[1]
	Bromodichloromethane	µg/L	< 0.5	1.5	↑ > 190	<0.5	1.7	↑ >240	NA[1]
	Chloroform	µg/L	1.5	1.3	↓ 13	1.2	1.5	↑ 30	NA[1]
	Total THM	µg/L	1.5	5.5[2]	↑ 263	1.2	4.2	↑ 265	80
SWRCB Surrogates	Total Chlorine Residual	mg/L	0.07	4.0	↑ 5,610	0.05	2.2	↑ 4,200	NA[1]
Other Chemicals	Formaldehyde	µg/L	15	8.8	↓ 39	15	11	↓ 30	100

[1]NA = not applicable, NTU = nephelometric turbidity unit.

[2]Bromoform was detected in one of the two RO permeate samples at a concentration of 2.4 µg/L, but not detected in the other sample. As a result, the total THM value (which includes bromoform) is higher than the sum of the THM species shown in Table 7-10.

7.3.3 AOP Results

The full suite of Title 22+ parameters was sampled on March 2, 2011, May 15, 2012, and May 22, 2012; only the polybrominated diphenyl ether compounds and trace organic constituents were measured on March 9, 2011. Twenty analytes (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6) were consistently detected in the MBR-RO effluent, and the concentrations of an additional four compounds (hexavalent chromium, copper, lead, and radium 228) rose to detectable levels in the AOP effluent. For Phase 1, only data from March 2, 2011, were considered, because no AOP samples were taken on March 9, 2012; consequently, the RO permeate concentrations do not necessarily match the values in Table 7-10. Because bromoform was detected on March 2, 2011, it is included in the analysis. Table 7-11 presents the results for these 27 analytes.

AOP had little observable effect on most of the analytes, in part because the RO permeate concentrations were very low. As a result, even relatively large percent changes in concentrations corresponded to small absolute changes. For example, the lead concentration increased by at least 32% across the AOP in Phase 1, but the absolute change was only 0.2 μg/L; it is difficult to determine whether this change was real or simply variability in the sampling or measurement. Similarly, the increase in radium 228 was only 0.03 pCi/L, occurred only in Phase 1, and may simply be a sampling artifact.

Concentrations of hexavalent chromium and copper increased across the AOP. The increase in copper levels was greater in Phase 1 with the Trojan UV reactor than in Phase 3 with the Calgon reactor. The increases in the concentrations of hexavalent chromium were similar for all three sets of samples. These increases may indicate that RO permeate leached metals from the UV reactors or fittings. The final concentrations of these metals in the AOP effluent remained well below the target concentrations, but care should be taken to minimize leaching in the full-scale system.

As with the UF-RO effluent, alkalinity decreased slightly, possibly due to the reaction of bicarbonate ions with hydroxyl radicals (Wang *et al*., 2000). UV photolysis of chloramines (Watts and Linden, 2007) likely caused the observed decrease in the total chlorine residual, and increases in the concentrations of nitrate, chloride, and TDS. Nitrate may also have been formed from the reaction of ammonia with hydroxyl radicals (Bonsen et al., 1997; Pollema et al., 1992); this reaction has been observed in photocatalytic TiO_2 systems, which also utilize hydroxyl radicals.

Among the organic compounds, total trihalomethane concentrations decreased, primarily due to decreases in the concentrations of dibromochloromethane and bromoform; this result is consistent with results published by Jo *et al*. (2011), who observed UV photolysis of these two compounds, but not chloroform. Formaldehyde concentrations increased across the AOP, which is consistent with literature reports of formaldehyde formation during UV treatment (Awad, 1993; Malley *et al*., 1995). The formaldehyde concentrations after AOP were largest in Phase 3 with the Calgon reactor and the LP lamp (63 μg/L), followed by the Calgon reactor with the MP lamp (41 μg/L), then the Trojan reactor with the LP lamp (23 μg/L); these concentrations were below the target of 100 μg/L.

Overall, the water quality resulting from AOP treatment was similar for the Trojan and Calgon reactors, and in the Calgon reactor for the LP and MP lamps, with the possible exceptions of copper and formaldehyde, as discussed above. Although the concentrations of some parameters increased across the AOP, the target concentrations (where applicable) were met in all cases except boron, which was unchanged across the AOP.

Table 7-11. Title 22+ Results for AOP (MBR Train)

Category	Analyte	Units	Phase 1 RO Permeate[1]	Phase 1 AOP Effluent	Phase 1 % Change	Phase 3 RO Permeate	Phase 3 LP AOP Effluent	Phase 3 % Change	Phase 3 MP AOP Effluent	Phase 3 % Change
General	Alkalinity, Total	mg $CaCO_3$/L	6.1	3.9	↓ 36	4.5	3.8	↓ 17	4.0	↓ 12
Parameters	Ammonia	mg N/L	0.6	0.3	↓ 53	0.3	0.2	↓ 18	0.3	↓ 2
	Boron	mg/L	0.44	0.48	↑ 9	0.62	0.62	0	0.62	0
	Bromide	µg/L	140	140	0	79	78.5	↓ 1	84	↑ 6
	Chloride	mg/L	2.4	3.8	↑ 58	5.8	6.8	↑ 17	6.9	↑ 19
	Fluoride	mg/L	0.11	0.11	0	0.07	0.08	↑ 4	0.07	0
	Nitrate	mg N/L	0.8	1.0	↑ 20	3.4	3.5	↑ 1	3.5	↑ 3
	Nitrate + Nitrite, Total	mg N/L	0.8	1.0	↑ 20	3.4	3.5	↑ 1	3.5	↑ 3
	Odor	TON	[2]	1	[2]	1	1	0	[2]	[2]
	pH	-	5.6	5.2	↓ 7	6.4	6.3	↓ 2	6.3	↓ 1
	Sodium	mg/L	5.2	5.6	↑ 8	12	12	↓ 4	12	0
	Specific Conductance, 25ºC	µmho/cm	39	36	↓ 8	62	62	↑ 1	64	↑ 4
	Total Dissolved Solids	mg/L	13	19	↑ 46	37	38	↑ 3	38	↑ 4
	Turbidity	NTU	0.07	0.06	↓ 16	0.10	0.11	↑ 8	0.12	↑ 19
	UV Transmittance (254 nm)	%	93.8	99.5	↑ 6	98.0	99.0	↑ 1	99.4	↑ 1
Trace	Chromium, Hexavalent	µg/L	< 0.05	0.09	↑ > 80	< 0.02	0.14	↑ > 575	0.12	↑ > 475
Metals	Copper	µg/L	< 2	21	↑ > 950	< 2	3.2	↑ > 60	3.3	↑ > 65
Sampling	Lead	µg/L	< 0.5	0.66	↑ > 32	< 0.5	< 0.5	0	< 0.5	0
Radiological	Radium 228	pCi/L	<0.970	1.0	↑ 3	< 1	< 1	--	< 1	--
Volatile	Bromoform	µg/L	2.4	< 0.5	↓ > 79	< 0.5	< 0.5	--	< 0.5	--
Organic	Chlorodibromomethane	µg/L	1.5	< 0.5	↓ > 67	1.0	< 0.5	↓ > 48	[2]	[2]
Compounds	Bromodichloromethane	µg/L	1.2	0.82	↓ 32	1.7	1.3	↓ 26	1.4	↓ 18
	Chloroform	µg/L	1.0	1.0	0	1.5	1.4	↓ 10	1.4	↓ 10
	Total THM	µg/L	6.2	1.9	↓ 69	4.2	2.7	↓ 38	3	↓ 29
SWRCB Surrogates	Total Chlorine Residual	mg/L	5.2	0.6	↓ 89	2.2	0.3	↓ 85	0.6	↓ 71
Other	Formaldehyde	µg/L	6.6	23	↑ 248	11	63	↑ 503	41	↑ 288

[1]Values are from only March 2, 2011, when matching samples from the AOP were taken; these numbers may not match the average RO values in Table 7-10.
[2]Inconsistently detected.

7.4 COMPARISON OF THE UF AND MBR TRAINS

7.4.1 Comparison of the UF and MBR

Tables 7-12 and 7-13 list the 44 analytes whose concentrations changed across the UF or MBR. Analytes that were removed to similar degrees by the UF and MBR were likely removed by filtration of solids by the 0.04 μm membranes in both units. These analytes include turbidity, phosphorus, iron, aluminum, and most of the microbiological organisms. The exceptions were heterotrophic plate count (HPC) and total coliform, which had lower concentrations in the UF filtrate. High levels of HPC in MBR permeates have been reported previously in the literature (Friedler *et al*., 2006; Rahman and Al-Malack, 2006; King County, 2004).

The MBR was operated to nitrify ammonia in the secondary effluent. As discussed in Chapter 5, this process reduced concentrations of ammonia, organic nitrogen, alkalinity, and organic carbon (TOC and DOC) and increased concentrations of nitrate. Literature indicates that biological activity may have also been responsible for the lower levels, relative to the UF effluent, of color, t-butyl alcohol, trihalomethanes, and dichloromethane (Williams and Pirbazari, 2007; Morrison *et al*., 2002; Wahman *et al*., 2006; Wahman *et al*., 2005; IPCS, 1996).

In addition, the lower manganese levels in the MBR effluent may be attributable to uptake and oxidation by microbes in the MBR. (Nealson, *et al*., 1998) Although reduced manganese is soluble, the oxidized form precipitates and can be filtered out by the membranes. Microbial oxidation of manganese can be faster than abiotic oxidation by oxygen or chlorine, which is relatively slow at neutral pH. (Nealson *et al*., 1988; Crittenden *et al*., 2005)

Differences in chlorine addition may have also caused some differences between the UF and MBR effluents. Chlorine was added to the secondary effluent in the UF train, and was added upstream of the RO in the MBR train. For this study, MBR permeate samples were taken upstream of the ammonia addition point. As a result, the total chlorine residual was higher in the UF filtrate than in the MBR permeate. The addition of chlorine may have also caused higher concentrations in the UF filtrate of cyanide and formaldehyde, which are known DBPs of chlorination (USEPA, 1999; Kavanaugh et al., 2003; Na and Olson, 2006; Krasner et al., 1989), and chlorate, which is formed in hypochlorite solutions due to the decomposition of hypochlorite (Bolyard *et al*., 1992).

Both the UF and MBR provided removal of some of the trace organic constituents, but likely for different reasons. It is likely that this removal is due to sorption to solids that were removed by the UF membranes (Snyder *et al*., 2007; Coleman *et al*., 2009; Cirja *et al*., 2006), although it is also possible that the compounds reacted with the chlorine that was added to form chloramines (Tang et al., 2010). The MBR was more effective than the UF at removing most of these compounds, probably due to biological activity and/or to sorption of the compounds to the higher solids concentration in the MBR (Drewes *et al*., 2006; Snyder et al., 2007; Schröder et al., 2006; Chen et al., 2008; Coleman et al., 2009).

Table 7-12. Comparison of UF and MBR for Title 22+ General Parameters, Trace Metals, Radiological Analytes, and Microbes

			Phase 1				Phase 3	
Category	**Analyte**	**Units**	**UF Filtrate**	**% Change**	**MBR Permeate**	**% Change**	**MBR Permeate**	**% Change**
General Parameters	Alkalinity, Total	mg $CaCO_3$/L	360	↑ 1	110	↓ 71	103	↓ 73
	Ammonia	mg N/L	38	0	0.06	↓ 100	0.08	↓ 100
	Apparent Color	ACU	45	↓ 10	40	↓ 27	30	↓ 50
	Cyanide	mg/L	0.021	↑ 182	*	*	0.009	↑ 30
	Nitrate	mg N/L	< 0.05	0	38	↑ 75,900	43	↑ 42,900
	Nitrate + Nitrite, Total	mg N/L	< 0.1	0	38	↑ 37,900	43	↑ 42,900
	Organic Nitrogen	mg N/L	1.3	↓ 44	<1	↓ > 60	<1	↓ > 68
	Total Organic Carbon	mg/L	12	↓ 19	10	↓ 38	9.0	↓ 49
	Total Phosphorus	mg P/L	0.15	↓ 67	0.11	↓ 72	0.32	↓ 58
	Turbidity	NTU	0.13	↓ 95	0.14	↓ 92	0.16	↓ 96
	UV Transmittance (254 nm)	%	57.4	↑ 25	57.5	41	59.8	↑ 49
Trace Metals	Aluminum	µg/L	< 20	↓ > 7.5	< 20	↓ > 22	<20	↓ > 20
	Iron	mg/L	0.1	↓ 90	0.1	↓ 91	0.1	↓ 92
	Manganese	µg/L	89	↓ 5	51	↓ 50	7.2	↓ 93
Radiological	Uranium	pCi/L	1.3	0	2.3	↑ 64	1.8	↑ 30
Microbes	Cryptosporidium	Oocysts/10L	< 1	↓ > 50	< 1	↓ > 33	NS	NS
	Giardia	Cysts/10L	0.5	↓ 100	< 1	↓ 100	NS	NS
	Heterotrophic Plate Count	cfu/mL	66	↓ > 98	3,350	↓ > 41	**	**
	Total Coliform	MPN/100 mL	< 1.1	↓ > 95	6.6	↓ > 71	5.1	↓ > 78
	Fecal Coliform	MPN/100 mL	< 1.1	↓ > 95	1.1	↓ > 95	<1.1	↓ > 96
	E. Coli	MPN/100 mL	< 2	↓ > 91	< 2	↓ > 91	<1.1	↓ > 96

*Cyanide was inconsistently detected in both the MBR influent and permeate.

**Values appeared to be unreliable, and are not included in this table. Based on samples taken on other dates, HPC values (in cfu/mL) for the secondary, MBR, and UV effluents were expected to be >5,700, approximately 3,000, and < 30, respectively. However, on May 15, 2012, the secondary effluent HPC was < 1 cfu/mL, and LP UV was > 5,700 cfu/mL. On May 22, 2012, the MBR permeate HPC was < 1 and the LP UV HPC was 2,500 cfu/mL. It is likely that these two sets of samples were switched.

Table 7-13. Comparison of UF and MBR for Other Title 22+ Parameters

			Phase 1				Phase 3	
Category	**Analyte**	**Units**	**UF Filtrate**	**% Change**	**MBR Permeate**	**% Change**	**MBR Permeate**	**% Change**
Hormones	Estrone	ng/L	14	↓ 53	<10	↓ > 51	<1.2	↓ 97
Industrial EDCs	Bisphenol A	ng/L	35	↓ 76	34	↓ 87	22	↓ 96
	4-Nonylphenol (tech mix)	ng/L	475	↓ 55	170	↓ 85	210	↓ 92
	Nonylphenol monoethoxylate	ng/L	1,850	↓ 26	419	↓ 86	275	↓ 94
	Nonylphenol diethoxylate	ng/L	7,600	↑ 13	875	↓ 90	584	↓ 92
	4-tert Octylphenol	ng/L	305	↓ 44	63	↓ 91	32	↓ 95
	Octylphenol monoethoxylate	ng/L	1,070	↓ 12	<125	↓ 89	<62.5	↓ > 94
	Octylphenol diethoxylate	ng/L	4,470	↓ 1	191	↓ 95	<62.5	↓ > 96
PPCPs	Acetaminophen	ng/L	23	↑ 15	22	↑ > 120	41	↑ 1
	DEET	ng/L	476	↓ 6	294	↓ 26	234	↓ 66
	Gemfibrozil	ng/L	1,120	↑ 5	353	↓ 69	128	↓ 91
	Sulfamethoxazole	ng/L	712	↓ 27	1,710	↑ 52	1,350	↑ 77
	Triclosan	ng/L	348	↓ 28	86	↓ 81	61	↓ 91
Other Wastewater Indicators	Caffeine	ng/L	395	↑ 6	231	↓ 43	282	↓ 62
Volatile	Dichloromethane	µg/L	2.7	↓ 7	0.57	↓ 85	<0.5	↓ > 83
Organic	Chloroform	µg/L	10	↓ 1	1.5	↓ 87	1.2	↓ 89
Compounds	Total THM	µg/L	11	↓ 5	1.5	↓ 88	1.2	↓ 89
SWRCB	Dissolved Organic Carbon	mg/L	12	↓ 3	9.4	↓ 28	8.8	↓ 37
Surrogates	Total Chlorine Residual	mg/L	4.2	↑ > 8,600	< 0.08	0	<0.05	0
Other Chemicals	t-Butyl Alcohol	µg/L	9.2	↑ 16	<2.0	↓ > 77	<2.0	↓ > 73
	Chlorate	µg/L	615	↑ 1,438	<10	↓ > 63	<10	↓ > 53
	Formaldehyde	µg/L	40	↑ 116	15	↓ 22	15	↓ 32
	Phenol	µg/L	0.23	↓ 19	<0.20	↓ > 45	0.46	↑ 70

7.4.2 Comparison of the RO Permeates

Table 7-14 lists the 26 analytes remaining after UF-RO or MBR-RO. Many of the differences that were observed between the UF and MBR disappeared after RO. For example, trace organic constituents (with the exception of the nitrosamines and 1,4-dioxane, which were discussed in Chapter 6) were not detected in the RO permeate from either the UF or MBR train.

Some differences did carry over to the RO permeates, such as differences caused by nitrification in the MBR. The nitrate concentrations were higher in the MBR-RO permeate than in the UF-RO permeate, and alkalinity and ammonia levels were lower.

The location of chlorine addition also caused differences in removals between the two RO permeates. Chlorine was added to the secondary effluent in the UF train, and was added upstream of the RO in the MBR train. Consequently, in the UF train, chlorine residuals and DBP concentrations increased across the UF, and decreased across the RO. In the MBR train, chlorine residuals and DBP concentrations increased across the RO. As a result, the percent removals were different for the UF-RO and MBR-RO; however, the RO permeate concentrations were similar between the two units, particularly within Phase 1 (both the chlorine residuals and THM concentrations were slightly lower in Phase 3).

Interestingly, the distribution of halogenated methanes differed between the UF-RO and MBR-RO trains. Three dihalomethanes (dibromomethane, bromochloromethane, and dichloromethane) were detected in the UF-RO permeate, but not in the MBR-RO permeate. In addition, the THMs in the UF-RO permeate were entirely composed of chloroform, but were evenly distributed among chloroform, bromodichloromethane, and chlorodibromomethane in the MBR-RO permeate. These distributions may reflect differences in the levels of precursor organics at the two points of chlorine addition: the UF influent and MBR permeate.

7.4.3 Comparison of the AOP Effluents

Tables 7-15 and 7-16 compare the AOP results for the UF-RO and MBR-RO trains, for the compounds that were detected in the RO and/or UV effluent, excluding the analytes discussed in Chapter 6. Note that the Phase 1 data include only the first day of sampling, because no AOP samples were taken on the second day of sampling; consequently, the RO permeate concentrations do not necessarily match the values in Table 7-14. As discussed in Section 7.3.3, the RO permeate concentrations were low; because these low values caused potentially misleading removal values, RO permeate concentrations are provided instead in Tables 7-15 and 7-16. Note that the Phase 1 RO permeate values are single values from the day that the AOP samples were also taken, and do not match the average values given in Table 7-14.

AOP had similar effects on most compounds in both effluents, such as the decrease in alkalinity. Formaldehyde concentrations increased for both effluents; the concentrations after AOP remained well below the target level of 100 μg/L.

Table 7-14. Comparison of UF-RO and MBR-RO

Category	Analyte	Units	Phase 1				Phase 3	
			UF-RO Permeate	% Change	MBR-RO Permeate	% Change	MBR-RO Permeate	% Change
General Parameters	Alkalinity, Total	mg $CaCO_3$ /L	19	↓ 95	6.5	↓ 94	4.5	↓ 96
	Ammonia	mg N/L	1.3	↓ 97	0.5	↑ 650	0.3	↑ 213
	Boron	mg/L	0.59	↓ 33	0.46	↓ 54	0.62	↓ 32
	Bromide	µg/L	32	↓ 98	101	↓ 94	79	↓ 95
	Chloride	mg/L	6.8	↓ 99	2.6	↓ 99	5.8	↓ 99
	Fluoride	mg/L	0.09	↓ 91	0.09	↓ 95	0.07	↓ 96
	Nitrate	mg N/L	< 0.05	[1]	1.1	↓ 97	3.4	↓ 92
	Nitrate + Nitrite, Total	mg N/L	< 0.1	[1]	1.1	↓ 97	3.4	↓ 92
	pH	-	5.7	↓ 23	5.7	↓ 21	6.4	↓ 18
	Sodium	mg/L	10	↓ 97	6.2	↓ 98	12	↓ 97
	Specific Conductance, 25ºC	µmho/cm	71	↓ 97	37	↓ 99	62	↓ 97
	Total Dissolved Solids	mg/L	26	↓ 98	14	↓ 99	37	↓ 97
	Turbidity	NTU	< 0.05	↓ > 60	0.06	↓ 55	0.10	↓ 37
	UV Transmittance (254 nm)	%	96.6	↑ 68	95.4	↑ 66	98.0	↑ 64
Volatile Organic Compounds	Dibromomethane	µg/L	0.59	↓ 9	< 0.5	[1]	< 0.5	[1]
	Bromochloromethane	µg/L	0.64	↑ 3	< 0.5	[1]	<0.5	[1]
	Dichloromethane	µg/L	2.5	↓ 8	< 0.5	[1]	< 0.5	[1]
	Chlorodibromomethane	µg/L	< 0.5	[1]	1.5	↑ > 190	0.96	↑ >92
	Bromodichloromethane	µg/L	< 0.5	[1]	1.5	↑ > 190	1.7	↑ >240
	Chloroform	µg/L	5.7	↓ 46	1.3	↓ 13	1.5	30
	Total THM	µg/L	5.7	↓ 46	5.5[2]	↑ 263	4.2	↑ 265
SWRCB Surrogates	Total Chlorine Residual	mg/L	4.1	↓ 6	4.0	↑ 5,610	2.2	↑ 4,200
Other Chemicals	Chlorate	µg/L	13	↓ 98	< 10	[3]	<10	[3]
	Formaldehyde	µg/L	6.8	↓ 83	8.8	↓ 39	10.5	↓ 30

[1]Concentration was below detection in both the RO influent and permeate.

[2]Bromoform was detected in one of the two RO permeate samples at a concentration of 2.4 µg/L, but not detected in the other sample. As a result, the total THM value (which includes bromoform) is higher than the sum of the THM species shown in Table 7-14.

[3]Inconsistently detected.

Table 7-15. Comparison of AOP Treatment on the UF and MBR Trains: General Parameters, Trace Metals, and Radiological Analytes

			Phase 1				Phase 3		
			UF Train		MBR Train		MBR Train		
Category	Analyte	Units	RO Permeate[1]	AOP Effluent	RO Permeate[1]	AOP Effluent	RO Permeate	LP AOP Effluent	MP AOP Effluent
General	Alkalinity, Total	mg $CaCO_3$/L	22	14	6.1	3.9	4.5	3.8	4.0
Physical	Ammonia	mg N/L	1.3	1.3	0.6	0.3	[3]	0.2	0.2
and Mineral	Boron	mg/L	0.57	0.60	0.44	0.48	0.62	0.62	0.62
Sampling	Bromide	µg/L	31	48	140	140	79	79	84
	Chloride	mg/L	6.8	9.1	2.4	3.8	5.8	6.8	6.85
	Fluoride	mg/L	0.09	0.1	0.1	0.1	0.08	0.08	0.07
	Nitrate	mg N/L	< 0.05	0.16	0.8	1.0	3.4	3.5	3.5
	Nitrate+Nitrite, Total	mg N/L	< 0.1	0.16	0.8	1.0	3.4	3.4	3.4
	pH	-	5.5	5.6	5.6	5.2	6.4	6.3	6.3
	Odor	TON[2]	< 1	< 1	[3]	1	1	1	[3]
	Sodium	mg/L	10	11	5.2	5.6	12	12	12
	Specific Conductance, 25ºC	µmho/cm	74	72	39	36	62	62	64
	Total Dissolved Solids (TDS)	mg/L	26	30	13	19	37	38	38
	Turbidity	NTU[2]	< 0.05	< 0.05	0.07	0.06	0.10	0.11	0.12
	UV Transmittance (254 nm)	%	97.0	99.0	93.8	99.5	98.0	99.0	99.4
Trace	Chromium, Hexavalent	µg/L	< 0.05	0.13	< 0.05	0.09	< 0.02	0.14	0.12
Metals	Copper	µg/L	< 2	27	< 2	21	< 2	3.2	3.3
Sampling	Lead	µg/L	< 0.5	0.68	< 0.5	0.66	< 0.5	< 0.5	< 0.5
Radiological	Radium 228	pCi/L	< 0.89	< 0.84	< 0.97	1.00	< 1	< 1	< 1

[1]Phase 1 values are from only from the first day of sampling (when corresponding AOP samples were taken) and may not match the RO values in Table 7-14.
[2]TON = threshold odor number, NTU = nephelometric turbidity unit.
[3]Not consistently detected.

Table 7-16. Comparison of AOP Treatment on the UF and MBR Trains: Other Parameters

			Phase 1				Phase 3		
			UF Train		MBR Train		MBR Train		
Category	**Analyte**	**Units**	**RO Permeate[1]**	**AOP Effluent**	**RO Permeate[1]**	**AOP Effluent**	**RO Permeate**	**LP AOP Effluent**	**MP AOP Effluent**
Volatile	Dibromomethane	µg/L	0.67	< 0.5	< 0.5	< 0.5	<0.5	<0.5	<0.5
Organic	Bromochloromethane	µg/L	0.66	0.57	< 0.5	< 0.5	1.7	1.3	1.4
Compounds	Dichloromethane	µg/L	1.8	1.6	< 0.5	< 0.5	<0.5	<0.5	<0.5
	Bromoform	µg/L	< 0.5	< 0.5	2.4	< 0.5	< 0.5	< 0.5	<0.5
	Chlorodibromomethane	µg/L	< 0.5	< 0.5	1.5	< 0.5	1.0	< 0.5	0.6
	Bromodichloromethane	µg/L	< 0.5	< 0.5	1.2	0.8	1.7	1.3	1.4
	Chloroform	µg/L	5.9	5.2	1.0	1.0	1.5	1.4	1.4
	Total THM	µg/L	5.9	5.2	6.2	1.9	4.2	2.6	3
SWRCB	DOC	mg/L	< 0.50	0.65	< 0.50	< 0.50	[2]	[2]	[2]
Surrogates	Total Chlorine Residual	mg/L	3.7	0.4	5.2	0.6	2.2	0.3	0.6
Other	Chlorate	µg/L	11	< 10	< 10	< 10	<10	[2]	<10
Chemicals	Formaldehyde	µg/L	7.3	27	6.6	23	11	63	41

[1]Phase 1 values are from only from the first day of sampling (when corresponding AOP samples were taken) and may not match the RO values in Table 7-14.
[2]Not consistently detected.

One difference between the two effluents was the larger decrease in total THM concentrations in the MBR-RO effluents. In the UF-RO effluent, the total THMs were comprised completely of chloroform, which is not susceptible to UV photolysis; in the MBR-RO effluent, much of the THMs consisted of bromoform and chlorodibromomethane, which can be photolyzed by UV (Jo, et al., 2011). Consequently, the total THM concentration in the AOP effluent was slightly lower in the MBR train than the UF train; however, concentrations in both effluents were well below the target concentration of 80 μg/L.

Differences were also observed for copper and lead. The increases in Phase 1 were similar for the MBR and UF train; both sets of samples were taken from the Trojan UV reactor. The levels of these two metals were lower in Phase 3 with the Calgon reactor, possibly due to differences in the reactors or changes in the water quality between Phase 1 and Phase 3. Ultimately, the final concentrations of these metals in the AOP effluent remained well below the targets.

7.5 SUMMARY

For the three sets of Title 22+ sampling events, 291 parameters were measured (excluding 1,4-dioxane and the nitrosamines, which were discussed in Chapter 6). Of these parameters, only 78 were consistently detected in at least one set of samples.

The UF and MBR were both effective at removing analytes that were associated with particulate matter, such as turbidity, phosphorus, iron, aluminum, and microbiological organisms. Biological nitrification in the MBR caused lower concentrations of ammonia, organic nitrogen, alkalinity, and organic carbon (TOC and DOC), and higher concentrations of nitrate. Biological activity may also be responsible for the lower levels, relative to the UF effluent, of manganese, color, formaldehyde, t-butyl alcohol, trihalomethanes, and dichloromethane. Concentrations of some trace organic constituents (the alkylphenols and alkylphenol ethoxylates, bisphenol A, caffeine, DEET, gemfibrozil, and triclosan) were also lower in the MBR permeate than in the UF filtrate, possibly due to biological activity and/or sorption to solids in the MBR mixed liquor.

The RO units were effective at removing most of the compounds, such as the trace organic constituents. Some differences, such as the nitrogen speciation, remained even after RO treatment. In addition, the distribution of the halogenated methane DBPs differed between the two trains, which may reflect the organic content of the two effluents at the point of chlorination: secondary effluent for the UF train, and MBR permeate for the MBR train.

The AOP processes behaved similarly on both trains. Alkalinity decreased slightly, and concentrations of hexavalent chromium, copper, and lead increased, likely due to contamination from fittings. Formaldehyde concentrations increased for both effluents but remained well below the target concentration of 100 μg/L. The total THM concentrations were similar in the RO permeates from the two trains, but were slightly lower in the AOP effluent from the MBR train than from the UF train, due to the fact that the THM species in the MBR-RO effluent were more susceptible to UV photolysis than the THM species present in the UF-RO effluent; however, concentrations in both effluents were well below the target concentration of 80 μg/L.

Overall, the Title 22+ sampling tested a broad range of analytes. The processes on both trains effectively treated the 291 parameters discussed in this chapter, and with the exception of boron (discussed in more detail in Section 5.3.1) and pH (Section 5.4.2), the AOP effluent met all water quality targets.

8. SUMMARY

The project results are reviewed in this chapter. Section 8.1 provides a comparison of UF and MBR trains. Water quality results and the ability of the pilot-scale system to meet the target concentrations are presented in Section 8.2. Section 8.3 provides a brief summary of the conclusions.

8.1 COMPARISON OF THE UF AND MBR TRAINS

Both the UF and MBR trains successfully treated secondary effluent from the JWPCP for most constituents of interest, and both were operated successfully at a flux of approximately 20 gfd. A summary of the differences between the two trains is presented in Table 8-1, and Sections 8.1.1 and 8.1.2 provide more details on differences in operations and water quality, respectively.

Table 8-1. Comparison of the UF and MBR Trains

	UF-RO-AOP	MBR-RO-AOP
Operation	Operations of UF was more affected by the secondary effluent water quality; poor secondary effluent water quality increased fouling and cleaning requirements	Operation of MBR was less affected by secondary effluent water quality; tertiary MBR could be operated at a flux similar to the UF flux
Design	Required a smaller footprint	Required aeration tank(s) as well as membrane tank(s)
Chemical Use	Sulfuric acid dose to lower the pH of UF filtrate was higher	Sulfuric acid dose to lower the pH of MBR permeate was much lower because the MBR consumed 75% of the secondary effluent alkalinity during nitrification
Energy Use	Energy to operate the UF system was lower	MBR system required air scouring of the membranes, therefore using more energy; air used for membrane scouring was sufficient to fully nitrify the secondary effluent in this study
Effluent Water Quality	Median total nitrogen concentration was ~2 mg NH_3-N/L TOC concentration was occasionally higher than the target of 0.5 mg/L	Median total nitrogen concentration was ~3 mg NO_3-N/L TOC concentration was consistently below the target of 0.5 mg/L AOP removal of nitrosamines and 1,4-dioxane was slightly better because of lower alkalinity and/or higher UVT in the RO permeate.

8.1.1 Operations

The UF had the advantage of simplicity over the MBR: it had a smaller footprint, and because it lacked biological treatment, it required fewer components, and less process air and energy. The UF also recovered from process upsets more quickly; days or weeks were sometimes required to bring the MLSS concentration in the MBR back to the desired value after an upset.

However, the UF was prone to fouling and was more sensitive than the MBR to changes in the JWPCP secondary effluent water quality due to events such as rain storms. The greater resistance to fouling by the MBR membranes may be due to biological activity, which could attenuate and degrade some organic foulants in the secondary effluent, or could be due to the MBR operation and cleaning cycles, which are designed to maintain performance in the concentrated environment of mixed liquor. As a practical implication of this difference, the MBR may require less cleaning maintenance than the UF, particularly toward the end of the membrane life.

For the two RO units, the biggest difference in operations was the sulfuric acid dose required to reach the target pH value. Doses ranged from 97 to 162 mg/L for the UF treatment train, and from 3 to 53 mg/L for the MBR treatment train. These differences are due to the nitrification reaction that occurred in the MBR, which produced acid and consumed alkalinity in the water, thereby reducing the buffering capacity and the scaling potential of the effluent.

To meet targets in the AOP system, the hydrogen peroxide dose in MBR-RO permeate was 1-2 mg/L lower than in the UF-RO permeate. This difference was likely caused either by lower levels of alkalinity, which is a scavenger of hydroxyl radicals, or by the higher UV transmittance in the MBR-RO permeate. The cost savings from the reduced doses of both sulfuric acid and hydrogen peroxide could be a significant advantage for the MBR-RO-AOP process over the UF-RO-AOP process.

8.1.2 Water Quality

Several water quality differences were observed between the effluents of the UF and MBR trains due to biological activity in the MBR, which likely caused the following trends in the MBR train:

- An increase in nitrate concentrations across the MBR due to nitrification, and decreases in the concentrations of ammonia and TKN.
- A decrease in alkalinity (due to nitrification), which decreased chemical usage in the downstream processes, as explained in Section 8.1.1.
- Consumption of organic matter (TOC and COD). The decrease in TOC levels across the MBR may have helped to maintain MBR-RO permeate concentrations below the target of 0.5 mg/L in Phases 1 and 2, while the UF-RO permeate concentrations occasionally exceeded the target; however, this benefit may be marginal, as both trains consistently met the target in Phase 3, after the membranes in both RO units were replaced.
- Better removal of five nitrosamine compounds: NDMA, NDPA, NDBA, NPIP, and NPYR.
- Reduced levels of some trace organic constituents: alkylphenols and alkylphenol ethoxylates, bisphenol A, caffeine, DEET, gemfibrozil, and triclosan. Sorption to solids in the MBR mixed liquor, followed by filtration through the MBR membrane, may have also played a role in removing these compounds from secondary effluent.
- Lower levels of manganese, color, formaldehyde, t-butyl alcohol, trihalomethanes, and dichloromethane.

The RO units were effective at removing most compounds but some differences remained even after RO treatment. For example, the dominant nitrogen species was ammonia in the UF-RO permeate, and nitrate in the MBR-RO permeate.

In addition, the distribution of the halogenated methane DBPs differed between the two trains, which may reflect the organic content of the two effluents at the points of chlorination: secondary effluent for the UF train, and MBR permeate for the MBR train. Three dihalomethane species (dibromomethane, bromochloromethane, and dichloromethane) were detected in the UF-RO permeate, but not in the MBR-RO permeate. Total THM levels were similar in the two RO permeates, but were entirely composed of chloroform in the UF-RO permeate, and were distributed among the four species in the MBR-RO permeate. Because chloroform is not susceptible to UV photolysis, THM concentrations did not decrease with AOP treatment of the UF-RO permeate. THM concentrations were lower in the MBR-RO-AOP effluent, because UV photolyzes bromoform and chlorodibromomethane. However, total THM concentrations in both effluents were well below the target concentration of 80 μg/L.

8.2 MEETING WATER QUALITY TREATMENT GOALS

The water quality targets for this project were based on requirements for groundwater recharge in California (Section 3.5). Tables 8-2 and 8-3 list the target concentrations and and the RO effluent concentrations for each of these parameters. Data from the routine water quality samples (Section 3.2) were used where available; otherwise, the Title 22+ data were used instead.

As seen in Tables 8-2 and 8-3, the concentrations of almost all parameters were below the target levels. The following compounds require additional explanation:

- Boron concentrations did not meet the target. Boron is difficult to remove, and although technologies such as ion exchange could be used, source control should be considered to reduce the concentrations entering the JWPCP.
- Median TOC concentrations met the target, but measured values occasionally exceeded the target in the UF-RO permeate during Phases 1 and 2. Target levels were consistently achieved during Phase 3 in the UF-RO permeate (after new membranes were installed), and in the MBR-RO permeate during all phases. Because TOC concentrations in RO permeates are generally < 0.5 mg/L in most AWT systems, TOC is unlikely to be a problem in a full-scale system, but should be monitored carefully.
- Median 1,4-dioxane concentrations met the target, but measured values occasionally exceeded the target. In addition, the CDPH DGRR specified that AOP be used to achieve 0.5-log removal for groundwater recharge through subsurface injection. The AOP is discussed in more detail below.
- Concentrations of NDMA, NDEA, and occasionally NDPA exceeded targets. The 2008 CDPH DGRR also specified that AOP be used to achieve 1.2-log removal for groundwater recharge through subsurface injection. AOP results are discussed below.
- Because sulfuric acid was added upstream of the RO units to help control inorganic fouling, the pH in the RO permeate was approximately 5.5, lower than the target of 6.5-8.5. As with most AWT systems, the RO permeate would likely need to be treated (e.g., with decarbonation and lime) to raise the pH before use.
- The reporting limits (RLs) for 17β-estradiol and 3-hydroxycarbofuran were greater than the target concentration, which was based on the monitoring trigger levels (MTLs) from the SWRCB; these MTLs are guidelines, not regulatory limits. The RL for 3-

hydroxycarbofuran was very close to the MTL, indicating that the concentrations were near the MTL or below it. The RL for 17β-estradiol decreased when the analytical method was improved in Phase 3; concentrations were < 0.5 ng/L in both Phase 3 MBR-RO samples, suggesting that the 17β-estradiol levels were also below the target.

Table 8-2. Target and Measured Median RO Permeate Concentrations for General Physical and Mineral Parameters, Trace Metals, and Radiological Analytes

			Target	Measured Median	
Category	**Constituent**	**Units**	**Conc.**	**UF-RO**	**MBR-RO**
General Physical and Mineral Parameters	Chloride	mg/L	100	8.7	5.8
	Color	ACU	15	< 3	< 3
	Conductivity	umho/cm	1,600	71	67
	Fluoride	mg/L	2	0.14	< 0.10
	Foaming Agents (MBAS)	mg/L	1	< 0.05	<0.05
	Nitrate	mg N/L	10	< 0.10	2.8
	Nitrite	mg N/L	1	< 0.01	< 0.01
	Odor	TON	3	< 1	< 1
	pH	-	6.5-8.5	5.5	5.7
	Sulfate	mg/L	100	< 0.5	< 0.5
	TDS	mg/L	450	36	34
	Total Nitrate + Nitrite	mg N/L	10	< 0.1	~2.8
	Total Nitrogen	mg N/L	10	~1.9	~2.8
	Total Organic Carbon	mg/L	0.5	< 0.5	< 0.5
	Turbidity	NTU	2	< 0.1	< 0.1
Trace Metals	Aluminum	µg/L	50	< 10	< 10
	Antimony	µg/L	6	< 1	< 1
	Arsenic	µg/L	10	< 1	< 1
	Barium	µg/L	1,000	< 0.5	< 0.5
	Boron	mg/L	0.5	0.64	0.62
	Chromium (Total)	µg/L	50	< 1	< 1
	Copper	µg/L	1300	< 2	< 2
	Iron	mg/L	0.3	< 0.02	< 0.02
	Lead	µg/L	15	< 0.5	< 0.5
	Manganese	µg/L	50	< 2	< 2
	Nickel	µg/L	100	< 5	< 5
	Selenium	µg/L	50	< 5	< 5
Radiological	Gross Beta	pCi/L	50	< 3	< 3
	Uranium	pCi/L	20	< 0.7	< 0.7

[1]TON = threshold odor number, NTU = nephelometric turbidity unit.

Table 8-3. Target and Measured Median RO Permeate Concentrations for Other Parameters

Category	Constituent	Units	Target Conc.	Measured Median UF-RO	Measured Median MBR-RO
1,4-Dioxane and Nitrosamines	1,4-Dioxane[1]	µg/L	1	0.5	0.4
	NDMA[2]	ng/L	10	245	180
	NDEA	ng/L	10	62	52
	NDPA	ng/L	10	11	< 2
	NPYR	ng/L	20	< 2	< 2
Hormones and EDCs	17β-estradiol	ng/L	1	< 2	< 2
	Bisphenol A	ng/L	350,000	< 10	< 10
	Nonylphenol	ng/L	500,000	< 25	< 25
	Octylphenol	ng/L	50,000	< 5	< 5
PPCPs and Wastewater Indicators	Acetaminophen	ng/L	350,000	< 10	< 10
	Azithromycin	ng/L	3,900	< 10	< 10
	Carbamazepine	ng/L	1,000	< 10	< 10
	Gemfibrozil	ng/L	45,000	< 10	< 10
	Ibuprofen	ng/L	34,000	< 10	< 10
	Meprobamate	ng/L	260,000	< 10	< 10
	Sulfamethoxazole	ng/L	35,000	< 10	< 10
	Triclosan	ng/L	350	< 10	< 10
	DEET	ng/L	2,500	< 10	< 10
	Caffeine	ng/L	350	< 10	< 10
	Iopromide	ng/L	750,000	< 30	< 30
	TCEP	ng/L	2,500	< 10	< 10
VOCs[3]	Dichloromethane	µg/L	5	2.5	< 0.5
	MTBE	µg/L	5	< 0.5	< 0.5
	Total THMs	µg/L	80	5.7	4.7
SVOCs[3]	Di (2-Ethylhexyl) Phthalate	µg/L	4	< 0.6	< 0.6
Pesticides	3-hydroxycarbofuran	µg/L	0.42	< 0.5	< 0.5
Other	Formaldehyde	µg/L	100	6.8	10
	Tertiary Butyl Alcohol	µg/L	12	< 2	< 2
	Carbon disulfide	µg/L	160	< 0.5	< 0.5
	Chlorate	µg/L	800	13	< 10

[1]1,4-dioxane had an additional treatment requirement of 0.5-log removal in both the 2008 and 2011 DGRRs.

[2]NDMA had an additional treatment requirement of 1.2-log removal in the 2008 DGRR; this requirement was removed in the 2011 draft, but was kept as a target for this project.

[3]VOCs refer to volatile organic compounds, and SVOCs refer to semi-volatile organic compounds.

AOP experiments were conducted to determine the doses required to meet the target concentrations for NDMA, NDEA, and NDPA, as well as the removal requirements for NDMA and 1,4-dioxane. It should be noted that UV EED values are reactor-specific and cannot be applied to any other reactor. The results are summarized in Table 8-4. The tested doses were sufficient to remove 1,4-dioxane, NDMA, and NDPA from the highest observed RO permeate concentrations to the target levels. However, meeting targets with the highest observed RO permeate concentration of NDEA required higher doses than were tested.

Table 8-4. Approximate Hydrogen Peroxide Doses (mg/L) Required to Meet Treatment Goals in the Trojan UV Reactor with the Maximum Observed Concentrations in the RO Permeates

	UV EED (kWh/kgal)		
Compound	2	4	6
1,4-dioxane	4-6	2-3	~2
NDMA	x	0	0
NDEA	x	x	x
NDPA	x	6	4

x: Did not meet treatment goals at tested hydrogen peroxide doses.

During the Title 22+ sampling, the UV EED was 4 kWh/kgal and the hydrogen peroxide dose was 4 mg/L. Samples taken from the AOP reactors showed small increases in the concentrations of nitrate, chloride, formaldehyde, hexavalent chromium, copper, and lead. However, concentrations of all of these parameters remained well below the target levels. Concentrations of the other measured analytes showed no significant increase, or a decrease in concentrations.

8.3 CONCLUSIONS

In summary, the UF-RO-AOP and MBR-RO-AOP treatment trains successfully met the targets for almost all parameters, except the following:

- TOC occasionally exceeded the target concentration of 0.5 mg/L in the UF-RO-AOP treatment train.
- Boron concentrations exceeded the target in both treatment trains. It is difficult to remove, and although technologies such as ion exchange could be used, source control should be considered a priority to reduce the concentrations entering the JWPCP.
- The pH value was below the target range; additional treatment (e.g., with decarbonation and lime) would likely be needed to raise the pH before use.
- NDPA and NDEA are more recalcitrant than NDMA to AOP treatment. At the concentrations resulting from the UF-RO and MBR-RO systems, the requirements for the AOP doses are likely to be driven by the NDEA removal requirements.
- NDEA concentrations increased across both the UF and MBR. The increase across the UF may be due to chloramination of the secondary effluent. However, the MBR permeate samples were not chloraminated. More work is needed to better understand the formation mechanisms of NDEA.

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APPENDIX A

ACRONYMNS

AOP: advanced oxidation process
AWT: advanced water treatment

BOD: biochemical oxygen demand
BW: backwash

CDPH: California Department of Public Health
CEB: chemically enhanced backwash (UF)
CIP: clean in place (UF)
COD: chemical oxygen demand
CRWRF: Carson Regional Water Recycling Facility
CTS: centrate thickening system (at JWPCP)

DBP: disinfection byproduct
DEET: N,N-Diethyl-meta-toluamide
DGRR: Draft Groundwater Recharge Regulations (by CDPH)
DOC: dissolved organic carbon

EC: extended clean (UF)
EDC: endocrine disrupting compound
EED: electrical energy dose (for UV)
EPA: Environmental Protection Agency

gal: gallons
gfd: gallons per square foot per day
gpm: gallons per minute
GWRS: Groundwater Replenishment System

HPC: heterotrophic plate count
HRT: hydraulic residence time

JWPCP: Joint Water Pollution Control Plant

kgal: kilogallon (1,000 gallons)
kWh: kilowatt-hour

LADPW: Los Angeles Department of Public Works
LP: low pressure (UV lamp)

MBR: membrane bioreactor
MC: maintenance clean
MCL: maximum contaminant level
MF: microfiltration
MGD: million gallons per day
MLSS: mixed liquor suspended solids
MP: medium pressure (UV lamp)
MTBE: methyl tertiary-butyl ether
MTL: monitoring trigger level
MWD: Metropolitan Water District of Southern California

NA: not applicable or not available
ND: not detected
NDBA: N-nitrosodi-n-butylamine
NDEA: N-nitrosodiethylamine
NDMA: N-nitrosodimethylamine
NDPA: N-nitrosodi-n-propylamine
NL: notification level
NMEA: N-nitrosomethylethylamine
NPIP: N-nitrosopiperidine
NPYR: N-nitrosopyrollidine
NS: not sampled
NTU: nephelometric turbidity unit

OCSD: Orange County Sanitation District
OCWD: Orange County Water District
OD: outer diameter

PBDE: polybrominated diphenyl ether
PLC: programmable logic controller
PMCL: primary maximum contaminant level
PP: polypropylene
PPCPs: pharmaceuticals and personal care products
PVDF: polyvinylidene fluoride

RL: reporting limit
RO: reverse osmosis
RWC: recycled water contribution

SCOD: soluble COD
SM: Standard Methods
SMCL: secondary maximum contaminant level
SRT: solids retention time
SVOC: semi-volatile organic compound
SWRCB: State Water Resources Control Board

TCEP: Tris (2-chloroethyl) phosphate
TDS: total dissolved solids
THM: trihalomethane
TIWRP: Terminal Island Water Reclamation Plant
TKN: total Kjeldahl nitrogen
TMP: transmembrane pressure
TOC: total organic carbon
TSS: total suspended solids

UF: ultrafiltration
UV: ultraviolet
UVT: UV transmittance

VOC: volatile organic compound

WBMWD: West Basin Municipal Water District
WPCF: Water Pollution Control Facility
WRD: Water Replenishment District
WRF: water reclamation facility
WRP: water reclamation plant

APPENDIX B

LITERATURE REVIEW

Case Studies of Indirect Potable Reuse in the United States and Australia

Prepared by
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August 2011

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ABBREVIATIONS AND ACRONYMS

AOP ..... *advanced oxidation process*
Barrier plant ..... *West Coast Basin Barrier Project*
Basin Plans ..... *Water Quality Control Plans*
BOD ..... *biological oxygen demand*
CCR ..... *California Code of Regulations*
CDPH ..... *California Department of Public Health*
CFR ..... *Code of Federal Regulations*
CHSC ..... *California Health and Safety Code*
CTR ..... *California Toxics Rule*
CWC ..... *California Water Code*
DBP ..... *disinfection byproduct*
DO ..... *dissolved oxygen*
EDC ..... *endocrine disrupting compound*
FCWA ..... *Fairfax County Water Authority*
gfd ..... *gallons per square foot per day*
gpm ..... *gallons per minute*
Griffith ..... *Frederick P. Griffith, Jr. Water Treatment Plant*
GWRS ..... *Groundwater Replenishment System*
IAP ..... *Independent Advisory Panel*
LACSD ..... *Los Angeles County Sanitation District*
LBWRP ..... *Long Beach Water Reclamation Plant*
LSI ..... *Langelier Saturation Index*
MCL ..... *maximum contaminant level*
MDL ..... *method detection limit*
MF ..... *microfiltration*
MFI ..... *Modified Fouling Index*
MGD ..... *million gallons per day*
MOA ..... *Memorandum of Agreement*
NDMA ..... *N-Nitrosodimethylamine*
NPDES ..... *National Pollutant Discharge Elimination System*
OCSD ..... *Orange County Sanitation District*
OCWD ..... *Orange County Water District*
PCB ..... *polychlorinated biphenyls*
PPCP ..... *pharmaceuticals and personal care products*
ppm ..... *parts per million*
RO ..... *reverse osmosis*
RQ ..... *risk quotient*
RWP ..... *Recycled Water Policy*
RWQCB ..... *Regional Water Quality Control Board*
SDI ..... *Silt Density Index*
SIP ..... *Policy for Implementation of Toxics Standards for Inland Surface Waters, Enclosed Bays, and Estuaries of California*
SWRCB ..... *State Water Resources Control Board*
TDS ..... *total dissolved solids*

TOC ..... *total organic carbon*
TON ..... *threshold odor number*
TSS ..... *total suspended solids*
TTHM ..... *total trihalomethane*
UF ..... *ultrafiltration*
UOSA ..... *Upper Occoquan Service Authority*
USEPA ..... *United States Environmental Protection Agency*
UV ..... *ultraviolet*
UVT ..... *UV light transmittance*
VOC ..... *volatile organic compounds*
WBMWD ..... *West Basin Municipal Water District*
WRD ..... *Water Replenishment District of Southern California*
WRP ..... *Water Reclamation Plant*
WTP ..... *water treatment plant*
WWTP ..... *wastewater treatment plant*

SUMMARY

This report provides three case studies of indirect potable reuse in California, two examples in Western Australia, and one example from Virginia. The three California-based case studies include the Groundwater Replenishment System in Fountain Valley, the West Coast Barrier Project in El Segundo, and the Alamitos Barrier Recycled Water Project in Long Beach. Each of these projects is in full-scale operation. For Western Australia, the two case studies are the full-scale Kwinana Water Reclamation Plant and a pilot plant at the Beenyup Wastewater Treatment Plant. The Virginia example is the Millard H. Robbins, Jr. Water Reclamation Plant in Centreville, Virginia, which discharges to surface waters feeding the Occoquan Reservoir. The purpose of this report is to provide a summary of recent findings regarding the implementation of indirect potable reuse. Areas covered in this report include (a) a brief regulatory overview, (b) source and product water quality, (c) compliance with all Federal and State maximum contaminant levels (MCLs), notification levels, and water treatment and disinfection and disinfection by-products rules, and (d) removal of non-regulated compounds (e.g., pharmaceuticals and personal care products [PPCPs] and endocrine disrupting compounds [EDCs]).

In California, regulatory oversight of recycled water projects is carried out by the California Department of Public Health (CDPH), State Water Resources Control Board (SWRCB), and the individual Regional Water Quality Control Boards (RWQCBs). Permit conditions are set based on federal and state primary and secondary MCLs, state notification levels, as well as the state Anti-degradation Policy and regional Basin Plans. CDPH requires the project to use demonstrated treatment technologies that provide multiple barriers in the design and operation of water reclamation facilities for indirect potable reuse to augment potable water supplies.

With the exception of the Millard H. Robbins, Jr. Water Reclamation Plant in Virginia, each plant treats either secondary or tertiary treated wastewater with a combination of microfiltration (MF), reverse osmosis (RO), or ultraviolet light oxidation (UV). The Groundwater Replenishment System and West Coast Barrier Project use UV in combination with hydrogen peroxide as an advanced oxidation process (AOP) to oxidize refractory compounds, such as 1,4-dioxane and N-nitrosodimethylamine (NDMA). Each of the MF-RO-UV plants serve as indirect potable reuse projects that augment groundwater supplies through either direct injection or spreading basins. The Millard H. Robbins, Jr. Water Reclamation Plant is designed for nutrient removal to improve the water quality of the Occoquan Reservoir. Given the difference in reuse objectives, the Millard H. Robbins, Jr. Water Reclamation Plant further treats secondary wastewater using lime clarification, media filtration, carbon contactors, and chlorine disinfection. The dechlorinated effluent provides approximately 20 percent of the surface water flow into the Occoquan Reservoir.

Each of the aforementioned plants met or exceeded their permit requirements. Water quality criteria include limits on total dissolved solids (TDS), total organic carbon (TOC), total nitrogen, total phosphorous, trace metals, disinfection byproducts (DBPs), and pathogens. This report contains brief overviews of health effects studies, unit process selection, MF and RO membrane performance studies, trace organic compound removal, post-treatment issues, and the effects of applying high purity water in groundwater aquifers.

SECTION 1. INTRODUCTION

Table 1 provides a summary of operational indirect potable reuse projects in California. Indirect potable reuse of treated municipal wastewater has been practiced in southern California since 1962 [*1*]. In California, indirect potable reuse has been limited to augmenting groundwater aquifers via either surface spreading, followed by percolation, or direct injection into the ground. This report provides three case studies of indirect potable reuse in California, two examples in Western Australia, and one example from Virginia. The three California-based case studies include the Groundwater Replenishment System in Fountain Valley, the West Coast Barrier Project in El Segundo, and the Alamitos Barrier Recycled Water Project in Long Beach. Each of these projects is in full-scale operation. For Western Australia, the two case studies are the full-scale Kwinana Water Reclamation Plant and a pilot plant at the Beenyup Wastewater Treatment Plant. The Virginia example is the Millard H. Robbins, Jr. Water Reclamation Plant in Centreville, Virginia, which provides water to the Occoquan Reservoir.

The purpose of this report is to provide a summary of recent findings regarding the implementation of indirect potable reuse. Areas covered in this report include (a) a brief regulatory overview, (b) source and product water quality, (c) compliance with all Federal and State MCLs, notification levels, and water treatment and disinfection and disinfection by-products rules, and (d) removal of non-regulated compounds (e.g., PPCPs and EDCs). The findings in this report are dynamic in nature and may change as additional data in the water reuse field are obtained.

SECTION 2. REGULATORY OVERVIEW FOR CALIFORNIA

The August 5, 2008, draft CDPH Title 22, Water Recycling Criteria does not provide an official definition of indirect potable reuse [*2*]. However, language found in Senate Bill (SB) 918 on water recycling, as submitted by Senator Pavley on February 1, 2010, provides the following definitions [*3*]:

- "Indirect potable reuse for groundwater recharge" means the planned use of recycled water for replenishment of a groundwater basin or an aquifer that has been designated as a source of water supply for a public water system;
- "Surface water augmentation" means the planned placement of recycled water into a surface water reservoir used as a source of domestic drinking water supply; and
- "Direct potable reuse" means the planned introduction of recycled water either directly into a public water system … or into a raw water supply immediately upstream of a water treatment plant."

SB 918 was chartered and signed into law on September 30, 2010 [*3*]. The law requires the CDPH to establish uniform statewide recycling criteria for:

- Indirect potable water reuse for groundwater recharge by December 31, 2013;
- Surface water augmentation by December 31, 2016, if a specified expert panel convened pursuant to the bill finds that the criteria would adequately protect public health; and
- Direct potable reuse by December 31, 2016. For direct potable reuse, CDPH shall only investigate the feasibility of such, and not develop uniform criteria.

For the purpose of this report, indirect potable reuse is defined as the augmentation of a drinking water source (surface water or groundwater) with recycled water followed by an environmental buffer that precedes normal drinking water treatment [*1*].

Current law establishes the SWRCB and the California regional water quality control boards as the principal state agencies with authority over matters relating to water quality. Regulatory oversight of recycled water projects is carried out by CDPH, SWRCB, and the individual RWQCBs. CDPH, by statutory mandate, has established uniform statewide reclamation criteria for the various uses of reclaimed water, as set forth in Title 22, Recycling Criteria [*2*]. These criteria establish the statutory authorities over water reclamation and include specified approved uses of reclaimed water, numerical limitations and requirements, treatment method requirements, reporting mechanisms, and performance standards. Use of recycled water is also regulated through the California Water Code (CWC) and the California Health and Safety Code (CHSC). It should also be noted that the Recycling Criteria could be considered primarily focusing on domestic waste, as indicated in CWC §60302, which states that "*the requirements in this chapter shall only apply to recycled water from sources that contain domestic waste, in whole or in part.*"

Based on a Memorandum of Agreement (MOA) between CDPH and the SWRCB, CDPH has the responsibility to identify when and under what conditions a raw water supply is suitable for potable purposes [*4*]. In California, CDPH has primacy in enforcing both Federal (United States Environmental Protection Agency [USEPA], Title 40, Chapter 1 of the Code of Federal Regulations [CFR]) and the State (Title 22, Division 4, Chapter 15 of the California Code of Regulations [CCR]) drinking water standards. In addition to establishing health-related drinking water standards, both USEPA and states have established secondary drinking water standards to assure a potable water supply acceptable in taste, odor, and appearance. For some constituents, in lieu of a maximum contaminant level (MCL), surface water treatment regulations may require a treatment technique to minimize the risk associated with raw surface water supplies. Title 22 MCLs have been used as a basis for effluent limitations in water recycling permits to protect the municipal and domestic supply beneficial use [*4*].

The RWQCBs rely on the expertise of CDPH for the establishment of permit conditions needed to protect public health. CDPH's requirements are then incorporated into the sponsor's RWQCB permit in accordance with the Title 22 Recycling Criteria. The SWRCB and the RWQCBs have the exclusive authority to enforce water reclamation requirements through permit enforcement.

The latest draft groundwater recharge regulations for indirect potable reuse proposed in 2008 [*5*] will be included in the Recycling Criteria if they are formally finalized and subsequently adopted. Selected requirements in the current published version of the draft regulations are summarized in Table 2. Several requirements specified in the draft regulations would also apply to direct potable reuse projects (e.g., industrial pretreatment and source control programs, an operations plan, and a contingency plan), and product water quality requirements would be at least as restrictive as those currently prescribed for indirect potable reuse and may be more restrictive for some constituents. The existing draft groundwater recharge regulations are being modified to set comprehensive, objective criteria that address both surface spreading and subsurface injection projects involving indirect potable reuse of the recovered water [*1*].

CDPH requires that multiple barriers be incorporated in the design and operation of water reclamation facilities that produce recycled water for indirect potable reuse to augment potable water supplies. The multiple barrier concept is based on the principle of establishing a series of barriers to preclude the passage of microbial pathogens and harmful chemical constituents into the water system to the greatest extent practical [*5*]. Such barriers may include the following:

- Source control programs designed to prevent the entrance of constituents of emerging concern into the wastewater collection system that will inhibit treatment or may preclude use of the water.
- A combination of treatment processes (which may include primary, secondary, and advanced treatment processes) where each process provides a specific level of constituent reduction.
- Constituent monitoring at various points of treatment.
- Design and operational procedures to rapidly detect abnormalities in treatment process performance so that corrective action can be taken.
- Environmental buffers that can provide dilution, natural attenuation of contaminants, and retention time.

An environmental buffer is considered by CDPH to be one of the necessary multiple barriers for indirect potable reuse projects to provide additional treatment and time to take corrective action in the event that all water quality requirements are not met in the product water. The environmental buffer in an indirect potable reuse project serves to isolate the public water system from an immediate concern, such as might be caused by the discharge of a toxic waste to the sewerage system or equipment or treatment problems at the wastewater treatment facility. Without this buffer, timely notification of problems (e.g., source water deterioration, treatment process operational failures, and inadequate water quality) becomes even more important.

SECTION 3. PERMIT REQUIREMENTS

As part of the permit application process, the applicant must submit an engineering report to CDPH and RWQCB for review and approval. CDPH must hold three public hearings before making a final determination on any public health aspects related to the project. After the public hearings, CDPH will consult with RWQCB regarding permit requirements. RWQCB would then issue a National Pollutant Discharge Elimination System (NPDES) permit after considering how the project complies with regional Water Quality Control Plans (Basin Plans), California Toxics Rule (CTR), and SWRCB's Recycled Water Policy (RWP) and Policy for Implementation of Toxics Standards for Inland Surface Waters, Enclosed Bays, and Estuaries of California (SIP). The Basin Plans contain water quality objectives that provide reasonable protection of the beneficial use of surface waters and groundwaters within the region. The RWP provides uniform guidelines such that individual RWQCBs conform with California's Anti-degradation Policy for water recycling and groundwater recharge projects. The Anti-degradation Policy requires the use of "best practical treatment and control" and that SWRCB balance the preservation of "high quality water" with the maximum benefit of the people of California. The SIP implements the requirements set for by the CTR [*6*].

The engineering report shall be prepared by a licensed engineer and hydrologist and shall clearly indicate the means by which the project will meet all regulatory requirements [*2*]. Basic elements that are included in the engineering report include source water characterization, proposed treatment process, effluent water quality monitoring, subsurface characterization, product water blending plan, downstream monitoring plan, and operations plan. All permitting aspects for proposed projects are case specific and may change based on discussions with CDPH and RWQCB staff.

The source water control plan includes an up-to-date inventory of contaminants discharged into the wastewater collection system, such that new contaminants of concern can be readily identified. Other aspects of the source water control plan include public outreach programs to manage and minimize the discharge of contaminates (e.g., methylene chloride or PPCPs), and monitoring programs for CDPH-specified contaminants.

For the selection of the treatment train, CDPH provides general guidelines of the level of treatment required depending on the fate of the final product water (Table 2). In general, for indirect potable reuse projects using direct injection, the treatment train involves MF, RO, followed by UV oxidation of post-secondary treated wastewater. CDPH also provides guidance as to the selection of treatment technologies for use in indirect potable recharge projects [*7*]. The pre-approved list was generated from a review of files and correspondence with CDPH detailing system performance, robustness, and ability to comply with the conditions set forth in the Water Recycling Criteria. All data were reviewed by CDPH and RWQCB staff, the sponsoring agency, and industry representatives. The treatment technology guidance list is periodically updated when new information becomes available.

Table 3 shows the level of effort needed to characterize the subsurface zone within the groundwater recharge area. Mandated retention times between the injection and extraction wells vary from 6 to 24 months, depending on the method used in determining the subsurface retention time. CDPH prefers that a tracer test using an inert compound be conducted. For those projects having a valid tracer test, the travel time within the groundwater aquifer before final product water reaches a drinking water production well needs to be greater than or equal to 6 months.

Monitoring plans for the final product water need to include:

- Regulated contaminants—measure all federal and state regulated drinking water compounds on a quarterly basis, including:
    - Inorganic chemicals
    - Radionuclides
    - Organic chemicals
    - Disinfection by-products
    - Lead and copper;
- Total nitrogen—three methods for nitrogen control are proposed. The applicant may choose which compliance method to use depending on the circumstances:
    - ≤ 5 mg/L total nitrogen, samples to be taken at no less than three days apart;
    - ≤ 10 mg/L total nitrogen if dissolved oxygen (DO), biological oxygen demand (BOD), nitrate, nitrite, ammonia are within MCLs and limits established in the engineering report. Sampling frequency to be determined by CDPH;
    - ≤ MCLs for nitrate and nitrite. This option is only allowed for projects in operation greater than 20 years with no evidence of degradation of the receiving water body.
- Total organic carbon (TOC) ≤ 0.5 mg/L for samples taken once per week. TOC compliance is based on a 20-week running average;
- Recycled water contribution—each month, the reuse project shall calculate the running monthly average of the blend of final product water and blend water (e.g., surface water). The initial maximum recycled water contribution shall not exceed 50 percent for subsurface application projects with or without RO, and advanced oxidation processes (AOP; e.g., ultraviolet (UV) oxidation with hydrogen peroxide) to achieve greater than 1.2 log N-Nitrosodimethylamine (NDMA) reduction and 0.5 log 1,4-dioxane reduction. The maximum percent contribution by recycled wastewater is based on the following formula:

$$TOC_{max} = 0.5 \text{ mg/L}/(\text{recycled water contribution}) \quad (1)$$

Whereby the TOC_{max} for the receiving water is determined in the engineering report. For example, using Equation 1 above, the relative recycled water contribution for the final blended receiving water would be calculated thus [*8*]:

TOC_{max} (mg/L)	Recycled Water Contribution
5.0	10% or 0.10
2.5	20% or 0.20
1.43	35% or 0.35
1.0	50% or 0.50
0.67	75% or 0.75

Note that TOC is calculated on a 20-week running average, while recycled water contribution is calculated on a 60-month running average.

- Unregulated contaminants with Notification Levels. Unregulated contaminants shall not exceed the CDPH Notification Levels, as these chemicals have been identified in typical wastewater sources. Examples of unregulated contaminants with notification levels (in parentheses) identified in typical wastewater sources include:
  - Boron (1 mg/L),
  - Chlorate (0.8 mg/L),
  - NDMA (0.00001 mg/L),
  - N-Nitrosodiethyamine (NDEA; 0.00001 mg/L),
  - N-Nitrosodi-n-propylamine (NDPA; 0.00001 mg/L),
  - 1,2,3-Trichloropropane (0.000005 mg/L),
  - Formaldehyde (0.1 mg/L),
  - Vanadium (0.05 mg/L), and
  - 1,4-Dioxane (0.001 mg/L).
- Unregulated Contaminants without Notification Levels. Additional compounds indicated by CDPH for additional monitoring include:
  - Chromium-6 (hexavalent chromium),
  - Diazinon, and
  - Nitrosamines for which USEPA has developed analytical methods.

Two classes of compounds have also received increased interest in recent years. These chemical classes are PPCPs and EDCs. CDPH is interested in collecting information that relates to the presence of these compounds in municipal wastewater and final recycled water effluent. While CDPH does not recommend specific chemicals to monitor, it does advocate that representative constituents for these classes, or surrogates for their presence be monitored. Monitoring programs may be short in duration (e.g., twice a year for two to three years). Again, while CDPH does not recommend monitoring for specific compounds at this time, CDPH does recommend the reuse project investigate the following sub-classes of compounds [*2*]:

- Hormones:
    - Female hormones,
    - Male hormones, or
    - Appropriate surrogates;
- "Industrial" EDCs:
    - Bisphenol A,
    - Nonylphenol and nonylphenol polyethoxylates,
    - Octylphenol and octylphenol polyethoxylates, and
    - Polybrominated diphenyl ethers, or
    - Appropriate surrogates that could represent one or more of the industrial EDCs;
- Pharmaceuticals:
    - Acetominophen,
    - Amoxicillin,
    - Azithromycin,
    - Carbamazepine,
    - Ciprofloxacin,
    - Dilantin,
    - Gemfibrozil,
    - Ibuprofen,
    - Lipitor,
    - Meproamate,
    - Sulfamethoxazole,
    - Trimethoprim,
    - Salicylic acid, or
    - Appropriate surrogates that could represent one or more pharmaceuticals;
- Personal Care Products:
    - Triclosan,
    - DEET, or
    - Appropriate surrogates that could represent one or more personal care products;
- Other:
    - Caffeine,
    - Iodinated contrast media,
    - Fire retardants such as TCEP, or
    - Appropriate surrogates that could represent one or more these compounds.

Note CDPH does not intend for the aforementioned compounds to comprise a definitive list and compounds may be added or deleted depending on the outcome of the source water monitoring program.

- Diluent Water Monitoring. CDPH requires monitoring of the diluent water (e.g., surface water, groundwater, or stormwater runoff). The diluent water must meet all primary

MCLs and Notification Levels, as well as be monitored quarterly for nitrate and nitrite. Additional monitoring may be required by CDPH based on the source water monitoring results.

- Monitoring of Subsurface Blended Water. Prior to the drinking water well, the project shall construct monitoring wells whereby the injected water has been retained 1–3 months, or at least 3 months prior to being pumped for domestic supply well. Two sampling events shall be conducted prior to the project start up and quarterly thereafter. Water quality samples shall include TOC, total nitrogen, nitrate, nitrite, total coliform bacteria, and any water quality constituents specified by CDPH.

During the first year of operation, and all time thereafter, the treatment facility shall operate in a fashion providing optimal contaminant removal. Within six months of operation, the treatment plant shall update the operations plan to include any changes in operational procedures and submit the revised operations plan to CDPH for review.

SECTION 4. CASE STUDIES

Groundwater Replenishment System

The Groundwater Replenishment System (GWRS) is a joint water reuse project conducted by the Orange County Water District (OCWD) and Orange County Sanitation District (OCSD). Located in Fountain Valley, California, the GWRS began operations in January 2008. The plant supplements existing groundwater supplies through application of the product water to recharge basins in the Orange County Groundwater Basin or injected directly to prevent seawater intrusion. Near-term plans are to increase the capacity of the facility from its current rating of 70 million gallons per day (MGD) to 100 MGD [*9*]. While the GWRS consists of three major components ([1] the Advanced Water Purification Facility and pumping stations; [2] pipeline connecting the treatment facilities to existing recharge basins; and [3] an expanded seawater intrusion barrier well system), for the purposes of this report, the term GWRS refers to just the Advanced Water Purification Facility portion of the project. The GWRS consists of microfiltration (MF) pretreatment, followed by reverse osmosis (RO) membrane treatment and UV light exposure with hydrogen peroxide (H_2O_2) for advanced oxidation [*10*] (Figure 1).

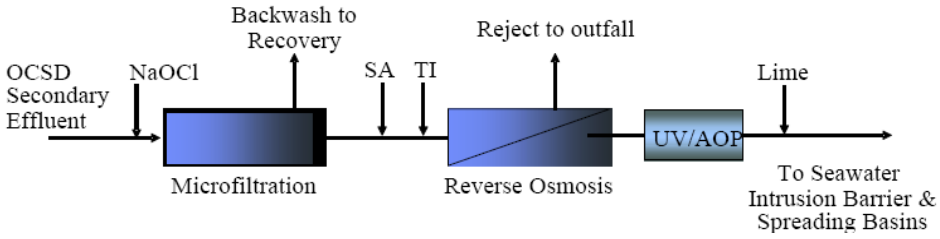


Figure 1. Schematic Process Diagram of GWRS.
SA = sulfuric acid; TI = threshold inhibitor (i.e., antiscalant) [*10*]

Per OCWD's permit, the key operational requirements for GWRS are [*11*]:

- 100 percent RO and AOP treatment for all final product water;
- Meet or exceed all federal and state drinking water requirements;
- ≤ 0.5 mg/L TOC;
- ≤ 5 mg/L total nitrogen;
- ≤ 10 ng/L (parts per trillion) NDMA;
- ≥ 6 month travel time within the groundwater aquifer before final product water reaches a drinking water production well;
- Initial blending of seawater intrusion barrier water to a 75:25 ratio with imported drinking water;
- Monitor select PPCPs and EDCs in the final product water and report values to RWQCB on a quarterly basis; and
- Establish an Independent Advisory Panel (IAP) to review the plant operations on a periodic basis. All recommendations from the IAP must be addressed, but the decision to implement those recommendations is at the discretion of OCWD.

Source Water

Source water for the GWRS originates from the neighboring OCSD Plant No. 1. OCSD service area covers over 479 square miles of central and northwest Orange County and treats wastewater derived from residential, commercial, and industrial sources. Industrial sources comprise approximately 16 percent of the wastewater entering OCSD's Plant No. 1 [*12*]. The water sent to GWRS is a secondary effluent from either trickling filtration or activated sludge treatment. The initial agreement between OCWD and OCSD stipulated that OCWD receive a blend of 80 percent activated sludge and 20 percent trickling filter effluent. Since that time, the 80/20 blend has been lifted in an effort to maximize production. The secondary effluent is a partially nitrified effluent with up to 31 mg/L excess ammonia as nitrogen.

Table 5 presents a list of average and maximum values for compounds analyzed by OCWD from the OCSD Plant No. 1 effluent from February 2008 through April 2010 [*13*]. For those data below the method detection limit (MDL), values were reported as less than the MDL. Blank data entries indicate that no data were provided for that compound.

GWRS influent water quality data revealed the secondary treated water contained high levels of ammonia (21 mg/L NH_3-N average and 31 mg/L NH_3-N maximum), color, turbidity, total and fecal coliforms, total dissolved solids (TDS), total nitrate and nitrite, and various trace metals. Based on permit requirements, limited trace organic compounds were monitored in the GWRS influent. However, 1,4-dioxane (1.7 µg/L average and 12.6 µg/L maximum) and N-nitrosodimethylamine (NDMA) (38 ng/L average and 330 ng/L maximum) were measured at levels that would require further treatment. For radiologicals, OCWD monitors only for tritium in the influent water. Average and maximum tritium values were 149 (± 221) pCi/L and

766 (± 232) pCi/L, respectively. It should be noted that the average tritium level was below the counting error for tritium.

Pretreatment

Clarified secondary effluent from OCSD Plant No. 1 travels by gravity to the screening facility and then to the MF system. The screening facility has four rotating 2-mm gravity screens to remove larger particles from the secondary effluent ahead of the MF process. OCWD reported that upstream screening was vital to maintaining MF performance and is required as part of the MF membrane manufacturer warranty conditions [*14*]. The full-scale MF system consists of 26 submerged MF (CS, Siemens Water Technology [formerly US Filter/Memcor], Warrendale, Penn.) cells, each with 608 polypropylene modules. The nominal hollow fiber pore size is 0.2 micron, and the recovery rate is between 88 percent and 90 percent. The MF system has a filtrate capacity of 86 MGD. Each cell operates at 20 gallons per square foot per day (gfd), 22 minute backwash cycles, and 21 day cleaning intervals. Prior to MF treatment, a 3–5 mg/L chloramine residual was maintained to control biological activity for both the MF and RO systems. In this regard, only chlorine was added, as ambient ammonia was sufficient to convert all added chlorine to chloramines. The MF filtrate water has low turbidity (< 0.2 NTU) and a 15-minute Silt Density Index (SDI) below 3 [*14*].

Reverse Osmosis

The RO system includes the RO transfer pump station, RO pretreatment chemical addition, cartridge filtration, high pressure membrane feed pumps, RO treatment trains, flushing systems, and clean-in-place systems. The RO transfer pump station pumps MF effluent from the MF filtrate tank through 10-µm cartridge filters to the RO high pressure membrane feed pumps. Chemical feeds include sulfuric acid to adjust pH from 7.5 to 6.5–6.8 and a proprietary antiscalant to protect against calcium carbonate and calcium phosphate scaling. The RO system consists of 15 RO trains of 5 MGD capacity each, for a total of 70 MGD RO permeate capacity. The RO trains operate at 85 percent recovery and a maximum permeate flux of 12 gfd. Each train includes 150 pressure vessels with 7 RO elements (ESPA2, Hydranautics, Oceanside, Calif.) per vessel arranged in a 78:48:24 array.

During the first year of operation and continuing through July 2010, the RO system showed a general trend of increased third stage fouling [*14*]. Calcium phosphate was projected to be the primary limiting scalant at 85 percent water recovery. However, membrane autopsies indicated that aluminum silicates were fouling the terminal elements. Average RO influent concentrations for aluminum and silica were 12 µg/L and 22 mg/L, respectively—levels at which most RO modeling software packages do not predict as being problematic. Additionally, one of the diaphragm antiscalant feed pumps stopped feeding. Hence, a significant loss in specific flux was observed in July 2008 (Figure 2). Supervisory control and data acquisition (SCADA) screens, as well as operator checks, failed to notice the problem in a timely manner.

Cleaning with a 2 percent citric acid solution proved ineffective in restoring membrane flux. Subsequent cleaning of the third array using a proprietary peroxide-based silica cleaner restored a majority, but not all, of the lost membrane flux capacity. OCWD continues to investigate new cleaning regimes and threshold inhibitors to increase and maintain water production. In addition, OCWD now varies the feed pH to the RO system on a seasonal basis to help control scale while also reducing sulfuric acid costs. In the hotter summer months the feed pH is kept near 6.5 to 6.6 while in the colder winter months, when the feedwater is cooler, the pH is held near 6.7 to 6.8.

UV Oxidation

The UV system utilizes low-pressure, high-output UV lamps (TrojanUVPhox™, Trojan Technologies, Ontario, Canada) to treat the RO permeate. The UV facility consists of nine lamp assemblies with each assembly designed to treat 8.75 MGD. The UV system is designed to provide a 4-log reduction of viruses and a 1.2-log reduction of NDMA. The addition of 3 mg/L H_2O_2 upstream of the UV system provides 0.5-log reduction capability for 1,4-dioxane.

Post Treatment

Lime stabilization to protect the conveyance pipelines, Product Water and Barrier Pump Stations, and appurtenances from the aggressive demineralized RO product water consists of decarbonation with partial bypass followed by lime addition. The GWRS utilizes a decarbonation system consisting of blowers and pack towers to partially strip the carbon dioxide from the water. After partial decarbonation, the UV product is stabilized with hydrated lime. The lime system consists of storage silos with powder hydrated lime (approximately 20 mg/L as calcium hydroxide), slurry mix tanks, slurry transfer pumps, saturators, and polymer addition system. A 7 percent lime slurry is pumped via peristaltic pumps from the lime storage building to a saturator/clarifier (IDI Accelerator). The saturator is dosed with an anionic polymer at a dose of 1.5 mg/L to aid in settling. The supernatant from the saturator is then dosed into the blend of decarbonated and non-decarbonated RO permeate water. Final product water guidelines include [*10*]:

- slightly positive Langelier Saturation Index (LSI),
- Aggressive Index (AI) of near 12, and
- pH between 6 and 9.

The stabilized product water will then be pumped to the seawater intrusion barrier and to groundwater recharge basins located 14 miles away from the plant site.

OCWD operators experienced problems associated with the lime post treatment system [*14*]. For the first five months of plant operation, the lime saturator was operated as a solids contact clarifier, per design. However, downstream injection wells receiving the GWRS product water began to foul at an increased rate. Subsequent tests found the final product water SDI and Modified Fouling Index (MFI) values were above 10. The SDI and MFI should be below 3 to

ensure the water does not have a significant fouling potential. OCWD staff determined that the saturator would operate better if operated in a sludge blanket mode. Figure 3 shows the improvement of the final product water SDI and MFI after the switch to sludge blanket operation of the saturator. In this mode, a layer of lime sludge is allowed to build up in the bottom of the saturator and acts as a means to increase the capture of slowly settable lime solids.

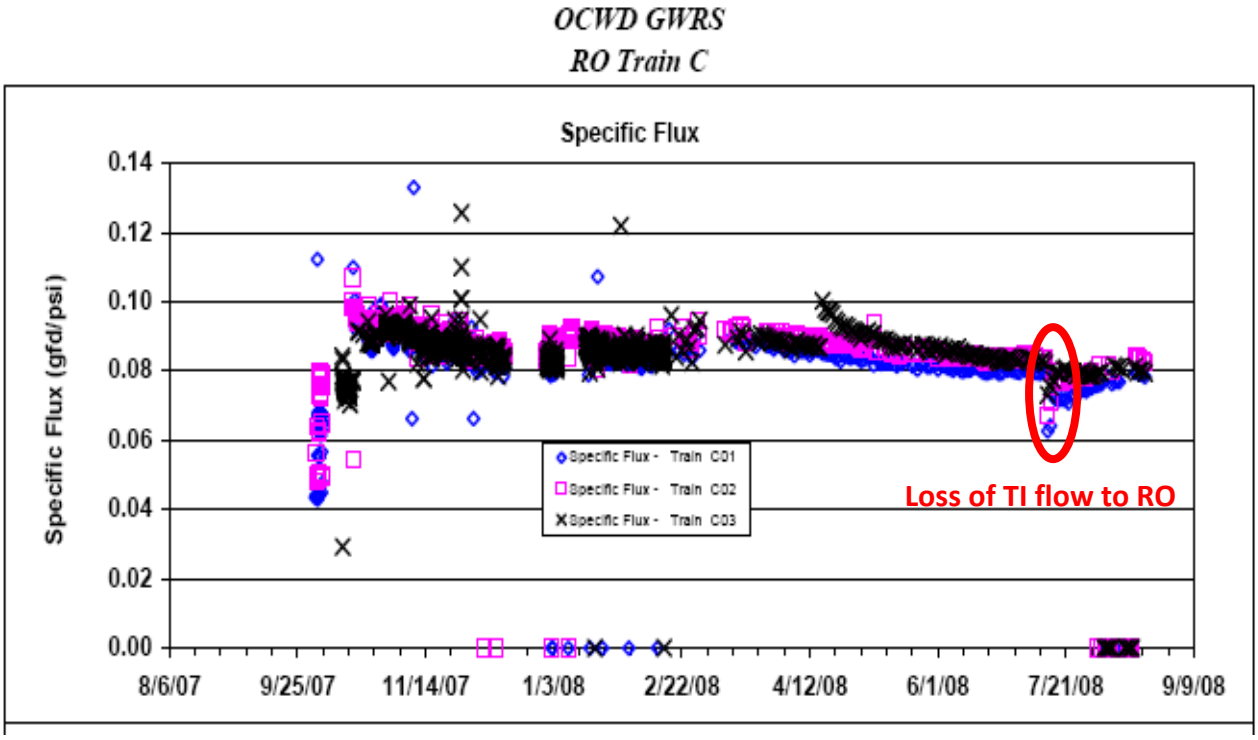


Figure 2. Specific flux for GWRS over time.
TI = threshold inhibitor (i.e., antiscalant) [*14*]

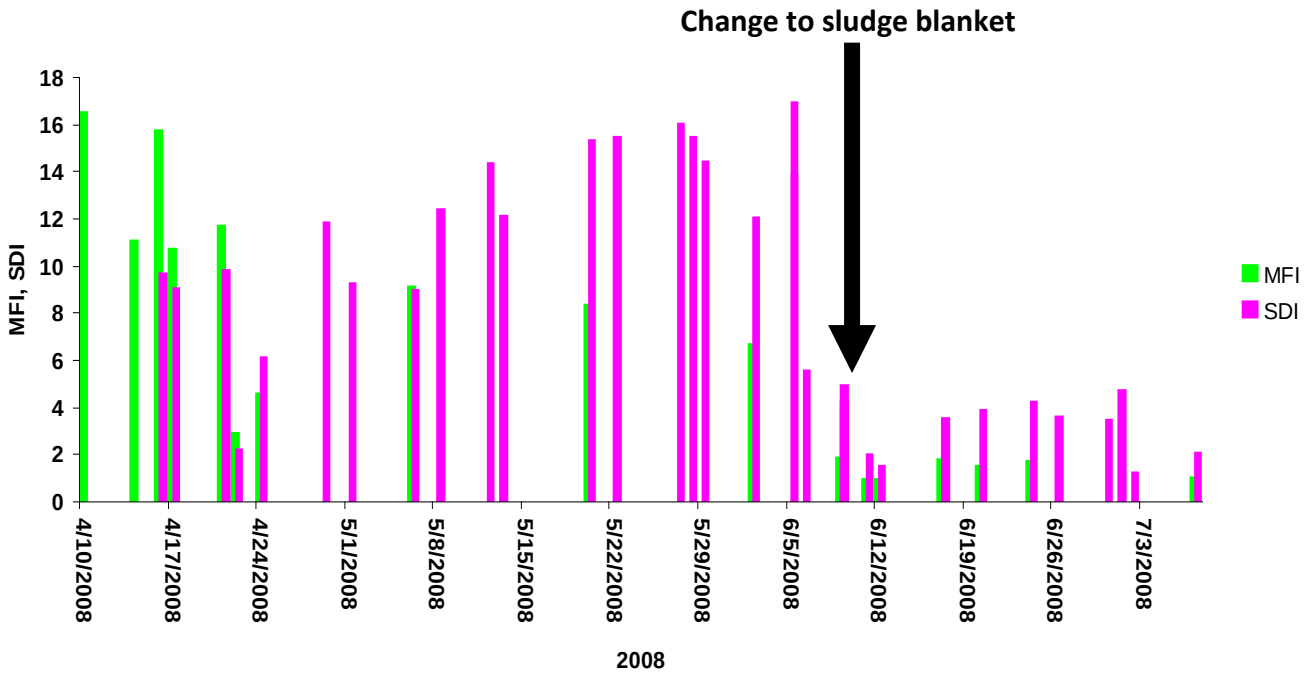


Figure 3. Improvement in SDI and MFI after Change to Sludge Blanket Operation [*14*]

Final Water Quality

Table 5 also shows the final product water quality for the GWRS. For the data shown, between February 2008 and April 2010, GWRS was able to meet or exceed all regulatory requirements. The following general water quality conditions were met:

- ≤ 86 mg/L TDS,
- ≤ 2.4 mg/L TOC,
- ≤ 2.5 mg/L total nitrogen,
- ≤ 0.01 mg/L total phosphorous,
- All trace metals below their respective MCL,
- No total or fecal coliforms,
- All radiological constituents below their respective MCL, and
- ≤ 0.3 µg/L total trihalomethanes (TTHMs).

Methylene chloride (0.0006 mg/L maximum) was detected in the final product water, but was far below the MCL of 0.005 mg/L. NDMA prevalence data showed an average concentration of 1 ng/L and a maximum value of 14 ng/L, above the 10 ng/L notification level. Gemfibrozil, an unregulated PPCP, was detected in the final product water at less than 1.2 ng/L concentrations.

Special Studies

Pretreatment Selection

Between 2000 and 2003, pilot-scale MF and ultrafiltration (UF) evaluations were conducted to pre-qualify pretreatment systems for the GWRS [*10*,*15*]. Products from several MF manufacturers were evaluated in order to qualify for participation in the project and to determine operating conditions and design criteria. Manufacturers included Siemens Water Technology (formerly US Filter/Memcor), Pall Corporation, and GE Zenon (formerly Zenon Environmental). Further demonstration testing of the same units was conducted between 2004 and 2006. From these tests, the final design criteria (e.g., membrane flux, backwash intervals, and cleaning cycles) were determined. Final selection of the pretreatment process (CS MF, Siemens Water Technology) was based on a competitive bid.

RO Membrane Selection

Pilot tests were conducted to evaluate various brackish water RO elements for use in the GWRS. Thin-film composite polyamide RO membranes from Dow, Koch Membranes, and Hydranautics were evaluated in either single-element test skids or a multi-arrayed RO skid capable of higher water recoveries. Through these tests, the Hydranautics ESPA2 membrane was selected and design criteria of 12 gfd and 85 percent recovery were determined [*10*].

UV Dose Determination

OCWD conducted pilot-scale investigations on UV oxidation of NDMA from secondary treated wastewater derived microfiltered RO permeate [*16*]. The study found that > 400 mJ/cm^2 of UV light was needed to remove NDMA from 150 ng/L to below the 10 ng/L CDPH Notification Level (1.2-log removal). Oxidative doses of UV light were more than four times that necessary for typical disinfection (80 mJ/cm^2) for wastewater applications [*17*]. A key finding was that UV system hydraulics, rather than lamp design (e.g., low-pressure high-intensity and medium-pressure high- intensity), had a profound effect on NDMA reduction. The feed water to the UV system must be distributed throughout the reaction chamber in a manner that allows maximum contact with ultraviolet light. The reactor hydraulics and lamp spacing design are very much size and flow dependent, which makes full-scale testing a must to ensure an effective UV system. Further, investigations found that for equivalent NDMA reduction, full-scale UV systems used between 40 and 80 percent less energy compared to pilot-scale systems. This conclusion that full-scale systems were more efficient in terms of NDMA destruction than pilot-scale systems was caused by better system hydraulics [*18*]. Final selection of the UV process (Trojan Technologies) was based on a competitive bid.

Health Effects Study

The OCWD and OCSD, in conjunction with a consultant, conducted a risk assessment to determine the relative increase or decrease in potential adverse public health outcomes associated with the GWRS project [*19*]. The basic hypothesis was "… the quality of the recycled water is expected to be better than that of alternative water supplies…" and "…the [groundwater] basin's

overall quality should actually improve." The purpose of the risk assessment was to use quantitative relative risk assessment methods to compare pilot plant effluent representative of the expected GWRS project effluent with existing water sources.

Study Methodology

The study methodology used estimates of the relative risks to human health associated with each water source. Water sampling data were compiled for GWRS RO permeate, Santa Ana River, Colorado River, and State Water Project waters. Summary statistics were compiled for each source water and for each constituent monitored. Constituents of potential concern in each of the source waters were identified as those that were detected in levels significantly greater than laboratory or travel blanks, and have associated health based criteria, which can be used to quantify the estimates of relative potential risk. Potential health risks associated with the exposure scenario described above were characterized for each constituent of potential concern in each of the recharge waters. The characterization of health risks was divided into non-carcinogenic health risks, carcinogenic health risks, and risks from microbiological contaminants. The hazard index—a metric used to calculate non-carcinogenic risk—was defined as follows:

$$\text{Hazard Index} = E_1/RfD_1 + E_2/RfD_2 \ldots + E_i/RfD_i \quad (2)$$

Where:

E_i = Exposure level to the i_{th} toxicant
RfD_i = Reference dose for the i_{th} toxicant
E_i/RfD_i = Hazard Quotient for the i_{th} toxicant

Carcinogenic risks were estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to a potential carcinogen. The numerical estimate of excess lifetime cancer risk was calculated as follows:

$$\text{Risk (probability/lifetime)} = \text{Chemical Intake (mg/kg/day)} \times \text{Slope Factor (mg/kg/day)}^{-1} \quad (3)$$

Cancer slope factors with 95th percentile confidence limits were based on experimental animal data and limited epidemiological studies, when available. A linear non-threshold mathematical model for low-dose extrapolation was used to calculate numerical cancer potency values.

Table 6, Table 7, and Table 8 show the non-carcinogenetic and carcinogenic risk factors calculated for both GWRS effluent, Santa Ana River, and imported surface waters. Note: neither E_i/RfD_i nor the slope factors were provided in the original report. Hence, the data contained in Tables 6–8 cannot be confirmed.

Risks Associated with Non-Carcinogenic Health Effects

Table 6 and Table 7 provide summaries of non-carcinogenic risks associated with direct consumption of GWRS product water, and Santa Ana River water and imported waters, respectively. Through the hazard index method, the non-carcinogenic health risk for drinking

GWRS product water (0.14) was lower than either Santa Ana River (0.65) or imported water (0.51).

Risks Associated with Carcinogenic Health Effects

Table 8 provides a comparison of estimate carcinogenic risk for individuals drinking either GWRS product water or Santa Ana river water. The general findings were:

- The estimated carcinogenic risks associated with direct consumption of GWRS product water was lower than that associated with direct consumption of either Santa Ana River or imported water;
- Although the levels of arsenic in all three source waters are below the existing and the proposed regulatory levels, arsenic is the constituent that accounts for the majority of the risk associated with continued reliance on the Santa Ana River;
- At an (assumed) maximum concentration of 20 ng/L, NDMA would present more carcinogenic risk than any other constituent of concern identified in GWRS product water; and
- The presence of arsenic is the dominant risk factor associated with blends in either water source.

Risks Associated with Microbiological Contaminants

GWRS product water was projected to present much lower risk than existing recharge waters from bacteria, parasites, and viruses, provided that all unit processes in the treatment facility were fully operational and operated properly. This conclusion was based on the expected pathogen levels in the raw wastewater influent (generally 10^3 pfu/L or less), the documented virus removal capabilities of the GWRS integrated treatment train, previously reported removal of parasites through an AWT treatment train, and the fact that ultraviolet disinfection would be part of the integrated treatment train [*19*].

Study Conclusions

The risk assessment study concluded that the relative health risk associated with the GWRS project was less than or equal to that associated with the current surface spreading operations. The caveats to this conclusion were:

- The concentration of NDMA does not exceed 20 ng/L, as used in the risk assessment;
- The concentration of the remaining non-microbial constituents do not increase more than a factor of five above that used for the risk assessment; and
- No degradation in water quality being observed based on continual monitoring of the GWRS product water.

Constituents of Emerging Concern Monitoring

OCWD conducted several projects to evaluate the effectiveness of advanced water treatment technologies to remove PPCPs and EDCs from secondary or tertiary treated wastewater effluents [*20,21*]. The objectives of these projects varied, but the main thrust was to gain a better

understanding of PPCP and EDC removal rates across advanced water treatment processes for indirect potable reuse. Bench-scale work developed a model whereby specific PPCP and EDC removal rates across RO and NF membranes could be estimated *a priori*. This theoretical model was based on complex physico-chemical interactions between the compounds of interest and membrane properties. The following key solute parameters were identified to primarily affect solute rejection: molecular weight (MW), molecular size (length and width), acid disassociation constant (pK_a), hydrophobicity/hydrophilicity (log K_{ow}), and diffusion coefficient (D_p) [*22*]. Key membrane properties affecting rejection that were identified include molecular weight cut-off (MWCO), pore size, surface charge (measured as zeta potential), hydrophobicity/ hydrophilicity (measured as contact angle), and surface morphology (measured as roughness).

Full-scale water quality monitoring indicated that GWRS's MF-RO-AOP treatment train produced water of sufficient quality to meet all State and Federal primary drinking water standards (Table 5). With the exception of gemfibrozil, all PPCPs and EDCs detected in the MF feedwater were reduced to levels below method detection limits in the final product water.

Arsenic Leaching

Per OCWD's permit, a blend of 75 percent reclaimed water and 25 percent imported drinking water was maintained between 2008 and 2010. Starting in 2010, this provision was lifted as OCWD was able to show no degradation of the aquifer water quality was caused by GWRS operations at the 75 percent blend. However, shortly after going to 100 percent reclaimed water, higher than expected arsenic levels were observed in several monitoring wells near the Kramer and Miller spreading grounds. While the source of the arsenic was not identified, it was believed that the increased quantity of reclaimed water may have contributed to the dissolution of arsenic in the basin soil. OCWD has since returned to the 75:25 blend and reduced the product water pH from 9.0 to 7.5 until the source of the elevated arsenic could be better understood [*6*].

West Coast Basin Barrier Project

The Edward C. Little Water Recycling Facility, operated by West Basin Municipal Water District (WBMWD), consists of three separate treatment processes currently designed to produce a total of up to 50 MGD of various quality recycled water. This report will focus solely on the West Coast Basin Barrier Project (hereafter referred to as the Barrier plant), an advanced purification facility designed to provide recycled water for injection into a seawater intrusion barrier. The Barrier plant was upgraded to 12.5 MGD in 2006 and consists of newly installed MF, RO, and advanced oxidation (UV and hydrogen peroxide) systems [*23*].

Source Water

The source water for the Edward C. Little Water Recycling Facility is secondary effluent from the Hyperion Treatment Plant that is owned and operated by the City of Los Angeles. Industrial wastewater sources ranges from 10 to 15 percent of Hyperion's influent flow [*24*]. Primary treatment is provided by sedimentation tanks in order to remove 85 percent of organic and

inorganic solids from raw wastewater. Primary effluent then treated through high-purity oxygen activated sludge basins followed by secondary clarification tanks where settling of the biomass occurs. The Barrier plant uses a side stream of the secondary treated effluent prior to being discharged into the Santa Monica Bay as the feed. Sodium hypochlorite is added to this water to generate between 3 and 5 mg/L chloramines prior to the MF pretreatment.

Table 5 provides a summary of the influent water quality data for the Barrier plant. These data were taken from the City of Los Angeles' 2009 Annual Monitoring Report for the Hyperion Treatment Plant [*25*]. Barrier plant influent water quality data revealed the secondary treated water contained high levels of ammonia (41 mg/L NH_3-N average and 44 mg/L NH_3-N maximum), turbidity (9 NTU avg. and 14 NTU max.), TOC (17 mg/L avg. and 18 mg/L max.), and total suspended solids (TSS; 18 mg/L avg. and 25 mg/L max.). Of the permit regulated trace organic compounds, most were below the MDLs and all were below MCLs. NDMA was not detected in the Hyperion Treatment Plant effluent; however the MDL was only 0.5 µg/L. Hyperion effluent did contain minimal levels of gross alpha (3.57 pCi/L avg. and 5.83 pCi/L) and gross beta (9.4 pCi/L avg. and 12.7 pCi/L max.) emitters. No fecal or total coliform data were reported.

Pretreatment

The current MF units consist of Siemens CMF-S with 0.2 µm polypropylene membranes. The MF system operates at a design flux of 21 gfd and a recovery of 91 percent.

Reverse Osmosis

RO is a two-stage 72:36 array, with seven 8-inch diameter by 40-inch long membrane elements (ESPA2, Hydranautics, Oceanside, Calif.) per vessel. The RO train operates at 85 percent recovery at a flux rate of 12 gfd. Chemical feeds to the RO influent include sulfuric acid to lower the pH to 6.4 and antiscalant to protect against mineral scaling.

UV Oxidation

The UV system (TrojanUV Phox^{TM}, Trojan Technologies) achieves oxidation/disinfection via a combination of direct photooxidation using low pressure high intensity amalgam lamps that emit a UV dose of greater than 115 mJ/cm^2 at approximately 254 nanometers. Three parts per million (ppm) hydrogen peroxide are also added for indirect photooxidization from highly oxidative OH radicals.

Post Treatment

Product water from the UV/Peroxide AOP is decarbonated, and, finally, approximately 33 mg/L lime is added to adjust the pH to approximately 8, and additional sodium hypochlorite is added prior to distribution to barrier injection wells.

Final Product Water Quality

Table 5 also shows the final product water quality for the Barrier plant [*26*]. For the data shown for 2007 and 2009, the Barrier plant was able to meet or exceed all regulatory requirements. The following general water quality conditions were met:

- ≤ 83 mg/L TDS,
- ≤ 0.3 mg/L TOC,
- ≤ 3.2 mg/L total nitrogen,
- All trace metals below their respective MCLs,
- No total or fecal coliforms,
- All radiological constituents below their respective MCLs, and
- ≤ 1.26 µg/L TTHMs.

Methylene chloride (0.001 mg/L max.) was detected in the final product water, but was far below the MCL of 0.005 mg/L. NDMA data showed an average concentration of 6.4 ng/L and a maximum value of 20 ng/L—above the 10 ng/L CDPH Notification Level. Of the EDCs and PPCPs monitored, only bisphenol-A (5 ng/L avg. and 17 ng/L max.) and ethinyl estradiol (2.6 ng/L max.) were detected above the MDLs.

Special Studies

Pretreatment Selection

WBMWD considered three manufacturers to supply MF treatment for the Barrier plant. The three manufacturers were Siemens Water Technology (formerly US Filter/Memcor), Pall Corporation, and GE Zenon (formerly Zenon Environmental) [*27*]. Final selection of the pretreatment process (CMF-S MF, Siemens Water Technology) was based on a competitive bid.

RO Membrane Selection

No data on membrane selection were found. Based on personal communications with WBMWD staff, RO membranes were selected based on OCWD's GWRS results [*28*].

UV Oxidation Selection

UV oxidation in tandem with H_2O_2 addition was studied to evaluate NDMA removal from post-RO water [*27*]. The main objectives of the UV studies were to:

1. Evaluate both low- and medium-pressure UV lamps in terms of NDMA removal (with and without H_2O_2), energy consumption, and maintenance, and space requirements; and
2. Examine NDMA re-formation potential in post chlorinated RO water.

Major conclusions from these studies were:

- NDMA removal efficiency was not predicated on lamp design (i.e., low- or medium-pressure lamps),
- NDMA was able to be reduced from 200 ng/L to less than 2 ng/L on a reliable basis. It should be noted that WBMWD did not report a specified UV dose for NDMA destruction, only an approximate energy consumption (1.22–3.54 kWh/1000 gallons for medium-pressure lamps and 0.38–0.76 kWh/1000 gallons for low-pressure lamps),
- UV efficacy for NDMA removal not dependant on H_2O_2 concentration,
- Simulated distribution testing did not indicate that NDMA would reform once water was treated with UV and subsequently chlorinated with a two-day contact time.
- Technical advisory panel recommended to CDPH (formerly California Department of Health Services) that H_2O_2 addition be continued to provide an added level of protection against as yet unidentified constituents of emerging concern.

Constituents of Emerging Concern Monitoring

WBMWD, in conjunction with Separation Processes, Inc., conducted a study to evaluate removal rates of trace-organic compounds commonly found in secondary treated wastewater through the full-scale advanced water purification processes (MF, RO, and UV plus hydrogen peroxide) [*29*]. A total of 158 trace-organic compounds were analyzed in this study, and 23 were detected in levels suitable to determine removal rates as shown in Table 9. The compounds detected included pharmaceuticals, trihalomethanes, endocrine disrupting compounds, plasticizers, solvents, herbicides, and industrial byproducts.

Overall, MF was less effective than RO and UV for removal of the selected organic compounds shown in Table 9. RO can effectively remove dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), bromoform, methyl-tert-butyl ether, toluene, 1,4 dioxane, and dalapon. UV demonstrates better performance than RO for removal of 1,4-dichlorobenzene (p-dichlorobenzene), dibromochloromethane, dibromomethane, tetrachloroethene, and bromochloromethane. It appears that none of processes can effectively remove methylene chloride and bromochloromethane. These results were similar to previous pilot-scale testing performed by WBMWD [*30*].

Alamitos Barrier Recycled Water Project

The Alamitos Barrier Recycled Water Project was undertaken by the Water Replenishment District of Southern California (WRD) to supplement the imported water supply used to protect drinking water aquifers in the Central Basin of Los Angeles County. As such, the Leo J. Vander Lans Advanced Water Treatment Facility was commissioned in 2003. The 3-MGD design capacity plant treats disinfected tertiary effluent from the Los Angeles County Sanitation Districts' (LACSD's) Long Beach Water Reclamation Plant (LBWRP) with MF pretreatment, followed by RO and UV. The Advanced Water Treatment Facility is designed to produce

recycled water that meets the CDPH requirements for indirect potable reuse using intermediate groundwater storage.

Source Water

The source water for the Leo J. Vander Lans Advanced Water Treatment Facility is disinfected tertiary effluent from the LBWRP. The original source water for the LBWRP is predominantly comprised of residential and commercial wastewater, with only 5 percent of the flow of industrial origin. There were no known chemical, pharmaceutical, photographic, or biological production facilities within the LBWRP's catchment area [*31*]. Primary treatment involves settling tanks to remove grit and debris. Secondary and tertiary treatments include activated sludge aeration tanks to reduce biological oxygen demand (BOD) and multi-media filtration and chlorination for pathogen and virus inactivation, respectively.

Table 5 shows influent water quality data for the Leo J. Vander Lans facility (i.e., effluent from the LBWRP) [*32*,*33*]. The final filtered effluent from the LBWRP is permitted as Title 22 quality recycled water for non-potable (e.g., irrigation and industrial) uses. Leo J. Vander Lans average (maximum) influent water quality data revealed the tertiary treated water contained 1.11 mg/L ammonia as nitrogen (1.72 mg/L NH_3-N), 0.76 mg/L (5.8 mg/L) TSS, 0.53 NTU (0.85 NTU) turbidity, 5.85 mg/L (7.71 mg/L NO_3-N) nitrate as nitrogen, and various trace metals. The majority of trace organic compounds were below the MDLs. However, NDMA averaged 470 ng/L with a maximum value of 1,400 ng/L. Radiologicals (e.g., gross alpha, gross beta, and uranium) were detected in the influent water, though below their respective MCLs. No total or fecal coliforms were detected in the source water to the Leo J. Vander Lans facility.

Pretreatment

The selection of pretreatment equipment was pre-qualified by WRD engineers through a review of OCWD and WBMWD's pilot- and demonstration-scale test data. Of the two pre-qualified vendors (UF Filter/Memcor and Pall Corporation), the Pall MF system (module model #USV-6203, Pall Corporation, Port Washington, NY) was chosen through a competitive bid process. The 3.53 MGD MF system consists of "outside-in" hollow fiber membranes with 200 MF modules arranged in 8 racks (25 modules per rack). The design operating flux for the MF system is approximately 33 gfd on a 24-hour basis. The MF system does not have feed pumps, but uses modulating valves to regulate the pressure from the LBWRP distribution system (60–100 psi) to filter the tertiary treated wastewater [*34*]. Chlorine was fed prior to the MF unit to protect against biofouling. The chlorine combined with ambient ammonia to form chloramines, with the chloramine residual being maintained throughout the MF process.

Reverse Osmosis

The RO design criteria were developed by the WRD's consultants (Camp Dresser and McKee Inc., and Separation Processes, Inc.). RO treatment consists of a single 3.0-MGD 2:1 array system designed to operate at 10 gfd membrane flux, 85 percent feed water recovery and 90 percent operational reliability. Each of the 72 first-stage and 36 second-stage vessels house

seven 8-inch diameter by 40- inch long spiral wound membrane elements (ESPA2, Hydranautics, Oceanside, CA). Chemical feeds to the RO influent include sulfuric acid and antiscalant to protect the system against mineral scaling.

UV Oxidation

A UV system (Model 30AL50, TrojanUVPhox™, Trojan Technologies, Ontario, Canada) was added downstream of the RO system to oxidize NDMA found in the LBWRP effluent water. An engineering study conducted by the WRD identified UV oxidation was the preferred method for controlling NDMA [*35*]. WRD required that the UV system be able to reduce NDMA concentrations from an average of 420 ng/L to below 10 ng/L—the CDPH Notification Level (a 1.6-log reduction). Data from OCWD and WBMWD were sited showing NDMA was rejected by RO membranes by approximately 50 percent. The major assumption in the UV design was that an estimated average of 600 ng/L NDMA in the Leo J. Vander Lans influent would conservatively experience 30 percent removal across the RO system; hence the 420 ng/L NDMA average value was used. Thus, at 2,000 gallons per minute (gpm) and a UV light transmittance (UVT) of 95 percent, the UV dosage to achieve 1.6-log photolysis of NDMA was estimated to be 149 mJ/cm^2. These design criteria were developed through pilot testing by the UV manufacturer and WRD [*35*].

Post Treatment

Post treatment of the RO permeate includes packed-tower decarbonation step to remove excess carbon dioxide and pH adjustment to 8.7 with sodium hydroxide. Final target pH and LSI once permeate water is blended with surface water prior to injection is 8.1 and 0.1, respectively [*31*].

Final Product Water Quality

Table 5 also shows the final product water quality for the Leo J. Vander Lans Advanced Water Treatment Facility. For the data shown, between January 2008 and December 2009, the Leo J. Vander Lans plant was able to meet or exceed all regulatory requirements. The following general water quality conditions were met:

- ≤ 72 mg/L TDS,
- ≤ 0.48 mg/L TOC
- ≤ 1.6 mg/L total nitrogen,
- All trace metals below their respective MCLs,
- No total or fecal coliforms,
- All radiological constituents below their respective MCLs, and
- ≤ 8.7 µg/L TTHMs.

NDMA data showed an average concentration of 4.3 ng/L and a maximum value of 6.4 ng/L, below the 10 ng/L Notification Level. Gemfibrozil, an unregulated PPCP, was detected in the final product water at less than 1.3 ng/L.

Special Studies

Improving System Performance

Between 2003 and 2008, the Leo J. Vander Lans plant was not able to operate continuously at design conditions (85 percent water recovery, 10 gfd flux, and 3.0 MGD capacity) [*34*]. Despite running at lower operating flux (8–9 gfd) and water recovery rates (81 percent), the plant experienced excessive membrane fouling, which led to 2–3 week chemical cleaning intervals. A consultant evaluated the Leo J. Vander Lans plant's operating data and determined the following:

- The MF system was operating within design parameters (turbidity ≤ 0.15 NTU, SDI 3–5 units, and ≤ 0.001 percent fiber breakage);
- Primary RO mineral scalants (calcium carbonate and calcium phosphate) were within design limits;
- The major cause of membrane fouling was a byproduct of elevated aluminum (130–170 µg/L) in the plant influent, most likely caused by the use of aluminum sulfate coagulation at the LBWRP. The residual aluminum precipitated on the RO membranes as aluminum hydroxide, aluminum phosphate, or aluminum silicate. Sequential acid-base chemical cleanings were able to restore membrane performance. LBWRP subsequently discontinued alum addition and RO membrane performance improved, as evidenced by reduced rates in increasing applied feed pressure from initially 10 psi/day to 3 psi/day.
- Biofouling may also have been a minor cause of membrane fouling. Sodium bisulfite was fed at the RO influent to quench the chloramine residual to protect the membranes against membrane oxidation. The sodium bisulfite feed was eliminated in August 2008.

After the elimination of alum fed at the LBWRP and sodium bisulfite feed at the RO influent, the RO system was able to meet design set points. The most critical factor was the discontinuation of the alum feed at the LBWRP.

Western Australia

A research consortium comprised of various governmental entities (Government of Western Australia's Department of Health, Department of Water, Department of Environment and Conservation, National Measurement Institute, CSIRO, and the Chemistry Centre of Western Australia), a private company (the Water Corporation), and two universities (University of Western Australia, Curtin University of Technology) conducted a three-year study to determine the feasibility of augmenting drinking water supplies in Western Australia through groundwater replenishment [*36*]. The research was conducted to determine the feasibility of using MF and RO treatment to provide water to supplement water supplies through groundwater injection. While UV treatment was recommended for future studies, no UV testing was part of this report. The aims of the project were to:

- Characterize the microbial and chemical constituents of the large metropolitan wastewater treatment plants (WWTPs) that could serve as the source for potential water recycling plants. Please note that while three WWTPs source waters were studied in the report, this document will only report on two of them (Woodman Point and Beenyup), as these plants had MF-RO data associated with them.
- Analyze the permeate to assess the performance of MF followed by RO treatment at the Kwinana Water Reclamation Plant (WRP) fed by Woodman Point WWTP and the specially constructed Beenyup pilot plant, to consistently produce water meeting health and environmental requirements.
- Use the research results to develop and refine health and environmental guidelines.

Source Water

The Perth Metropolitan wastewater system comprises mainly with urban and commercial sources, with low industrial loadings. The three main wastewater treatment plants are Beenyup, Subiaco, and Woodman Point WWTPs. The 36-MGD Beenyup WWTP serves the north of the city, which is mainly residential. The Woodman Point WWTP treats up to 34 MGD and serves the south metropolitan region. Source water for the Woodman Point WWTP comes from residential, non-residential (majority from food manufacture and processing or restaurant industries), industrial (six percent), and medical waste (less than 0.071 percent).

The Beenyup WWTP process train includes screening, grit removal, activated sludge treatment with aerated and anoxic zones (designed for denitrification) and clarification. The Woodman Point plant uses screening, grit removal and activated sludge treatment via sequencing batch reactor. This process conducts activated sludge treatment in batches that are subject to aeration and non-aeration periods (designed for nitrification and denitrification) followed by decanting the clarified wastewater. The Subiaco plant will not be discussed further in this document as the Subiaco plant has no MF or RO facilities associated with it.

Table 5 shows the combined influent water quality data for the Beenyup pilot plant and Kwinana WRP taken between 2005 and 2008 [*36*]. Individual WWTP data, where available, are noted in Table 5 through various superscripts. Both the Woodman Point (source water for the Kwinana WRP) and Beenyup WWTPs have partially nitrified effluent. As such, the average influent water quality data for the secondary treated effluents were 4.48 mg/L NH_3-N, 17.9 mg/L total TSS, 8.68 NTU turbidity, 4.4 mg/L NO_3-N, and various trace metals. The majority of trace organic compounds were below the MDLs. However, NDMA was above the CDPH 10 ng/L Notification Level with an average of 16 ng/L and maximum value of 43 ng/L. Low levels of gross alpha and gross beta emitters were detected in the influent water, though below their respective MCLs. No total or fecal coliforms data were reported. However, *enterococcus* and thermotolerant coliforms were present in all samples taken from the Beenyup WWTP. Enteric virus and coliphages, while not quantified, were also regularly detected in Beenyup WWTP effluent.

Pretreatment

Pretreatment for the full-scale Kwinana WRP involves initial 2-mm course screening, chloramination (1–2 mg/L), pH adjustment (pH 5.8–6.4), and hollow-fiber, outside-in, polypropylene-membrane MF (Memcor CMF S10T, Siemens). Antiscalant (PC-191T, Nalco Company, Naperville, Illinois) was dosed prior to RO membrane treatment.

Pretreatment for the containerized Beenyup pilot plant consisted of 1-mm course screening, followed by pressurized MF using polyvinylidene fluoride (PVDF) membranes (Memcor CMF-L 6L10V, Siemens). Chemical feeds included ammonia and sodium hypochlorite to form 1–2 mg/L chloramines, sulfuric acid to maintain an RO feed pH of 6.0, and antiscalant (Hydrex 4101, Veolia Water Solutions & Technologies**,** Pyrmont, New South Wales, Australia) for mineral scale control.

Reverse Osmosis

RO treatment for Kwinana WRP consisted of 8-in wide x 40-in long polyamide membranes (BW30-400-FR, Dow Flimtec, Minnetonka, Minn.) designed for approximately 9 gfd at 70 percent water recovery. The pilot-scale RO system at the Beenyup WWTP utilized 4-in long x 40-in long polyamide RO membranes (ESPA2, Hydranautics, Oceanside, Calif.) operated at 9.3 gfd between 69–80 percent water recovery.

UV Oxidation

During this study period, no UV treatment was conducted by either plant. However, UV oxidation (200 mJ/cm^2) was used at the Beenyup groundwater replenishment project in later testing [*37*]. No UV data are available at this time.

Post Treatment

Post treatment for the Kwinana WRP was sodium hypochlorite and sodium hydroxide to raise pH. No chlorine or pH set points were specified in the report. No post treatment was conducted at the Beenyup pilot plant.

Final Product Water Quality

Table 5 also shows the final product water quality for the Beenyup pilot plant and Kwinana WRP. For an abbreviated list of chemical constituents for the Beenyup pilot plant, see Table 10. For the data taken between 2005 and 2008, both plants were able to meet or exceed all regulatory requirements. The following general water quality conditions were met:

- ≤ 5 mg/L TDS (data taken prior to post stabilization),
- ≤ 0.35 mg/L TOC
- ≤ 1.0 mg/L total nitrogen,
- All trace metals were below their respective MCLs,
- No detectable pathogens or viruses,
- All radiological constituents were below their respective MCLs, and

- ≤ 8.7 µg/L TTHMs.

NDMA data showed an average concentration of 4.5 ng/L, but had a maximum value of 30 ng/L—above the 10 ng/L CDPH Notification Level. Many organic chemicals that were detected in wastewater were also reported in at least one post-RO water sample. Acrylonitrile was detected in 83 percent of the post-RO samples followed by 1,4-dioxane (29 percent), azobenzene (24 percent) and butylbenzylphthalate (14 percent). The following analytes were only measured in one sample from Kwinana WRP: 4-chlorophenoxybenzene, 4-bromophenoxybenzene, hexachlorobenzene, and MTBE. Apart from MTBE (1.66 µg/L), the highest median concentrations were 0.12 µg/L for 1,4-dioxane and 0.13 µg/L for acrylonitrile. The median concentration of all other chemicals was lower than 0.04 µg/L. It was unclear as to why MBTE concentration in the post-RO sample was higher than that found in the corresponding wastewater sample. For acrylonitrile, the median concentration in post-RO water (0.13 µg/L) was higher than that in secondary wastewater (0.04 µg/L), and percentage detections in post-RO water (83 percent) were also higher than in secondary wastewater (50 percent). Of the 36 pharmaceutical compounds analyzed, only clofibric acid (1.6 ng/L), diazepam (26.4 ng/L), and naproxen (15 ng/L) were detected in the post-RO effluent. In should be noted that these data were taken without any additional UV/peroxide treatment [*36*].

Special Studies

Risk Quotients

Figure 4 shows the three-tiered chemical risk assessment approach used by the Western Australia government to establish water quality guidelines for indirect potable reuse within the region [*37*]. Risk quotients (RQs)—indicators of potential health risks—were assigned to each constituent of concern. Constituents of concern included trace metals, radiologicals, pesticides, DBPs, *N*-nitrosamines, volatile organic compounds (VOCs), miscellaneous organics (e.g., phenols, dioxins, furans, polychlorinated biphenyls [PCBs], 1,4-dioxane, and MTBE), PPCPs, and estrogenic hormones. RQs were calculated by dividing the measured concentration (MC) of a detected contaminant by either its guideline value for a regulated compound (Tier 1), health value for unregulated chemicals with toxicity information (Tier 2), or threshold of toxicological concern value for unregulated chemicals without toxicity information (Tier 3). Water quality guideline and health values were based on data found in Australian Drinking Water Guidelines, World Health Organization, USEPA, Title 22: CCR, and European Union water quality regulations. When data were lacking on toxicological significance, the Western Australia government consulted with Australia's International Agency on Cancer Research, Integrated Risk Information System, Risk Assessment Information System, and National Toxicology Program [*36*]. An RQ less than 1 implies a low health risk [*36*]. RQs before and after RO were calculated using median and maximum concentrations (RQ_{median} and RQ_{max}).

For all radiologicals, VOCs, miscellaneous organics, PPCPs, and estrogenic hormones measured, RQs were below "1"—indicating low health risks for these compounds. The trace metals aluminum and nickel and pesticides atrazine and propiconazole had RQs equal to "1"; otherwise all other RQs for compounds in these two classes were below "1". The highest RQs based on measurable constituents of concern were the DBPs bromochloroacetaldehyde (RQ_{max} = 1.4) and dibromoacetaldehyde (RQ_{max} = 1.3), and the *N*-nitrosoamines NDMA (RQ_{max} = 3), *N*-nitroso-morpholine (RQ_{max} = 2.2), *N*-nitrosodi-n-bultyldiamine (RQ_{max} = 2.1), *N*-nitrosopiperidine (RQ_{max} = 1.5), and *N*-nitrosodi-n-propylamine (RQ_{max} = 1.4) [*36*]. It is worth noting that the concentrations of DBPs observed in the post-RO water were approximately 10 to 100 times lower than typical concentrations in Perth drinking water [*36*]. The authors did recommend further studies on *N*-nitrosamine precursor removal, post-RO treatment (e.g., UV oxidation), and natural degradation in the environment be conducted. The authors also suggested that NDMA be used as a chemical indicator to gauge treatment efficacy (see *Chemical Indicators of Treatment Performance* below) [*36*].

Viral Challenges

Two challenge tests were undertaken at Beenyup pilot plant using the coliphage MS2 as an indicator of enteric viruses to assess the capacity of the RO membranes to exclude such viruses. The results showed that the RO membranes alone were able to achieve at least a 4-log removal (i.e., 99.99 percent removal) of viruses. However, the authors cautioned that integrity monitoring was vital to ensure that rejection of viruses, bacteria, and pathogens was maintained.

Table 11 shows the log-removal/inactivation credits adopted for the Beenyup Advanced Water Treatment Plant in Western Australia [*37*,*38*]. These performance criteria were adopted based on literature values, as well as pilot- and full-scale data where applicable. As shown in Table 11, the proposed Beenyup Advanced Water Treatment Plant would exceed removal/inactivation credits for bacteria, viruses, and protozoa.

Chemical Indicators of Treatment Performance

The key outcome of this research was the identification of chemical indicators of RO treatment performance and recycled water quality indicators relevant for Western Australia. The results from this project were analyzed to derive a group of indicators appropriate for monitoring chemical removal for different chemical groups by MF followed by RO. Rejection of chemical contaminants by MF followed by RO is related to interactions between RO membrane characteristics, filtration operating conditions, and compound properties. While chemicals of low molecular weight and high polarity are expected to be poorly rejected by the membranes, the presence of any of the chemical indicators with large molecular weight in the post-RO water will indicate a failure of the treatment system.

Of the 396 compounds investigated in the study, 25 were determined to have percentage detections in post-RO water greater than 25 percent. Eight of these compounds were disinfection

by-products (seven halogenated DBPs, one N-nitrosamine, and one inorganic disinfection by-product), while six were metals or metalloids, four were VOCs, and the remaining compounds were from the classes of complexing agents, phenols, or miscellaneous chemicals. Only the N-nitrosamines pose a potential concern from a health point of view. Eight compounds had higher percentage detection in post-RO than in secondary wastewater, and this was attributed to contamination (e.g., toluene), formation during chloramination (e.g., halomethanes), or unintentional addition during the MF followed by RO process (e.g., acrylonitrile, chlorate). These constituents demonstrate that chloramination procedure, membrane materials, and anti-scalant chemical usage also need to be considered as potential sources of chemicals in post-RO water.

Table 12 shows proposed surrogates to be used in gauging the day-to-day operation of the overall treatment process [*36*]. Surrogates were chosen for their ease in monitoring through the use of calibrated on-line probes. Specific surrogates include dissolved oxygen, turbidity, conductivity, TOC, UV light intensity, and pH.

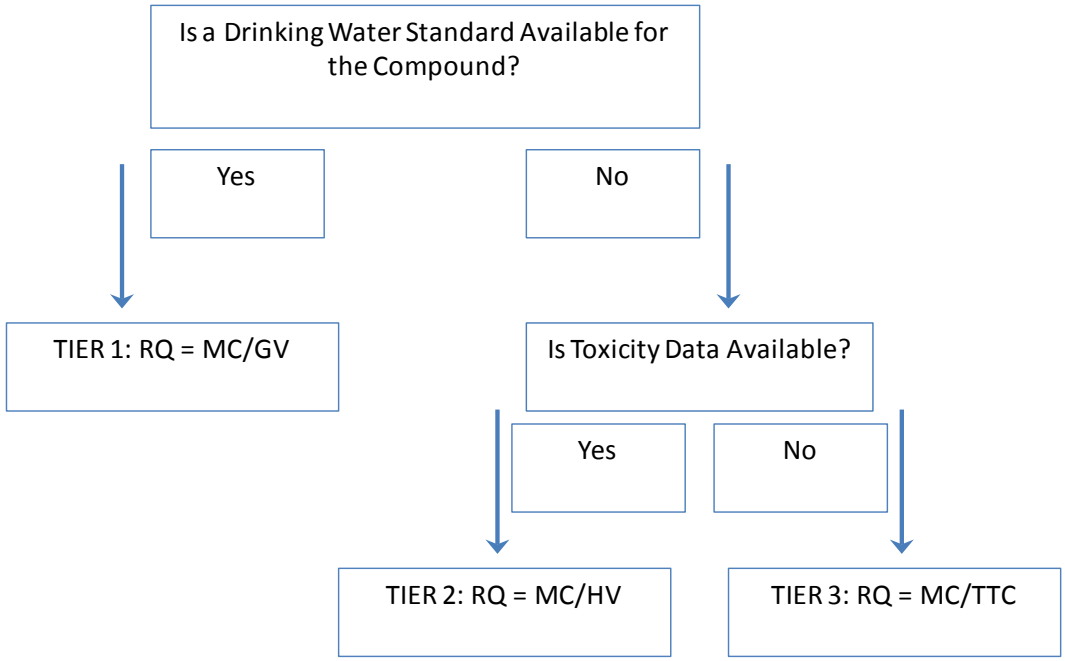
Table 13 presents the selected chemical indicators of MF followed by RO treatment performance, as identified by the Western Australian research team [*36*]. The chemical indicators cover chemical groups with different:

- Molecular weights (ranged from 10.8 to 296 g/mol),
- Hydrophobicity properties (log K_{ow} ranged from -0.64 to 3.4), and
- Acidic/basic characteristics (pKa ranged from 2.13 to 10.4).

Indicator chemicals were selected based on the following criteria:

- Commonly detected in secondary wastewater (most more than 90 percent of the time);
- Detected at higher concentrations than other chemicals of the same group. If more than one compound was commonly detected in secondary wastewater at similar concentrations, the one with the lower percentage of rejection was selected as it is considered more sensitive to assess the performance of the treatment;
- Partially removed under normal operating conditions. Indicator compounds that are partially removed by the treatment process are more sensitive indicators of system failure than poorly removed compounds;
- Have characteristics that can be linked to a predominant removal mechanism (e.g., filtration, adsorption, or oxidation), because different treatment processes target different properties;
- Be present in concentrations that are representative of the broader class of compounds and that are sufficiently high to determine a meaningful degree of reduction through a unit process or a sequence of processes; and
- Be quantifiable using an established, and preferably accredited, analytical method.

Table 14 shows additional compounds that may provide chemical indicators of recycled water quality. Recycled water quality indicators have the purpose of demonstrating safety of recycled water with respect to specific chemical groups, and hence provide additional confidence beyond treatment performance indicators found in Table 13. This can be particularly important for some chemical groups such as hormones and pesticides for which no chemical was selected as a treatment performance indicator.



Flow Chart shows a three tiered approach, with
RQ =risk quotient,
MC = measured concentration,
GV = guideline value,
HV = health value, and
TTC = threshold of toxicological concern

Figure 4. Chemical Risk Assessment Approach for Western Australia. Adapted from [*37*]

Occoquan Reservoir, Virginia

The Occoquan Reservoir is a component in a water supply system that currently serves over 1.7 million residents of Northern Virginia [*39*]. In the 1960s, the Occoquan watershed began transforming from a largely rural to a predominately urban/suburban region. This rapid growth resulted in deterioration of water quality in the eleven-billion-gallon (34,000-acre-feet) Occoquan Reservoir. The reservoir's water quality degradation resulting in [*40*]:

- Frequent and intense algal blooms;
- Periodic episodes of taste and odor in the finished drinking water;
- Low dissolved oxygen levels;
- Periodic fish kills; and
- Generation of hydrogen sulfide in the lower reaches of the reservoir.

Initial studies showed that the water quality deterioration in the reservoir was caused by substandard wastewater discharges from eleven secondary wastewater treatment plants and non-point sources of pollution. The Upper Occoquan Service Authority (UOSA) plant replaced the eleven small secondary treatment plants in the region. Unlike the previous four case studies, the UOSA plant was designed to reduce the nutrient loading in the surface waters feeding the Occoquan Reservoir, rather than augmenting groundwater supplies. More specifically, the UOSA plant was designed to:

- Prevent the release of sediment bound phosphorus;
- Reduce the release of ammonia from reservoir sediments;
- Prevent the reduction of sulfate to sulfide in the bottom layers of the reservoir;
- Possibly prevent the release of manganese (II) from sediments; and
- Maintain green algae and diatoms species dominance and preventing the proliferation of less desirable blue-green algae.

The subsection below describes the advanced water treatment system used to improve the water quality of the Occoquan Reservoir. The following subsection describes the drinking water treatment plants (WTPs) operated by the Fairfax County Water Authority (FCWA) that use the Occoquan Reservoir as the source water. Prior to 2007, both the Lorton and Occoquan Water Treatment Plants treated Occoquan Reservoir water. However, once the Frederick P. Griffith, Jr. (Griffith) Water Treatment Plant was commissioned in May 2006, these older plants were phased out and decommissioned [*41*].

Upper Occoquan Service Authority

The Millard H. Robbins, Jr. Water Reclamation Plant, operated by the Upper Occoquan Service Authority (UOSA) [formerly known as the Upper Occoquan Sewage Authority], is located in Centreville, Virginia. UOSA serves the western portions of Fairfax and Prince William counties, and the cities of Manassas and Manassas Park in the State of Virginia. The Millard H. Robbins Water Reclamation Plant includes primary and secondary treatment, followed by advanced wastewater treatment. The advanced wastewater treatment portion of the plant includes chemical clarification, two-stage recarbonation with intermediate settling, multimedia filtration, granular activated carbon adsorption, chlorination for disinfection and dechlorination (Figure 5). In 1978, the UOSA Regional Water Reclamation Plant (later renamed the Millard H. Robbins, Jr. Water Reclamation Plant) commenced operations. Through several expansions, the initial 10

MGD capacity of the Millard H. Robbins, Jr. Water Reclamation Plant was increased to 32 MGD in 1995, followed by another major expansion to 54 MGD in 2005 [*42*].

The UOSA plant is relatively unique in that the highly treated output from the plant supplies roughly 20 percent of the inflow into the Occoquan Reservoir, which provides drinking water used by the FCWA. During drought periods the plant may briefly provide up to 90 percent of the reservoir inflow. In effect, Fairfax Water is drawing a portion of its influent from recycled sewage. UOSA has demonstrated that treated plant effluent is actually far cleaner than the stream sources of surface water inflow into the Occoquan Reservoir [*43*].

UOSA operates under a Virginia Pollutant Discharge Elimination System Permit, which is issued by the Virginia's Department of Environmental Quality. Given the age of the Millard H. Robbins, Jr. Water Reclamation Plant, no publicly available data were found regarding the regulatory issues associated with permitting an indirect surface water augmentation project in the 1970s. The publicly available permit limitations are listed in Table 15 [*44,45*].

Source Water

Table 5 shows the influent water quality data for the Millard H. Robbins, Jr. Water Reclamation Plant taken between 2006 and 2010 [*46*]. The average (maximum) influent water quality data revealed: 29.4 mg/L ammonia as nitrogen (38.9 mg/L NH_3-N), 209 mg/L (808 mg/L) TSS, 5 mg/L (8.97 mg/L) total phosphorous, 5.8 mg/L (7.2 mg/L) foaming agents (MBAS), 41.6 mg/L (62.2 mg/L) total Kjeldahl nitrogen, and various trace metals. The majority of trace organic compounds, including NDMA, were below the MDLs (typically less than 0.01 mg/L), with the exception of chloroform (a chlorinated DBP; 0.0043 mg/L average [0.0174 mg/L max.]), phenols (0.0125 mg/L average [0.0178 mg/L max.]), and xylenes (0.0003 mg/L average [0.0007 mg/L max.]). No influent radiological (e.g., gross alpha, gross beta, and uranium) data were provided.

While UOSA did monitor for *Clostridium perfringens*, fecal and total coliforms, and *E. coli, Enterococcus*, coliphage, enterovirus, *Cryptosporidium*, and *Giardia* in the influent water, these data were presented as log removal data in the final product water (Table 16) [*46*]. As such, no directly reportable plant influent microbiological data were provided. See *Final Product Water Quality* for further discussion.

Primary and Secondary Treatment

Figure 5 provides a schematic drawing of the overall treatment train for the Millard H. Robbins, Jr. Water Reclamation Plant [*42*]. Primary and secondary treatment includes:

- Mechanically cleaned bar screens (0.5-inch openings);
- 24-ft diameter vortex grit chambers;
- 125-ft diameter circular center-feed primary clarifiers with primary scum collection;
- Archimedes screw primary effluent lift pumps;
- Aerobic biological selectors;

- Activated sludge aeration basins;
    - Most basins fine-bubble diffusers
    - All basins operate in nitrifying mode with active D.O. control
    - Four basins have modified Ludzack–Ettinger denitrification processes;
- Multistage centrifugal blowers (total of 5,700 horsepower capacity [96,200 scfm]);
- 125-ft diameter circular center-feed secondary clarifiers with draft tubes, slot-valve draft control, and biofoam collection;
- Continuous monitoring of secondary effluent TSS and nitrate.

Advanced Water Treatment

UOSA uses the high-lime process to reduce phosphorus to below 0.10 mg/L. This process also serves as a barrier to viruses, captures organics leaving secondary treatment, and precipitates heavy metals. Basic unit processes include [*42*]:

- Silos with total storage for 240 tons of calcium oxide as pebble quicklime;
- Detention-type lime slakers with lime aging tanks;
- Rapid mix basins for lime slurry addition with feedback control of pH to 11;
- Declining-rate flocculation basins with anionic polymer addition;
- 125-ft circular chemical clarifiers;
- First stage recarbonation to lower pH to 10 and second stage to lower pH to 7. Both stages use coarse-bubble diffusers and introduce carbon dioxide from digester boiler, carbon furnace, and pelletizer exhaust gasses, as well as purchased CO_2 as necessary;
- Recarbonation clarifiers between first and second stages to collect precipitated calcium carbonate;
- Gravity thickeners to concentrate chemical and recarbonation sludge;
- Recessed chamber plate and frame filter presses to dewater sludge; and
- Onsite 2 million cubic yard captive landfill for dewatered lime solids.

The UOSA permit requires TSS below 1 mg/L and chemical oxygen demand below 10 mg/L. To meet these stringent levels, multimedia depth filtration and activated carbon are used. UOSA has two process trains: one with pressure filtration and one with gravity. The gravity system (L/2) is as follows:

- Six 100-hp vertical turbine pumps transfer effluent to filters
- Alum and/or polymer as filter aid.
- 10 multimedia filters with 36-in bed of anthracite, silica, and garnet
- Continuous online turbidity measurement
- High rate backwash with air scour
- Intermediate pump station with four 120-hp submersible pumps
- Eight upflow/downflow carbon contactors with 2 million pounds of activated carbon, 22-min contact time

- Transfer facilities and blow tanks

The pressure process train is similar:

- 12 horizontal multimedia filters
- 32 upflow carbon contactors
- Eight post-filters for carbon fine removal

Activated carbon is regenerated onsite with a multi-hearth furnace

Disinfection

The final barrier to pathogens is a chlorination and dechlorination process. UOSA uses sodium hypochlorite and sodium bisulfite, and is designed to use these chemicals for breakpoint chlorination as necessary.

- Storage for 36,000 gallons of sodium hypochlorite;
- Three primary disinfection chlorination pumps and three backups (52 gph);
- Three primary breakpoint chlorination pumps and three backups (1086 gph);
- Two mix chambers and four 345,000 gallon covered labyrinth contact basins;
- Continuous online measurement of total and free residual chlorine at mix chamber and after 30-minute contact time;
- Bulk storage of 20,000 gallons of sodium bisulfite and transfer pumps for day tanks;
- Three bisulfite feed pumps (52 gph) and two breakpoint bisulfite feed pumps (250 gph);
- Continuous online measurement of pre-dechlorination total residual for bisulfite pacing;
- Continuous online measurement of post-dechlorination total residual; and
- Outfall to 180 million gallon final effluent reservoir

Final Product Water Quality

UOSA discharges the final product water into Bull Run, which is a major tributary of the Occoquan Reservoir. Table 5 provides average (maximum) final product water quality data. For the data shown, the UOSA Millard H. Robbins, Jr. Water Reclamation Plant was able to meet all regulatory permit requirements. Specifically, the following average (maximum) water quality data were observed [*46*]:

- *E. coli* < 1.0 per 100 ml
- Chemical oxygen demand = 6–9 mg/L
- TDS = 472 mg/L (702 mg/L)
- TOC < 3.1 mg/L (3.5 mg/L)
- TSS = 0.12 mg/L (0.9 mg/L)
- Turbidity = 0.16 NTU (0.45 NTU)
- Total phosphorous = 0.068 mg/L (0.14 mg/L)

- Surfactants (MBAS) = 0.023 mg/L (0.038 mg/L)
- Total Kjeldahl nitrogen = 0.3–0.5 mg/L
- Total nitrogen = 12.4 mg/L (36 mg/L)
- Ammonia = 0.034 mg/L (0.53 mg/L)
- Chlorine residual (during contact time) = 0.7–2.6 mg/L
- Chlorine residual (final) = non-detect

Final effluent radioactive materials included gross alpha emitters 0.12 pCi/L (1.1±1.2 pCi/L), gross beta emitters 14.24 pCi/L (19.4±2.0 pCi/L), radium 226 and 228 1.674 pCi/L (3.16±0.69 pCi/L), and uranium 0.046 µg/L (0.1±0.00 µg/L). Table 16 provides a microbial removal assessment across the Millard H. Robbins, Jr. Water Reclamation Plant. The lowest log-removal for any microbe monitored was for *Giardia* (3.8–4.6 log reduction). *Giardia* was detected at 1.1 oocysts/100 ml with detections in three out of fourteen samples. All other microbes (*Clostridium perfringens*, fecal and total coliforms, and *E. coli*, *Enterococcus*, coliphage, enterovirus, and *Cryptosporidium*) showed greater than 4-log reductions (i.e., 99.99 percent removal) across the treatment plant.

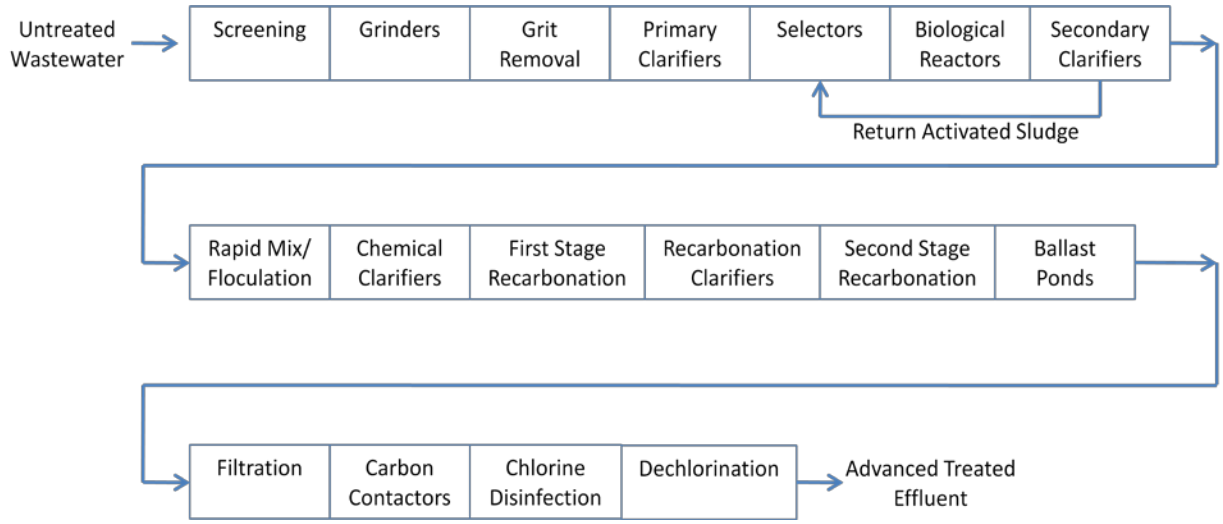


Figure 5. Treatment Process Flow Diagram for the Millard H. Robbins, Jr., Water Reclamation Facility. Adapted from [*41*]

Fairfax County Water Authority

Fairfax County Water Authority (FCWA) supplies drinking water to more than 1.7 million people in Northern Virginia. The primary water sources are the Potomac River and the Occoquan Reservoir [*41*]. This report will only discuss the Occoquan Reservoir water source. In previous years, FCWA operated two treatment plants using Occoquan Reservoir as the source

water: the Lorton and Occoquan WTPs—with a nominal combined treatment capacity of 111 MGD [*47*]. In May 2006, the 120 MGD Griffith WTP was brought online to replace the Lorton and Occoquan WTPs. The Griffith WTP is similar in design to the Lorton and Occoquan WTPs with the exception of the use of intermediate ozonation and granular activated carbon filters (Figure 6). The Griffith WTP was designed to help FCWA better reduce DBP formation potential and treat taste and odor episodes [*48*].

Source Water

Table 17 provides a summary of land uses within the Occoquan watershed [*49*]. The Occoquan watershed contains less than seven percent heavy industry, with more than 85 percent of the County's households and nearly all businesses connected to the public sewer [*50*]. The most significant point sources in Fairfax County are two large wastewater treatment plants: the Norman M. Cole, Jr. Pollution Control Plant, which is located in the southern portion of the County, and the UOSA Millard H. Robbins, Jr. Water Reclamation Plant in the Centreville area [*43*]. Water quality from the Millard H. Robbins, Jr. Water Reclamation Plant was discussed previously. In normal years, the UOSA plant supplies roughly 20 percent of the inflow into the Occoquan Reservoir, while in drought years, the UOSA plant may briefly provide up to 90 percent of the reservoir inflow [*51*].

Table 5 shows the influent water quality data for the Lorton and Occoquan WTPs taken in year 2005—the last year that complete inorganic and organic water quality data were posted online [*52*]. General average (maximum) water quality data include:

- TDS = 147 mg/L (208 mg/L)
- TOC = 5.1 mg/L (8.6 mg/L)
- Bromide = 0.02 mg/L (0.03 mg/L)
- Turbidity = 15 NTU (55 NTU)
- Total phosphorous = 0.01 mg/L (0.04 mg/L)
- Nitrate as N = 1.2 mg/L (2.7 mg/L)
- Ammonia as N = 0.11 mg/L (0.24 mg/L)

It should be noted that these data were for a single year and may not be representative of long-term water quality trends. No occurrence data for taste-and-odor compounds or algae were found in publicly available records.

Treatment Processes

Figure 6 shows the basic treatment processes for the Lorton and Occoquan WTPs, as well as the new Griffith WTP [*47*]. It should be noted that Figure 6 was developed while the Griffith WTP was under construction. In 2006, the Griffith WTP replaced both the Lorton and Occoquan WTPs. For the Lorton WTP, the original (old) and expanded (new) WTP module designs are shown separately. The Griffith WTP is similar in design to the Lorton and Occoquan WTPs with

the exception of the use of intermediate ozonation and granular activated carbon filters. Each WTP used a variation of conventional treatment, whereby alum and coagulant aid are added prior to flocculation, settling, and filtration. Lime or sodium hydroxide (NaOH) was added for pH adjustment. Reservoir water may also be treated with powdered activated carbon and/or potassium permanganate ($KMnO_4$) for taste and odor control, as well as for the removal of trihalomethane precursor compounds. Fluoride was added prior to filtration. After final pH adjustment, the water was chloraminated and orthophosphate corrosion inhibitor is added before distribution [*47*]. Doses for individual chemicals were not provided. Basic design criteria for individual unit processes can be found in Figure 6.

Finished Water Quality

The primary purpose for replacing the Lorton and Occoquan WTPs with the upgraded Griffith WTP was to lower DBPs in the treated water and provide greater protection against taste-and-odor episodes in the Occoquan Reservoir [*48*]. Towards this end, this report compares the water quality data from the Lorton WTP taken in 2005 (the last full year the plant was in operation) and the water quality data from the Griffith WTP taken in 2010 (Table 18) [*52*]. It should be noted that the Lorton WTP used conventional treatment (i.e., rapid mix, flocculation, sedimentation, filtration), whereas the Griffith WTP uses intermediate ozonation between the sedimentation and filtration steps (Figure 6). Additionally, the Lorton WTP used anthracite/sand filter media, whereas the Griffith WTP uses granular activated carbon filter media.

From Table 18, DBP data for HAAs and THMs from the Griffin WTP effluent were 72 percent and 33 percent lower than those for the Lorton WTP. The lower HAA and THM levels can be attributed to the lower usage of chlorine during the treatment process (average free and total chlorine residuals were 1.6 mg/L and 4.1 mg/L, respectively, for the Lorton WTP, and 0.9 mg/L and 3.1 mg/L, respectively, for the Griffith WTP). Though it should be noted that TOC levels in 2005 were slightly higher at the Lorton WTP than those reported in 2010 for the Griffith WTP (average = 5.1 mg/L and 4.6 mg/L, respectively). Higher TOC levels generally produce higher HAA and THM levels when exposed to free and total chlorine. No ultraviolet light absorbance data were reported.

TOC removal across the Lorton and Griffith WTPs were comparable at 53 and 48 percent, respectively. Therefore, no conclusion could be made regarding whether the Griffith WTP using ozone and GAC filters provided better TOC removal than the Lorton WTP using chlorine and anthracite/sand filters. However, the use of ozone at the Griffin WTP did result in the formation of low levels of bromate (average < 5 µg/L and maximum = 6 µg/L). Bromate formation was low due to the low levels of bromide in the source water (maximum 0.04 mg/L). It should also be noted that these data are for a single year per WTP, and may not represent long term trends.

Table 18 also provides two indicators of improved taste-and-odor removal from the Occoquan Reservoir source water: taste and threshold odor number (TON). Taste, presumably derived

through flavor profile analysis—though not indicated in the source material, improved from an average (maximum) of 3 (4) for the Lorton WTP to 2 (4) for the Griffith WTP. TON values were also lower for the Griffith WTP [average (maximum) = 5 (11) for Lorton WTP and 4 (8) for Griffith WTP]. It should also be noted that plant effluent turbidity improved from an average (maximum) of 0.56 NTU (3.1 NTU) for the Lorton WTP to 0.08 NTU (0.15 NTU) for the Griffith WTP. The data presented in Table 18 indicate that the overall objectives of lowering DBPs and improving taste-and-odor control were achieved by the new Griffith WTP through the use of ozone and granular activated carbon filters.

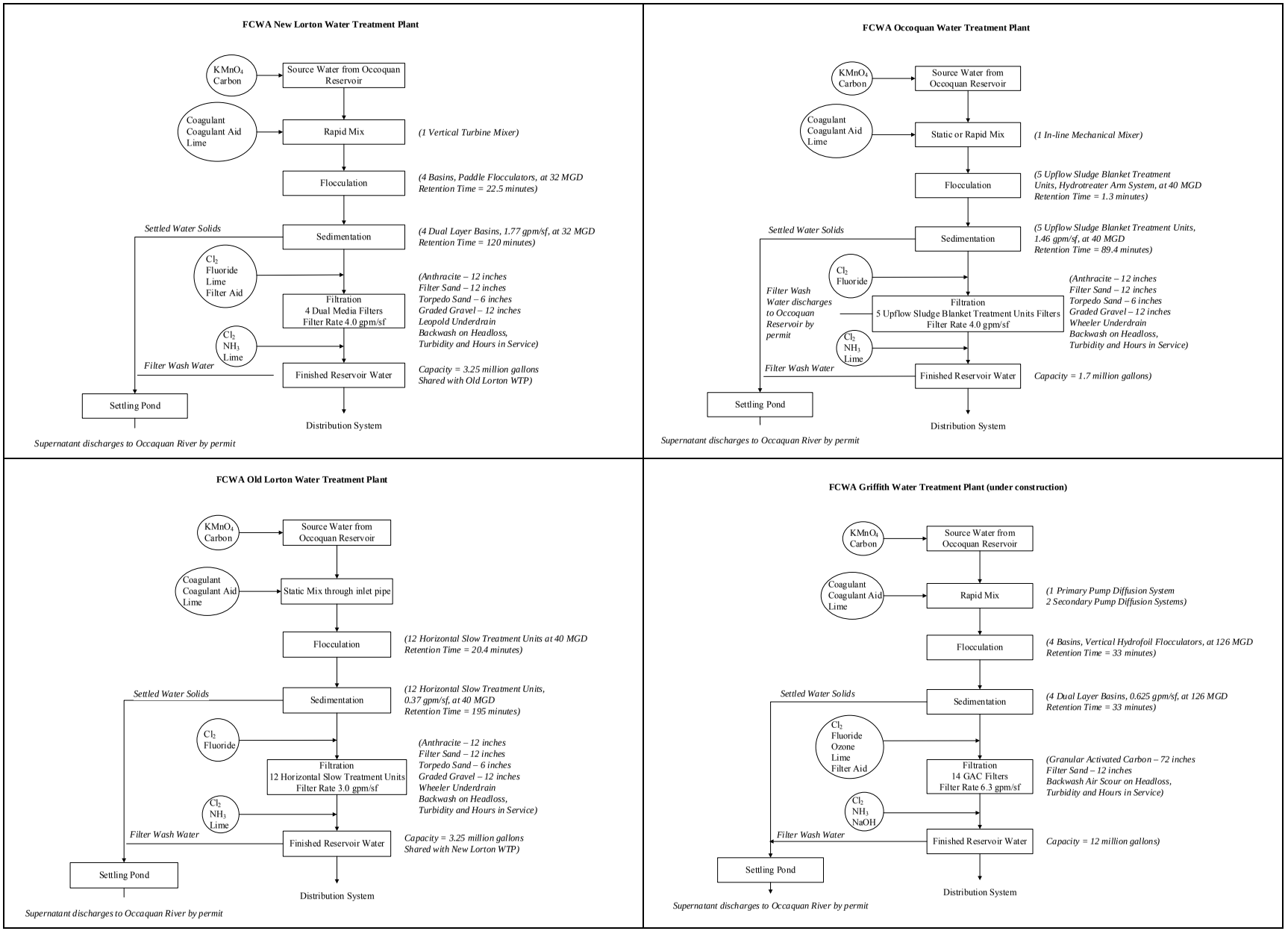


Figure 6. Fairfax County Water Authority Water Treatment Plant Process Flow Diagrams [*47*]

Table 1. Full-Scale Indirect Potable Reuse Projects in California

Project	Agency	Type of Indirect Potable Reuse	Start-Up Date
Montebello Forebay Groundwater Recharge Project	Water Replenishment District of Southern California	Groundwater recharge via surface spreading basins	1962
Water Factory 21 (decommissioned in 2004)	Orange County Water District	Seawater barrier via direct injection	1976
West Coast Basin Barrier Project	West Basin Municipal Water District and Los Angeles County Department of Public Works	Seawater barrier via direct injection	1996
Ely Basin Project	Inland Empire Utilities District (now part of the Chino Basin Groundwater Recharge Project)	Groundwater recharge via surface spreading basins	1997
Alamitos Barrier Project	Los Angeles County Department of Public Works, Water Replenishment District of Southern California, and City of Long Beach	Seawater barrier via direct injection	2005
Harbor Water Recycling Project Dominguez Gap Project	City of Los Angeles	Seawater barrier via direct injection	2006
Chino Basin Groundwater Recharge Project	Inland Empire Utilities Agency	Groundwater recharge via surface spreading basins	2005
Groundwater Replenishment System	Orange County Water District	Groundwater recharge via direct injection and surface spreading basins	2008
Groundwater Recharge Enhancement and Treatment (GREAT) Program	City of Oxnard	Groundwater recharge via direct injection and surface spreading basins	2010

Adapted from [*1*]

Table 2. Draft California Regulations for Groundwater Recharge into Potable Aquifers

Recycled Water Quality Limits	Treatment Required	Other Selected Requirements
• Drinking water MCLs • ≥ 5 log virus inactivation • ≤ 2.2 total *E. coli*/100 mL • ≤ 2 nephelometric turbidity units (NTU) • ≤ 0.5 mg/L TOC of wastewater origin • Action levels for lead and copper • Nitrogen limits vary: depend on method used	**Spreading** • Secondary • Filtration • Disinfection • Soil aquifer treatment **Injection** • Secondary • Filtration • Reverse osmosis • Advanced oxidation process (AOP)*	• Industrial pretreatment and source control program • ≥ 80% dilution for spreading (to start); • ≥ 50% dilution for spreading applications (to start) that provide reverse osmosis and AOP)* • ≥ 50% dilution for injection (to start) • 6-month retention time underground • Monitor recycled water and monitoring wells for priority toxic pollutants, chemicals with state notification levels specified by CDPH, and unregulated constituents specified by CDPH • Operations plan • Contingency plan

* AOP must reduce N-nitrosodimethylamine (NDMA) and 1,4-dioxane by at least 1.2 logs and 0.5 logs, respectively.
Adapted from [*1*]

Table 3. Comparison of Methods to Determine Retention Time to Drinking Water Wells

Method	General Accuracy	Level of Effort	Retention Time (months)	Safety Factor
Inert Tracer	Best	Track added tracer	6	1.0
Intrinsic Tracer	Good	Sampling of existing indicators	9	1.5
3-D Model	Fair	Extensive information on aquifer	12	2
Formula (Darcy's Eq.)	Poor	Minimal information on aquifer	24	4

Adapted from [*8*]

Table 4. General Process Trains for Three California Case Studies and Western Australia Utilizing Membrane Treatment

Plant	OCWD GWRS	West Coast Basin Barrier Project	WRD Leo Vander Lans	Western Australia
Scale	Full	Full	Full	Full / Pilot
Source Water	Secondary Effluent	Secondary Effluent	Tertiary Effluent	Secondary Effluent
	Pretreatment			
Pre-MF Chemicals				
Oxidant	NaOCl	NaOCl	NaOCl	NaOCl
Other	--	--	--	Ammonia
Treatment	Microfiltration	Microfiltration	Microfiltration	Microfiltration
Nominal Pore Size	0.2 µm	0.2 µm	0.1 µm	0.2 µm
Membrane Material	Polypropylene	Polypropylene	Polyvinylidene Fluoride (PVDF)	Polypropylene[†] PVDF[‡]
Model & Manufacturer	CS, Siemens	CMF-S, Siemens	USV-6203, Pall Corp.	CMF-S, Siemens
Post-MF Chemicals				
pH Adjustment	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Ammonia	--	--	--	--
Antiscalant	Yes	Yes	Yes	Yes
Dechlorination	--	--	$NaHSO_3$[*]	--
	RO			
Cartridge filtration	5 micron	5 micron	5 micron	5 micron
Membrane Type	BWRO	BWRO	BWRO	BWRO
Model # and Manufacturer	ESPA2, Hydranautics	ESPA2, Hydranautics	ESPA2, Hydranautics	BW30-FR, Dow[†] ESPA2, Hydranautics[‡]
	UV Oxidation			
Model # and Manufacturer	UVPhox™, Trojan Technol.	UVPhox™, Trojan Technol.	UVPhox™, Trojan Technol.	--
UV Dose	> 400 mJ/cm^2	> 115 mJ/cm^2	~149 mJ/cm^2	--
H_2O_2 Dose	3 mg/L	3 mg/L	--	--
	Post-Treatment			
Decarbonation	Partial	Yes	Yes	--
Disinfectant	--	NaOCl	--	NaOCl[†]
Alkalinity	Lime	Lime	--	--
pH Adjustment	--	--	NaOH	NaOH[†]
Inhibitors	--	--	--	--

* Discontinued in 2008
† Kwinana WWTP
‡ Beenyup pilot plant

Table 5. Water Quality Data for Five Case Studies

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Inorganic Sampling (General Physical)														
Color	(15 [2nd])	p.c.u	40.2	50		< 3				< 3				< 3
Odor	(3 [2nd])	T.O.N.				0			1.07	1.40			1	2
Total Suspended Solids		mg/L					18	25			0.76	5.8		
Turbidity	(5 [2nd])	NTU	3.3	12	0.2	0.5	9	14	0.05	0.12	0.53	0.85	0.09	0.15
Inorganic Sampling (General Mineral)														
Bicarbonate	NS	mg/L as $CaCO_3$			32	47			44	64				
Carbonate	NS	mg/L as $CaCO_3$			2.09	18.6			0.92	4.8				
Total Alkalinity	NS	mg/L as $CaCO_3$	282	335	34	47			45	64				
Calcium	NS	mg/L	82	92	9.2	14			12	20			< 1.0	1.1
Cyanide	0.2 (0.15)	mg/L	0.0065	0.035		< 0.005		< 0.004		< 0.0032	< 1	DNQ (< 0.002)		< 0.1
Bromide		mg/L				< 0.01								
Chloride	(250 [2nd])	mg/L	250	323	4.3	6.9			4.94	9.2	116	133	12	19
Fluoride	2 (1)	mg/L	0.88	1.7		< 0.1			0.11	0.12	0.7	0.76	< 0.05	0.059
Foaming Agents (MBAS)	(0.5 [2nd])	mg/L								< 0.023	0.0092	0.11	< 0.05	0.078
Magnesium	NS	mg/L	44	54	0.1	1.4			0.04	0.08				
Ammonia as N	NS	mg/L	21	31	1.2	1.9	41	44	2.01	2.9	1.11	1.72		
Nitrate as NO_3	45	mg/L	11.5	53.6	1.4	4.6								
Nitrate as N	10	mg/L	2.6	12	0.31	1.04	DNQ (est. 0.143)	DNQ (est. 0.17)	0.22	0.37	5.85	7.71		
Nitrite as N	1	mg/L	0.44	8.89	0.06	0.56			0.17	0.73	0.07	0.18	< 0.1	0.1
Total Nitrate + Nitrite as N	10	mg/L	3.04	12.5	0.37	1.09								
Total Nitrogen		mg/L	25.7	33	1.68	2.5			1.33	3.2	6.82	11.5	1.58	2
Perchlorate	***(0.006)***	mg/L				< 0.0025			< 0.00045	0.00066		< 0.0018		< 0.004
pH	NS	--	7.6	8.0	8.2	9.3			7.51	7.8	7.45	7.95		
Total Phosphorus		mg/L	0.65	1.43		< 0.01	3.2	3.6						
Potassium		mg/L	17.1	19.1	0.4	0.7			0.54	0.79			< 1	2
Sodium	NS	mg/L	215	245	6.4	8.0			6.7	11.0			16.5	25
Sulfate	(250 [2nd])	mg/L	233	311	0.3	2.4			1.21	2.2	97.6	138	1	2.9
Electrical Conductivity	(900 [2nd])	µmho/cm	1648	1950	86.6	128			54.0	79.5			89	140
TDS	(500 [2nd])	mg/L	949	1210	43	86			57	83			51	72
Total Hardness	NS	mg/L as $CaCO_3$	307	355	23	33			30	50	182	230		< 3
Total Organic Carbon	NS	mg/L	13.7	17.4	0.18	2.35	17.0	18.1	0.21	0.29	7.35	8.41	0.28	0.48
Asbestos	7 MFL	0.2 x 10^6 fibers/L > 10 µm				< 0.2				< 0.2				< 0.2
Ultra Violet 254 nm	NS	abs/cm				< 0.002								
Inorganic Sampling (Trace Metals)														
Aluminum	1 (0.2 [2nd]) (0.6)	mg/L	0.019	0.0465	0.00574	0.0141			0.001938	0.0043				< 0.025
Antimony	0.006 (0.02)	mg/L	0.000778	0.0014		< 0.0005	DNQ (est. 0.00094)	0.0013	0.00014	0.00014	0.00027	0.00057		< 0.001
Arsenic	0.01	mg/L	0.0014	0.004		< 0.001	DNQ (est. 0.00228)	0.00254	0.000608	0.00097	0.00273	0.00293		< 0.001

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Barium	1	mg/L	0.026	0.034		< 0.001			0.000495	0.0012	0.0428	0.0473		< 0.002
Beryllium	0.004	mg/L		< 0.0005		< 0.0005		< 0.0002		< 0.00031		< 0.00007		< 0.001
Boron	***(1)***	mg/L	0.38	0.43	0.24	0.28					0.33	0.362	0.31	0.32
Cadmium	0.005 (0.00007)	mg/L		< 0.001		< 0.001	< 0.0004	DNQ (est. 0.0002)		< 0.00012	< 0.00003	DNQ (< 0.00006)		< 0.0005
Chromium (Total)	0.05	mg/L	0.000512	0.0018		< 0.001	DNQ (est. 0.00128)	DNQ (est. 0.0002)	0.00067	0.00170	< 0.00005	DNQ (< 0.00027)		< 0.001
Hexavalent Chromium	(PHG **draft** 0.00006)	mg/L	0.00004	0.0001	0.0004	0.0017	< 0.0005	< 0.0005			< 0.047	DNQ (< 0.0049)		
Copper	1.3 (1.0 ^{2nd}) (0.3)	mg/L	0.0062	0.0097		< 0.001	0.0165	0.0211	0.004375	0.0088	0.0018	0.0031		< 0.002
Iron	(0.3 ^{2nd})	mg/L	0.389	0.892	0.005	0.033				< 0.0109				< 0.02
Lead	0.015 (0.0002)	mg/L		< 0.001		< 0.001	< 0.002	DNQ (est. 0.002)	0.000553	0.00165	0.000028	0.00033		< 0.0005
Manganese	(0.05 ^{2nd}) ***(0.5)***	mg/L	0.044	0.054	< 0.001	0.0014			0.000178	0.00024				< 0.002
Mercury	0.002 (0.0012)	mg/L	0.0003	0.0006		< 0.0001	< 0.000004	DNQ (est. 0.0000084)		< 0.0000229	0.0000013	0.0000022		< 0.0002
Nickel	0.1 (0.012)	mg/L	0.0072	0.0107		< 0.001	DNQ (est. 0.0061)	DNQ (est. 0.0076)	0.000344	0.00054	0.00131	0.00149		< 0.005
Selenium	0.05	mg/L	0.002	0.003		< 0.001	DNQ (est. 0.000741)	DNQ (est. 0.001)		< 0.00022	< 0.00018	DNQ (< 0.00056)		< 0.005
Silver	(0.1 ^{2nd})	mg/L		< 0.001		< 0.001	0.00017	0.00082		< 0.00019	< 0.00007	DNQ (< 0.00003)		< 0.0005
Thallium	0.002 (0.0001)	mg/L		< 0.0005		< 0.0005	< 0.00001	DNQ (est. 0.00011)	0.00011	0.00011		< 0.00006		< 0.001
Vanadium	*(0.05)*	mg/L	0.0016	0.0022		< 0.001				< 0.00023				< 0.003
Zinc	(5 ^{2nd})	mg/L	0.0224	0.0547	0.0010	0.0042	0.015	0.025	< 0.00044	0.0054	0.033	0.0436		< 0.005
Radiological														
Gross Alpha	15 pCi/L (gross α-uranium)	pCi/L				< 1.69	3.57	5.83	0.73	2	1.59	2.25		< 3
Gross Beta	4 millirems/yr *(50 pCI/L)*	pCi/L			< 2.36	2.79	9.4	12.7	1.75	4.95	6.51	9.78		< 3
Radium 226	5 (0.05)	pCi/L				< 0.192								< 1
Radium 228	5 (0.019)	pCi/L				< 0.934								< 1
Combined Radium 226 & 228	5	pCi/L			< 0.517	0.648								
Radon	NS	pCi/L												
Strontium-90	8 (0.35)	pCi/L				< 1.74						< 0.766		< 8
Tritium	20,000	pCi/L	149	766	631	7390						< 381		< 210
Uranium	20 (0.43)	pCi/L								< 1	1.32	2.11		< 0.7
Microbiology														
Heterotrophic Plate Counts	TT	CFU/100 ml												
Total Coliforms	5%***	MPN/100 ml	1,488,439	16,000,000		< 2			< 2	5.5		< 2		< 2.0
Fecal Coliforms	t	MPN/100 ml	519,671	16,000,000		< 2								
E. coli	t	CFU/100 ml												
Enterococcus		MPN/100 ml												

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Cryptosporidium	TT	oocysts/L												
Giardia	TT	cysts/L												
Enteric Viruses (Total Culturable Virus)	TT	MPN_{IU}/100 L												
Volatile Organic Compounds														
Benzene	0.001 (0.0005)	mg/L				< 0.0005		< 0.00011		< 0.00015		< 0.00015		< 0.0005
Bromobenzene	Unreg.A	mg/L				< 0.0005								
Bromochloromethane	Unreg.B	mg/L				< 0.0005								
Bromodichloromethane	(draft 0.0004)	mg/L				< 0.0005	DNQ (est. 0.000738)	DNQ (est. 0.00091)	0.000193	0.0003	0.013	0.0141	0.00215	0.0038
Bromoform	(draft 0.005)	mg/L				< 0.0005	DNQ (est. 0.00114)	0.00249		< 0.00017	0.00027	0.00054		< 0.0005
Bromomethane	Unreg.A	mg/L				< 0.0005		< 0.00102				< 0.00034		
sec-Butylbenzene	***(0.26)***	mg/L				< 0.0005				< 0.00015				< 0.0005
n-Butylbenzene	***(0.26)***	mg/L				< 0.0005				< 0.00015				< 0.0005
tert-Butylbenzene	***(0.26)***	mg/L				< 0.0005				< 0.00014				< 0.0005
Carbon Tetrachloride	0.0005 (0.0001)	mg/L				< 0.0005		< 0.00034		< 0.00018		< 0.0002		< 0.0005
Chlorobenzene	0.07	mg/L				< 0.0005		< 0.00015		< 0.00046		< 0.00012		< 0.0005
Chlorodibromomethane	(draft 0.0007)	mg/L												
Chloroethane	Unreg.A	mg/L				< 0.0005		< 0.00031		< 0.00018		< 0.00032		
Chloroform	(draft 0.005)	mg/L			< 0.0001	0.0003	0.00324	0.00394	0.000648	0.0011		< 0.00013	0.0019	0.0039
Chloromethane	Unreg.A	mg/L				< 0.0005	< 0.00016	DNQ (est. 0.00091)						
2-Chlorotoluene or o-Chlorotoluene	Unreg.A ***(0.14)***	mg/L				< 0.0005				< 0.00018				
4-Chlorotoluene or p-Chlorotoluene	***(0.14)***	mg/L				< 0.0005				< 0.00017				
Dibromomethane	Unreg.A	mg/L				< 0.0005								
1,2-Dichlorobenzene	0.6 (0.6)	mg/L				< 0.010	DNQ (est. 0.00021)	DNQ (est. 0.00026)		< 0.0003				< 0.0005
1,3-Dichlorobenzene	Unreg.A	mg/L				< 0.010		< 0.00023		< 0.00036				
1,4-Dichlorobenzene	0.005 (0.006)	mg/L				< 0.010		< 0.00024		< 0.00032				< 0.0005
1,2-Dichloroethane	0.0005 (0.0004)	mg/L				< 0.0005		< 0.00009		< 0.00014		< 0.00012		< 0.0005
1,1-Dichloroethane	0.005	mg/L				< 0.0005		< 0.00016		< 0.00015		< 0.00014		< 0.0005
1,1-Dichloroethene	0.006 (0.01)	mg/L				< 0.0005				< 0.00034		< 0.00022		< 0.0005
cis-1,2-Dichloroethene	0.006 (0.1)	mg/L				< 0.0005				< 0.00036				< 0.0005
trans-1,2-Dichloroethene	0.01 (0.06)	mg/L				< 0.0005				< 0.00032		< 0.00017		< 0.0005
Dichlorodifluoromethane (Freon12)	*(1)*	mg/L				< 0.0005				< 0.00026				< 0.0005
1,2-Dichloropropane	0.005 (0.0005)	mg/L				< 0.0005		< 0.00016		< 0.00015		< 0.00017		< 0.0005
1,3-Dichloropropane	Unreg.A	mg/L				< 0.0005								< 0.0005
2,2-Dichloropropane	Unreg.A	mg/L				< 0.0005								
1,1-Dichloropropene	Unreg.A	mg/L				< 0.0005								

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
1,3-Dichloropropene	0.0005 (0.0002)	mg/L								< 0.0001				< 0.0005
cis-1,3-Dichloropropene		mg/L				< 0.0005		< 0.00015				< 0.00013		
trans-1,3-Dichloropropene		mg/L				< 0.0005		< 0.0001				< 0.00011		
ETBE (Ethyl tertiary butyl ether)	Unreg B	mg/L				< 0.001				< 0.0013				
Ethylbenzene	0.7 (0.3)	mg/L				< 0.0005		< 0.00017		< 0.00017		< 0.00019		< 0.0005
Hexachlorobutadiene	Unreg.B	mg/L				< 0.0010		< 0.00017		< 0.00016		< 0.00014		
Isopropylbenzene	***(0.77)***	mg/L				< 0.0005				< 0.000170				< 0.0005
p-Isopropyltoluene	Unreg.B	mg/L												
Methylene Chloride (dichloromethane)	0.005 (0.004)	mg/L			< 0.0005	0.0006	DNQ (est. 0.00167)	0.00289	0.00071	0.001	< 0.00020	DNQ (< 0.00015)		< 0.0005
MTBE		mg/L				< 0.0002		< 0.0002		< 0.0011				< 0.001
Monochlorobenzene	0.013 (0.005 ^{2nd}) (0.013)	mg/L												< 0.0005
Naphthalene	***(0.17)***	mg/L				< 0.010		< 0.00013		< 0.0002		< 0.00016		< 0.0001
n-Propylbenzene	Unreg.B ***(0.26)***	mg/L								< 0.000150				< 0.0005
Styrene	0.1 (0.0005)	mg/L				< 0.0005				< 0.00016				< 0.0005
TAME (Tertiary amyl methyl ether)		mg/L				< 0.001				< 0.0012				
1,1,1,2-Tetrachloroethane	Unreg.A	mg/L				< 0.0005								< 0.0005
1,1,2,2-Tetrachloroethane	0.001 (0.0001)	mg/L				< 0.0005		< 0.00019		< 0.00017		< 0.00016		
Tetrachloroethene	0.005 (0.00006)	mg/L				< 0.0005				< 0.00026				< 0.0005
Toluene	0.15 (0.15)	mg/L				< 0.0005	DNQ (est. 0.000512)	DNQ (est. 0.0007)	< 0.00015	0.00041		< 0.00018		< 0.0005
1,2,3-Trichlorobenzene	Unreg.B	mg/L				< 0.0005								< 0.0005
1,2,4-Trichlorobenzene	0.07 (0.005)	mg/L				< 0.010		< 0.00027		< 0.00019		< 0.00017		
1,1,1-Trichloroethane	0.2 (1)	mg/L				< 0.0005		< 0.00029				< 0.00018		< 0.0005
1,1,2-Trichloroethane	0.005 (0.0003)	mg/L				< 0.0005		< 0.0002		< 0.00022		< 0.0001		< 0.0005
Trichloroethene	0.005 (0.0008)	mg/L				< 0.0005				< 0.00026				< 0.0005
Trichlorofluoromethane	0.15 (0.7)	mg/L				< 0.0005				< 0.00043				< 0.0005
1,2,3-Trichloropropane	Unreg.A ***(0.000005)***	mg/L				< 0.000005				< 0.0000015	< 0.0000012	DNQ (< 0.0000033)		
1,1,2-Trichloro-1,2,2-trifluoroethane (FREON)	1.2 (4)	mg/L				< 0.0005								< 0.0005
1,3,5-Trimethylbenzene	***(0.33)***	mg/L				< 0.0005				< 0.000150				
1,2,4-Trimethylbenzene	***(0.33)***	mg/L				< 0.0005				< 0.000160				
Vinyl Chloride	0.0005 (0.00005)	mg/L				< 0.0005		< 0.00025		< 0.00018		< 0.00037		< 0.0003

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Xylenes (single or sum of isomers)	1.75 (1.8)	mg/L				< 0.0005				< 0.00029				< 0.0005
Total THMs	0.080	mg/L			0.0002	0.0003			0.000749	0.00126			0.0050	0.0087
Semivolatile Organic Compounds														
Benzo (A) Pyrene	0.0002 (0.000004)	mg/L				< 0.010		< 0.00036		< 0.000073		< 0.00015		< 0.00002
Di (2-Ethylhexyl) Adipate	0.4 (0.2)	mg/L							0.00056	0.00078				< 0.0006
Di (2-Ethylhexyl) Phthalate	0.004 (0.012)	mg/L					DNQ (est. 0.001)	DNQ (est. 0.00102)	0.00086	0.00110		< 0.0003		< 0.0006
Fumigants														
Ethylene dibromide (EDB)	0.00005	mg/L								< 0.000007				< 0.00001
Dibromochloropropane (DBCP)	0.0002 (0.0000017)	mg/L								< 0.000003				< 0.00001
Organochlorine Pesticides														
Alachlor	0.002 (0.004)	mg/L				< 0.0005				< 0.00007				< 0.00005
Aldrin	Unreg. C ***(0.000002)***	mg/L				< 0.0001		< 0.000003		< 0.0000037		< 0.000002		< 0.00001
Chlordane	0.0001 (0.00003)	mg/L				< 0.0001		0		< 0.000045		< 0.00003		< 0.0001
Chlorothanlonil	Unreg. B	mg/L				< 0.005								
Dieldrin	Unreg. C ***(0.000002)***	mg/L				< 0.0001		< 0.000005		< 0.0000044		< 0.000001		< 0.00001
Endrin	0.002 (0.0018)	mg/L				< 0.0001		< 0.000005		< 0.000005		< 0.000002		< 0.00001
Heptachlor	0.00001 (0.000008)	mg/L				< 0.0001		< 0.000003		< 0.0000052		< 0.000001		< 0.00001
Heptachlor Epoxide	0.00001 (0.000006)	mg/L				< 0.0001		< 0.000003		< 0.0000058		< 0.000001		< 0.00001
Hexachlorobenzene	0.001 (0.00003)	mg/L				< 0.010		< 0.00018		< 0.0000050		< 0.00016		< 0.00005
Hexachlorocyclopentadiene	0.05 (0.05)	mg/L				< 0.010		< 0.0029		< 0.000019		< 0.00075		< 0.00005
Lindane	0.0002 (0.000032)	mg/L								< 0.0000050	0.000003	0.00001		< 0.00001
Methoxychlor	0.03 (0.03)	mg/L				< 0.001				< 0.0000064				< 0.00005
Polychlorinated Biphenyls	0.0005 (0.00009)	mg/L								< 0.0001				
Aroclor-1016 (PCB-1016)		mg/L				< 0.0005		< 0.00006		< 0.000083		< 0.00004		< 0.00007
Aroclor-1221 (PCB-1221)		mg/L				< 0.0005		< 0.00049		< 0.000084		< 0.0002		< 0.0001
Aroclor-1232 (PCB-1232)		mg/L				< 0.0005		< 0.0001		< 0.000064		< 0.0002		< 0.0001
Aroclor-1242 (PCB-1242)		mg/L				< 0.0005		< 0.0002		< 0.000070		< 0.00008		< 0.0001
Aroclor-1248 (PCB-1248)		mg/L				< 0.0005		< 0.0001		< 0.000049		< 0.00004		< 0.0001
Aroclor-1254 (PCB-1254)		mg/L				< 0.0005		< 0.00004		< 0.000068		< 0.00003		< 0.0001
Aroclor-1260 (PCB-1260)		mg/L				< 0.0005		< 0.00007		< 0.000069		< 0.00005		< 0.0001

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Propachlor	***(0.09)***	mg/L				< 0.0005								
Toxaphene	0.003 (0.00003)	mg/L				< 0.001		< 0.0001		< 0.000031		< 0.00005		< 0.0005
Organochlorine Herbicides														
Bentazon (Basagran)	0.018 (0.2)	mg/L				< 0.001				< 0.00023				< 0.0005
2,4-Dichlorophenoxyacetic acid (2,4-D)	0.02 (0.07)	mg/L				< 0.0005			< 0.00005	0.00001			< 0.0001	0.00016
Dalapon	0.2 (0.79)	mg/L				< 0.001				< 0.00004				< 0.001
Dicamba	Unreg.C	mg/L				< 0.000081								
Dinoseb	0.007 (0.014)	mg/L				< 0.0005				< 0.00005				< 0.0002
Pentachlorophenol	0.001 (0.0003)	mg/L				< 0.020		< 0.00094		< 0.00002		< 0.0038		< 0.00004
Pichloram	0.5 (0.5)	mg/L				< 0.0005				< 0.00034				< 0.0001
Silvex (2,4,5-TP)	0.05 (0.025)	mg/L				< 0.0005				< 0.00002				< 0.0002
Carbamate Pesticides														
Diuron	Unreg.B	mg/L				< 0.001								
Aldicarb	Unreg.C ***(0.007)***	mg/L				< 0.001								
Aldicarb sulfone	Unreg.C	mg/L				< 0.002								
Aldicarb sulfoxide	Unreg.C	mg/L				< 0.002								
Baygon (Propoxur)	***(0.03)***	mg/L				< 0.001								
Carbofuran	0.018 (0.0017)	mg/L				< 0.001				< 0.00063				< 0.0005
Carbaryl	Unreg.C ***(0.7)***	mg/L				< 0.002								
3-hydroxycarbofuran	Unreg.C	mg/L				< 0.002								
Methomyl	Unreg.C	mg/L				< 0.001								
Oxamyl	0.05 (0.026)	mg/L				< 0.002				< 0.00057				< 0.0005
Miscellaneous														
Diquat	0.02 (0.015)	mg/L				< 0.004				< 0.0009				< 0.0004
Endothall	0.1 (0.58)	mg/L				< 0.045				< 0.0035				< 0.005
Glyphosate	0.7 (0.9)	mg/L				< 0.025				< 0.0018				< 0.006
Paraquat		mg/L				< 0.004								
Polynuclear Aromatic hydrocarbon		mg/L												
Anthracene		mg/L												
Fluoranthene		mg/L												
Phenanthrene		mg/L												
Pyrene		mg/L												

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
2,3,7,8-TCDD Dioxin	3 x 10^{-8} (1 x 10^{-9})	mg/L				< 5 x 10^{-9}				< 6 x 10^{-13}		< 1.10 x 10^{-8}		< 5 x 10^{-9}
Nitrogen/Phosphorus Pesticides														
Atrazine	0.001 (0.00015)	mg/L				< 0.00001				< 0.000047				< 0.00005
Bromacil	Unreg.B	mg/L				< 0.0005								
Butachlor	Unreg.C	mg/L				< 0.00038								
Diazinon	***(0.006)***	mg/L				< 0.0001				< 0.000051				< 0.0001
Dimethoate	Unreg.B ***(0.001)***	mg/L				< 0.005								
Malathion	***(0.16)***	mg/L				< 0.010								
Metolachlor	Unreg.C	mg/L				< 0.0008								
Metribuzin	Unreg.C	mg/L				< 0.0002								
Molinate	0.02 (0.001)	mg/L				< 0.0005				< 0.000051				< 0.0001
Prometryn	Unreg.B	mg/L				< 0.0001								
Simazine	0.004 (0.004)	mg/L				< 0.0001				< 0.000083				< 0.00005
Thiobencarb (Bolero)	0.07 (0.001 ^{2nd}) (0.07)	mg/L				< 0.0005				< 0.000110				< 0.0002
Other Chemicals														
a-Benzene Hexachloride (a-BHC)	***(0.000015)***	mg/L					< 0.000003	< 0.000003				< 0.000001		
b-Benzene Hexachloride (b-BHC)	***(0.000025)***	mg/L						< 0.000003				< 0.000004		
2,4-Dimethylphenol	***(0.1)***	mg/L				< 0.010		< 0.00018				< 0.00011		
1,4-Dioxane	***(0.003)***	mg/L	0.0017	0.0126		< 0.001			< 0.00013	0.00037		< 0.0018		
Diphenamide	***(0.2)***	mg/L				< 0.0001								
Ethion	***(0.004)***	mg/L				< 0.0001								
Formaldehyde	***(0.1)***	mg/L				< 0.020			0.07073	0.37			0.019	0.022
Isopropyl N (3-Chlorophenyl) Carbamate (CIPC)	***(1.2)***	mg/L												
Methyl Isobutyl Ketone (MIBK)	***(0.12)***	mg/L				< 0.005				< 0.000180				< 0.005
Methyl Parathion	***(0.002)***	mg/L												
N-Nitrosodimethylamine (NDMA)	***(0.00001)***	mg/L	0.000038	0.000330	0.00047	0.000014		< 0.0005	0.0000065	0.00002	0.00047	0.0014	0.0000043	0.0000064
Parathion	***(0.040)***	mg/L				< 0.0005								
Pentachloronitrobenzene	***(0.02)***	mg/L												
Phenol	***(4.2)***	mg/L			< 0.00014	< 0.010		< 0.0004			< 0.00014	DNQ (< 0.00026)		< 0.005
Trithion	***(0.007)***	mg/L				< 0.0001								
Captan	***(0.015)***	mg/L				< 0.0001								
Chloropicrin	***(0.037)***	mg/L				< 0.0001								
Tert butyl alcohol	***(0.012)***	mg/L				< 0.002				< 0.000470				< 0.002
Carbon disulfide		mg/L				< 0.0005				< 0.000230				
Chlorate		mg/L				< 0.010			0.027	0.100				0.089
Ethylene glycol		mg/L								< 32				
HMX		mg/L												
N-Nitrosodiethyamine (NDEA)		mg/L				< 0.000002			0.000015	0.00019				< 0.000002

Constituent	CDPH MCL, PHG or NL	Units	OCWD GWRS (Feb 2008–Apr 2010)				WBMWD Barrier System				LACSD Leo Vander Lans (2009)			
			Influent		Effluent		Influent		Effluent		Influent (2009)		Effluent (2007–2009)	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
N-Nitrosodi-n-propylamine (NDPA)		mg/L				< 0.000002		< 0.00036				< 0.00012		
n-Propylbenzene		mg/L												
RDX		mg/L												
2,4,6-Trinitrotoluene (TNT)		mg/L												
Endocrine Disrupting Compounds														
Ethinyl estradiol		mg/L							< 0.000002	0.0000026				< 0.000005
17-α Ethinyl estradiol		mg/L												
17-β Estradiol		mg/L								< 0.000002				
Estrone		mg/L								< 0.0000014				< 0.000001
Bisphenol A		mg/L							0.000005	0.000017				< 0.000025
Nonylphenol (4-Nonyl phenol)		mg/L												< 0.000025
Pharmaceuticals and Other Chemicals														
Acetaminophen		mg/L				< 0.000010				< 0.0000044				< 0.000001
Caffeine						< 0.000300				< 0.000042				< 0.000001
Carbomazapine						< 0.000001								< 0.000005
Gemfibrozil		mg/L				0.0000012				< 0.00000065				0.000013
Ibuprofen		mg/L				< 0.000001				< 0.0000007				< 0.000001
Triclosan		mg/L				< 0.000001								< 0.000005
Diazepam														
Naproxen														
Clofibric acid														

ND	Not Detected
(#)	Number in parenthesis is a California Public Health Goal
(#)	Number in parenthesis and bold italics is a California Notification Level or archived Action Level
(# ^{2nd})	Indicates value is a California secondary MCL
NS	No Standard. Monitoring required in California
*	Ave CRW microbiological data from 1/2005-6/2009
***	No more than 5% of the samples/month may be positive
t	If a repeat total coliform sample is fecal-coliform or *E. coli*-positive, the system is in violation of the MCL for total coliforms
TT	Treatment technique in place of MCL
Unreg.A	Unregulated. Monitoring required for all community and non- transient, non-community water systems
Unreg.B	Unregulated. Monitoring required for all community and non- transient, non-community water systems if determined vulnerable
Unreg.C	Unregulated. Monitoring required for all community and non- transient, non-community water systems if determined vulnerable
Unreg.D	Unregulated. Monitoring may be required at State's discretion
Unreg.E	Unregulated. Monitoring required unless determined not vulnerable.
DNQ	Detected, but Not Quantifiable. Estimated concentration value in parenthesis
1	Beenyup only
2	Kwinana only
3	Manipulated data - $x_{ave} = (x_1n_1+x_2n_2)/(n_1+n_2)$, where x_i is the mean value for each plant and n_i is the number of samples taken to determine that mean value
****	Manipulated data - $x_{ave} = [(x1n1+x2n2)/(n1+n2)]*2.7*10^{-11}*10^{12}$, where x_i = mean value for each plant, n_i = number of samples taken to determine that mean value, $2.7*10^{-11}$ = number of Ci in 1 Bq, 10^{12} = number of pCi in 1 Ci

[a] 2006 to 2010
[b] 2010
[c] 2007 to 2010
[d] September 2002
[e] 2008 to 2010
[f] 2009 & 2010
[g] As total Kjeldahl nitrogen

Constituent	CDPH MCL, PHG or NL	Units	Combined Results for Kwinana and Beenyup				Upper Occoquan Service Authority				Lorton/Occoquan Water Treatment Plants	
			Influent		Effluent		Influent		Effluent		Influent	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Inorganic Sampling (General Physical)												
Color	(15 [2nd])	p.c.u	34.6 [1]		< 1 [1]					< 5.0[a]	58	170
Odor	(3 [2nd])	T.O.N.								< 1.0[a]	5	11
Total Suspended Solids		mg/L	17.9 [3]		4.54 [3]		209[b]	808[b]	0.12[b]	0.9[b]	9	35
Turbidity	(5 [2nd])	NTU	8.68 [3]		0.07 [3]				0.16[b]	0.45[b]	15.08	55
Inorganic Sampling (General Mineral)												
Bicarbonate	NS	mg/L as $CaCO_3$									47	65
Carbonate	NS	mg/L as $CaCO_3$									0	0
Total Alkalinity	NS	mg/L as $CaCO_3$	131.3 [3]		6.86 [3]				87.7[b]	122[b]	47	65
Calcium	NS	mg/L	35.2 [3]		0.07 [3]		54.1[b]	54.2[b]	74.9[b]	79.1[b]	19.2	23.0
Cyanide	0.2 (0.15)	mg/L	< 0.1 [3]		< 0.1 [3]			< 0.01[c]		< 0.01[c]		
Bromide		mg/L	0.28 [3]		< 0.2 [3]		0.1[b]	0.12[b]	0.054[b]	0.056[b]	0.02	0.03
Chloride	(250 [2nd])	mg/L	214 [3]		2.18 [3]		90.9[b]	102[b]	88.2[b]	93.1[b]	23.7	51.7
Fluoride	2 (1)	mg/L	0.86 [3]		0.10 [3]				1.1[a]	1.4[a]	< 0.2	0.2
Foaming Agents (MBAS)	(0.5 [2nd])	mg/L					5.8[b]	7.2[b]	0.023[b]	0.038[b]		
Magnesium	NS	mg/L	9.87 [3]		< 0.1 3		10.3[b]	10.4[b]	5.5[b]	6[b]	5.1	5.7
Ammonia as N	NS	mg/L	4.48 [3]		0.28 [3]		29.4[b]	38.9[b]	0.034[b]	0.53[b]	0.11	0.24
Nitrate as NO3	45	mg/L										
Nitrate as N	10	mg/L	4.4 [2]		0.1 [2]				12[b]	25.3[b]	1.3	2.7
Nitrite as N	1	mg/L	0.28 [3]		0.07 [3]				0.00012[b]	0.013[b]	0.05	0.14
Total Nitrate + Nitrite as N	10	mg/L	11.5 [1]		0.7 [1]				12.1[b]	25.3[b]		
Total Nitrogen		mg/L					41.6[bg]	62.2[bg]	12.4[b]	36[b]		
Perchlorate	***(0.006)***	mg/L							0.000275[a]	0.0011[a]		
pH	NS	--	6.97 [3]		6.23 [3]		7.3[b]	7.9[b]	7.4[b]	7.8[b]	7.0	7.7
Total Phosphorus		mg/L	6.89 [3]		0.05 [3]		5[b]	8.97[b]	0.068[b]	0.14[b]		
Potassium		mg/L	23.0 [3]		0.41 [3]						3.7	4.8
Sodium	NS	mg/L	178 [3]		4.36 [3]		71.9[b]	77.9[b]	75.9[b]	77.7[b]	16.1	26.8
Sulfate	(250 [2nd])	mg/L	95.9 [3]		0.28 [3]		76.5[b]	106[b]	87.5[b]	108[b]	20.5	29.4
Electrical Conductivity	(900 [2nd])	µmho/cm	1160 [3]		23.5 [3]		913[b]	917[b]	713[b]	928[b]		
TDS	(500 [2nd])	mg/L	683 [3]		< 5 [3]		459[b]	545[b]	472[b]	702[b]	147	208
Total Hardness	NS	mg/L as $CaCO_3$							173[b]	194[b]	73	94
Total Organic Carbon	NS	mg/L	9.56 [3]		0.35 [3]				3.05[b]	3.5[b]	5.1	8.6
Asbestos	7 MFL	0.2 x 10^6 fibers/L > 10 µm										
Ultra Violet 254 nm	NS	abs/cm							0.055[d]	0.057[d]		
Inorganic Sampling (Trace Metals)												
Aluminum	1 (0.2 [2nd]) (0.6)	mg/L	0.039	0.11	0.005	0.012				< 0.002[e]	0.529	1.586
Antimony	0.006 (0.02)	mg/L	0.0003	0.00081	< 0.0001	0.00021		< 0.0023[b]		< 0.0023[b]		< 0.004
Arsenic	0.01	mg/L		< 0.001		< 0.001	0.0022[b]	0.003[b]	0.0004[b]	0.0008[b]		< 0.002

Constituent	CDPH MCL, PHG or NL	Units	Combined Results for Kwinana and Beenyup				Upper Occoquan Service Authority				Lorton/Occoquan Water Treatment Plants	
			Influent		Effluent		Influent		Effluent		Influent	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Barium	1	mg/L	0.098	0.14		< 0.002	0.0672[b]	0.0845[b]		< 0.0363[b]	0.036	0.036
Beryllium	0.004	mg/L		< 0.0001		< 0.0001		< 0.0007[b]		< 0.0007[b]		< 0.001
Boron	***(1)***	mg/L	0.16	0.4	0.08	0.16						
Cadmium	0.005 (0.00007)	mg/L		< 0.0001		< 0.0001	0.000035[b]	0.0007[b]		< 0.00006[b]		< 0.001
Chromium (Total)	0.05	mg/L	0.0008	0.004	0.0005	0.0014	0.0042[b]	0.005[b]		< 0.0007[b]		< 0.001
Hexavalent Chromium	(PHG **draft** 0.00006)	mg/L		< 0.05		< 0.05				< 0.0039[b]		
Copper	1.3 (1.0 [2nd]) (0.3)	mg/L	0.008	0.02	0.034	0.14	0.0801[b]	0.0937[b]	0.0012[b]	0.0015[b]	0.0150	0.046
Iron	(0.3 [2nd])	mg/L	0.069	0.72	< 0.005	0.015				< 0.02[e]	0.573	1.812
Lead	0.015 (0.0002)	mg/L	0.0006	0.0025		< 0.0001	0.0012[b]	0.0013[b]		< 0.0005[b]	0.00341	0.01022
Manganese	(0.05 [2nd]) ***(0.5)***	mg/L	0.025	0.04		< 0.001				< 0.002[e]	0.241	0.592
Mercury	0.002 (0.0012)	mg/L		< 0.0001		< 0.0001		< 0.0002[b]		< 0.0002[b]		< 0.0005
Nickel	0.1 (0.012)	mg/L	0.003	0.006	0.001	0.002	0.0054[b]	0.0074[b]	0.0024[b]	0.0048[b]		< 0.005
Selenium	0.05	mg/L		< 0.001		< 0.001	0.0014[b]	0.0027[b]		< 0.002[b]		< 0.004
Silver	(0.1 [2nd])	mg/L		< 0.0001		< 0.0001	0.0007[b]	0.0014[b]		< 0.0007[b]		< 0.0005
Thallium	0.002 (0.0001)	mg/L		< 0.0001		< 0.0001		< 0.0023[b]		< 0.0007[b]		< 0.002
Vanadium	*(0.05)*	mg/L		< 0.005		< 0.005						
Zinc	(5 [2nd])	mg/L	0.06	0.12	0.0051	0.012	0.1435[b]	0.168[b]	0.0139[b]	0.168[b]	< 0.025	0.06
Radiological												
Gross Alpha	15 pCi/L (gross α-uranium)	pCi/L	1.81	2.7	0.62	0.91			0.12[a]	1.1 ± 1.2[a]		
Gross Beta	4 millirems/yr *(50 pCI/L)*	pCi/L	0.91	1.44	0.45	0.71			14.24[a]	19.4 ± 2.0[a]		
Radium 226	5 (0.05)	pCi/L							0.19[a]	0.37 ± 0.34[a]		
Radium 228	5 (0.019)	pCi/L							1.492[a]	3.0 ± 0.6[a]		
Combined Radium 226 & 228	5	pCi/L							1.674[a]	3.16 ± 0.69[a]		
Radon	NS	pCi/L										
Strontium-90	8 (0.35)	pCi/L										
Tritium	20,000	pCi/L										
Uranium	20 (0.43)	pCi/L							0.046[a]	0.1 ± 0.00[a]		
Microbiology												
Heterotrophic Plate Counts	TT	CFU/100 ml							3.4[a]	10[a]		
Total Coliforms	5%***	MPN/100 ml							0.85[b]	131.4[b]		
Fecal Coliforms	t	MPN/100 ml							ND	ND		
E. coli	t	CFU/100 ml								< 1.0[b]		

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			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Enterococcus		MPN/100 ml	1600 [1]	16000 [1]								
Cryptosporidium	TT	oocysts/L								< 0.044[a]		
Giardia	TT	cysts/L							0.01[a]	0.051[a]		
Enteric Viruses (Total Culturable Virus)	TT	MPN_{IU}/100 L										
Volatile Organic Compounds												
Benzene	0.001 (0.0005)	mg/L	0.00008	0.00011	0.00008	0.00014		< 0.01[c]		< 0.0005[a]		< 0.0005
Bromobenzene	Unreg.A	mg/L		< 0.000126		< 0.000126						< 0.0005
Bromochloromethane	Unreg.B	mg/L	0.0004	0.012	0.00012	0.0004						< 0.0005
Bromodichloromethane	(draft 0.0004)	mg/L	0.00006	0.0003	0.00006	0.0006		< 0.01[c]	0.0056[a]	0.007[a]		< 0.0005
Bromoform	(draft 0.005)	mg/L	0.0002	0.001	0.0001	0.0003		< 0.01[c]		< 0.0005[a]		< 0.0005
Bromomethane	Unreg.A	mg/L	< 0.000234	0.00025	< 0.000234	0.00025		< 0.01[c]		< 0.01[c]		< 0.0005
sec-Butylbenzene	***(0.26)***	mg/L		< 0.000025		< 0.000025						< 0.0005
n-Butylbenzene	***(0.26)***	mg/L			0.00007	0.00007						< 0.0005
tert-Butylbenzene	***(0.26)***	mg/L			0.00014	0.00014						< 0.0005
Carbon Tetrachloride	0.0005 (0.0001)	mg/L		< 0.000045		< 0.000045		< 0.01[c]		< 0.0005[a]		< 0.0005
Chlorobenzene	0.07	mg/L			< 0.000031	0.00006						< 0.0005
Chlorodibromomethane	(draft 0.0007)	mg/L	0.0002	0.0009	0.0001	< 0.0001		< 0.01[c]		< 0.01[c]		< 0.0005
Chloroethane	Unreg.A	mg/L	< 0.000031	0.00056	< 0.000031	0.00007		< 0.01[c]		< 0.01[c]		< 0.0005
Chloroform	(draft 0.005)	mg/L	0.0004	0.0054	0.0002	0.0008	0.0043[c]	0.0174[c]	0.00724[a]	0.0094[a]		< 0.0005
Chloromethane	Unreg.A	mg/L	0.00014	0.00056	0.00014	0.00042		< 0.01[c]		< 0.01[c]		< 0.0005
2-Chlorotoluene or o-Chlorotoluene	Unreg.A ***(0.14)***	mg/L		< 0.000162		< 0.000162						< 0.0005
4-Chlorotoluene or p-Chlorotoluene	***(0.14)***	mg/L		< 0.000241		< 0.000241						< 0.0005
Dibromomethane	Unreg.A	mg/L	0.00014		0.00007	0.00063						< 0.0005
1,2-Dichlorobenzene	0.6 (0.6)	mg/L	< 0.000027	0.00015				< 0.01[c]		< 0.0005[a]		< 0.0005
1,3-Dichlorobenzene	Unreg.A	mg/L	< 0.000053	0.000665	< 0.000053	0.000119		< 0.01[c]		< 0.01[c]		< 0.0005
1,4-Dichlorobenzene	0.005 (0.006)	mg/L	0.0008	0.0032	0.0002	0.0008		< 0.01[c]		< 0.0005[a]		< 0.0005
1,2-Dichloroethane	0.0005 (0.0004)	mg/L	< 0.000019	0.00006	< 0.000019	0.00006		< 0.01[c]		< 0.0005[a]		< 0.0005
1,1-Dichloroethane	0.005	mg/L		< 0.000056		< 0.000056		< 0.01[c]		< 0.01[c]		< 0.0005
1,1-Dichloroethene	0.006 (0.01)	mg/L						< 0.01[c]		< 0.0005[a]		< 0.0005
cis-1,2-Dichloroethene	0.006 (0.1)	mg/L	0.00006	0.00012	< 0.000028	0.00006		< 0.01[c]		< 0.0005[a]		< 0.0005
trans-1,2-Dichloroethene	0.01 (0.06)	mg/L		< 0.00037		< 0.00037				< 0.0005[a]		< 0.0005
Dichlorodifluoromethane (Freon12)	*(1)*	mg/L	< 0.000205	0.0007	< 0.000205	0.0007						< 0.0005
1,2-Dichloropropane	0.005 (0.0005)	mg/L	0.00004	0.0002				< 0.01[c]		< 0.0005[a]		< 0.0005
1,3-Dichloropropane	Unreg.A	mg/L		< 0.000077		< 0.000077						< 0.0005

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			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
2,2-Dichloropropane	Unreg.A	mg/L		< 0.000204		< 0.000204						< 0.0005
1,1-Dichloropropene	Unreg.A	mg/L		< 0.000037		< 0.000037						< 0.0005
1,3-Dichloropropene	0.0005 (0.0002)	mg/L						< 0.01[c]		< 0.01[c]		
cis-1,3-Dichloropropene		mg/L										< 0.0005
trans-1,3-Dichloropropene		mg/L										< 0.0005
ETBE (Ethyl tertiary butyl ether)	Unreg B	mg/L										
Ethylbenzene	0.7 (0.3)	mg/L			< 0.000071	0.00015		< 0.01[c]		< 0.0005[a]		< 0.0005
Hexachlorobutadiene	Unreg.B	mg/L		< 0.000173		< 0.000173		< 0.01[c]		< 0.01[c]		< 0.0005
Isopropylbenzene	***(0.77)***	mg/L		< 0.000142		< 0.000142						< 0.0005
p-Isopropyltoluene	Unreg.B	mg/L										< 0.0005
Methylene Chloride (dichloromethane)	0.005 (0.004)	mg/L	< 0.000092	0.00016		< 0.000092		< 0.01[c]		< 0.0005[a]		< 0.0005
MTBE		mg/L	< 0.00148	0.0065		< 0.00148						< 0.0005
Monochlorobenzene	0.013 (0.005 [2nd]) (0.013)	mg/L						< 0.01[c]		< 0.01[c]		
Naphthalene	***(0.17)***	mg/L			< 0.000036	0.00021		< 0.01[c]		< 0.01[c]		< 0.0005
n-Propylbenzene	Unreg.B ***(0.26)***	mg/L										< 0.0005
Styrene	0.1 (0.0005)	mg/L								< 0.0005[a]		< 0.0005
TAME (Tertiary amyl methyl ether)		mg/L										
1,1,1,2-Tetrachloroethane	Unreg.A	mg/L		< 0.000071		< 0.000071						< 0.0005
1,1,2,2-Tetrachloroethane	0.001 (0.0001)	mg/L		< 0.000024		< 0.000024		< 0.01[c]		< 0.01[c]		< 0.0005
Tetrachloroethene	0.005 (0.00006)	mg/L	0.0005	0.032		< 0.000109		< 0.01[c]		< 0.0005[a]		< 0.0005
Toluene	0.15 (0.15)	mg/L	0.00016	0.00024	0.00032	0.0008		< 0.01[c]		< 0.0005[a]		< 0.0005
1,2,3-Trichlorobenzene	Unreg.B	mg/L			< 0.000031	0.000105						< 0.0005
1,2,4-Trichlorobenzene	0.07 (0.005)	mg/L		< 0.000026		< 0.000026		< 0.01[c]		< 0.0005[a]		< 0.0005
1,1,1-Trichloroethane	0.2 (1)	mg/L		< 0.000035		< 0.000035		< 0.01[c]		< 0.0005[a]		< 0.0005
1,1,2-Trichloroethane	0.005 (0.0003)	mg/L	0.0001	0.0002				< 0.01[c]		< 0.0005[a]		< 0.0005
Trichloroethene	0.005 (0.0008)	mg/L	0.000035	0.0005	< 0.000027	< 0.000027		< 0.01[c]		< 0.0005[a]		< 0.0005
Trichlorofluoromethane	0.15 (0.7)	mg/L										< 0.0005
1,2,3-Trichloropropane	Unreg.A ***(0.000005)***	mg/L		< 0.000056		< 0.000056						< 0.0005
1,1,2-Trichloro-1,2,2-trifluoroethane (FREON)	1.2 (4)	mg/L		< 0.000029		< 0.000029						
1,3,5-Trimethylbenzene	***(0.33)***	mg/L										< 0.0005

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			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
1,2,4-Trimethylbenzene	***(0.33)***	mg/L	< 0.000037	0.00007	< 0.000037	0.00007						
Vinyl Chloride	0.0005 (0.00005)	mg/L		< 0.00007		< 0.00007		< 0.01[c]		< 0.0002[a]		< 0.0005
Xylenes (single or sum of isomers)	1.75 (1.8)	mg/L		< 0.00008	0.000168	0.36	0.0003[c]	0.0007[c]		< 0.0002[c]		< 0.0005
Total THMs	0.080	mg/L			0.0050	0.0087			0.0155[a]	0.0182[a]		
Semivolatile Organic Compounds												
Benzo (A) Pyrene	0.0002 (0.000004)	mg/L	0.000003	0.000024	0.000003	0.000006		< 0.01[c]		< 0.00002[a]		< 0.00002
Di (2-Ethylhexyl) Adipate	0.4 (0.2)	mg/L								< 0.0006[a]		< 0.0006
Di (2-Ethylhexyl) Phthalate	0.004 (0.012)	mg/L					0.00783[c]	0.0205[c]		< 0.0006[a]		< 0.0006
Fumigants												
Ethylene dibromide (EDB)	0.00005	mg/L		< 0.000058		< 0.000058				< 0.00001[a]		< 0.00001
Dibromochloropropane (DBCP)	0.0002 (0.0000017)	mg/L								< 0.00001[a]		< 0.00001
Organochlorine Pesticides												
Alachlor	0.002 (0.004)	mg/L		< 0.00002		< 0.00002				< 0.0001[a]		< 0.0001
Aldrin	Unreg. C ***(0.000002)***	mg/L		< 0.00001		< 0.00001		< 0.00005[a]		< 0.00005[a]		< 0.00001
Chlordane	0.0001 (0.00003)	mg/L		< 0.00001		< 0.00001		not detected[c]		< 0.0001[a]		< 0.0001
Chlorothanlonil	Unreg. B	mg/L		< 0.00002		< 0.00002						
Dieldrin	Unreg. C ***(0.000002)***	mg/L		< 0.00001		< 0.00001		< 0.00005[a]		< 0.00005[a]		< 0.00001
Endrin	0.002 (0.0018)	mg/L		< 0.00001		< 0.00001		< 0.00005[c]		< 0.00001[a]		< 0.00001
Heptachlor	0.00001 (0.000008)	mg/L		< 0.00002		< 0.00002		< 0.00005[c]		< 0.00004[a]		< 0.00004
Heptachlor Epoxide	0.00001 (0.000006)	mg/L								< 0.00002[a]		< 0.00002
Hexachlorobenzene	0.001 (0.00003)	mg/L	< 0.0000015	0.000005	0.000004	0.00003		< 0.010[c]		< 0.0001[a]		< 0.00005
Hexachlorocyclopentadiene	0.05 (0.05)	mg/L	< 0.000007	N/A	N/A	N/A		< 0.010[c]		< 0.0001[a]		< 0.00005
Lindane	0.0002 (0.000032)	mg/L		< 0.00001		< 0.00001		< 0.00005[c]		< 0.00002[a]		< 0.00002
Methoxychlor	0.03 (0.03)	mg/L		< 0.00001		< 0.00001		< 0.00005[a]		< 0.00005[a]		< 0.0001
Polychlorinated Biphenyls	0.0005 (0.00009)	mg/L						---		---		
Aroclor-1016 (PCB-1016)		mg/L						not detected[c]		< 0.00008[c]		< 0.00007
Aroclor-1221 (PCB-1221)		mg/L						not detected[c]		< 0.00019[c]		< 0.0001
Aroclor-1232 (PCB-1232)		mg/L						not detected[c]		< 0.00023[c]		< 0.0001
Aroclor-1242 (PCB-1242)		mg/L						not detected[c]		< 0.00026[c]		< 0.0001

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			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Aroclor-1248 (PCB-1248)		mg/L						not detected[c]		< 0.0001[a]		< 0.0001
Aroclor-1254 (PCB-1254)		mg/L						not detected[c]		< 0.0001[a]		< 0.0001
Aroclor-1260 (PCB-1260)		mg/L						not detected[c]		< 0.0002[a]		< 0.0001
Propachlor	***(0.09)***	mg/L		< 0.001		< 0.001						< 0.00005
Toxaphene	0.003 (0.00003)	mg/L						not detected[c]		< 0.001[a]		< 0.0005
Organochlorine Herbicides												
Bentazon (Basagran)	0.018 (0.2)	mg/L		< 0.005		< 0.005						< 0.0005
2,4-Dichlorophenoxyacetic acid (2,4-D)	0.02 (0.07)	mg/L	0.00005	0.018	< 0.00005	0.00005				< 0.0001[a]		< 0.0001
Dalapon	0.2 (0.79)	mg/L								< 0.001[a]		< 0.001
Dicamba	Unreg.C	mg/L		< 0.001		< 0.001						< 0.00008
Dinoseb	0.007 (0.014)	mg/L								< 0.0001[a]		< 0.0002
Pentachlorophenol	0.001 (0.0003)	mg/L						< 0.02[c]	0.000048[a]	0.00024[a]		< 0.001
Pichloram	0.5 (0.5)	mg/L								ND		< 0.0001
Silvex (2,4,5-TP)	0.05 (0.025)	mg/L								< 0.0001[a]		< 0.0002
Carbamate Pesticides												
Diuron	Unreg.B	mg/L		< 0.01		< 0.01				< 0.0005[f]		
Aldicarb	Unreg.C ***(0.007)***	mg/L		< 0.0001		< 0.0001						< 0.0005
Aldicarb sulfone	Unreg.C	mg/L								< 0.001[f]		< 0.0005
Aldicarb sulfoxide	Unreg.C	mg/L								< 0.001[f]		< 0.0005
Baygon (Propoxur)	***(0.03)***	mg/L		< 0.0004		< 0.0004				< 0.0005[f]		< 0.0005
Carbofuran	0.018 (0.0017)	mg/L		< 0.0004		< 0.0004				< 0.0005[f]		< 0.0005
Carbaryl	Unreg.C ***(0.7)***	mg/L		< 0.0004		< 0.0004				< 0.0005[f]		< 0.0005
3-hydroxycarbofuran	Unreg.C	mg/L								< 0.0005[f]		< 0.0005
Methomyl	Unreg.C	mg/L		< 0.0004		< 0.0004				< 0.0005[f]		< 0.0005
Oxamyl	0.05 (0.026)	mg/L								< 0.0005[f]		< 0.0005
Miscellaneous												
Diquat	0.02 (0.015)	mg/L								< 0.0004[a]		
Endothall	0.1 (0.58)	mg/L		< 0.001		< 0.001				< 0.009[a]		
Glyphosate	0.7 (0.9)	mg/L								< 0.006[a]		
Paraquat		mg/L								ND		
Polynuclear Aromatic hydrocarbon		mg/L										

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			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Anthracene		mg/L						< 0.01[c]		< 0.0001[f]		< 0.00002
Fluoranthene		mg/L						< 0.01[c]		< 0.0001[f]		< 0.0001
Phenanthrene		mg/L						< 0.01[c]		< 0.0001[f]		< 0.00002
Pyrene		mg/L						< 0.01[c]		< 0.0001[f]		< 0.00005
2,3,7,8-TCDD Dioxin	3 x 10^{-8} (1 x 10^{-9})	mg/L							< 0.000000005a	< 0.000000005[a]		
Nitrogen/Phosphorus Pesticides												
Atrazine	0.001 (0.00015)	mg/L	0.00036	0.0001	< 0.0001	0.0001				< 0.0001[a]	0.0002	0.0002
Bromacil	Unreg.B	mg/L		< 0.005		< 0.005				< 0.0001[f]		< 0.0002
Butachlor	Unreg.C	mg/L								< 0.0001[f]		< 0.00005
Diazinon	***(0.006)***	mg/L		< 0.00006		< 0.00006				< 0.0001[f]		< 0.0001
Dimethoate	Unreg.B ***(0.001)***	mg/L		< 0.00006		< 0.00006				< 0.0005[f]		< 0.0001
Malathion	***(0.16)***	mg/L		< 0.00006		< 0.00006				< 0.0001[f]		
Metolachlor	Unreg.C	mg/L	0.00029	0.01	< 0.00005	0.00005				< 0.0001[f]	0.00022	0.00022
Metribuzin	Unreg.C	mg/L		< 0.0001		< 0.0001				< 0.0001[f]		< 0.00005
Molinate	0.02 (0.001)	mg/L		< 0.0005		< 0.0005				< 0.0001[f]		< 0.0001
Prometryn	Unreg.B	mg/L								< 0.0001[f]		< 0.0005
Simazine	0.004 (0.004)	mg/L	0.0001	0.0036	< 0.0001	0.0001				< 0.00007[a]	0.0001	0.0001
Thiobencarb (Bolero)	0.07 (0.001 [2nd]) (0.07)	mg/L								< 0.0001[f]		< 0.0002
Other Chemicals												
a-Benzene Hexachloride (a-BHC)	***(0.000015)***	mg/L								< 0.0001[f]		
b-Benzene Hexachloride (b-BHC)	***(0.000025)***	mg/L								< 0.0001[f]		
2,4-Dimethylphenol	***(0.1)***	mg/L	0.0000021	0.0000028	0.0000021	N/A		< 0.01[c]		< 0.01[c]		
1,4-Dioxane	***(0.003)***	mg/L	0.0005	0.03	0.0001	0.0005						
Diphenamide	***(0.2)***	mg/L		< 0.0001		< 0.0001						
Ethion	***(0.004)***	mg/L		< 0.00006		< 0.00006				< 0.005[f]		
Formaldehyde	***(0.1)***	mg/L										
Isopropyl N (3-Chlorophenyl) Carbamate (CIPC)	***(1.2)***	mg/L										
Methyl Isobutyl Ketone (MIBK)	***(0.12)***	mg/L										
Methyl Parathion	***(0.002)***	mg/L		< 0.00006		< 0.00006				< 0.0005[f]		
N-Nitrosodimethylamine (NDMA)	***(0.00001)***	mg/L	0.000016	0.000043	0.0000045	0.00003		< 0.01[c]	0.00000093[c]	0.0000028[f]		
Parathion	***(0.040)***	mg/L								< 0.0005[f]		
Pentachloronitrobenzene	***(0.02)***	mg/L								< 0.0005[f]		
Phenol	***(4.2)***	mg/L					0.0125[c]	0.0178[c]		< 0.01[c]		
Trithion	***(0.007)***	mg/L										
Captan	***(0.015)***	mg/L		< 0.0005		< 0.0005						
Chloropicrin	***(0.037)***	mg/L	0.00014		0.00014	0.00035						
Tert butyl alcohol	***(0.012)***	mg/L										
Carbon disulfide		mg/L	< 0.000042	0.0007	< 0.000042	0.00014						

Constituent	CDPH MCL, PHG or NL	Units	Combined Results for Kwinana and Beenyup				Upper Occoquan Service Authority				Lorton/Occoquan Water Treatment Plants	
			Influent		Effluent		Influent		Effluent		Influent	
			Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.	Ave.	Max.
Chlorate		mg/L	0.014	1.61	0.014	0.049						
Ethylene glycol		mg/L										
HMX		mg/L										
N-Nitrosodiethyamine (NDEA)		mg/L		0.000004	0.000015	0.0000018				< 0.000005[c]		
N-Nitrosodi-n-propylamine (NDPA)		mg/L	0.000004	0.000089	< 0.00000188	0.000007		< 0.01[c]		< 0.000007[c]		
n-Propylbenzene		mg/L		< 0.000191		< 0.000191						
RDX		mg/L										
2,4,6-Trinitrotoluene (TNT)		mg/L										
Endocrine Disrupting Compounds												
Ethinyl estradiol		mg/L	< 0.000008		0.0000021	< 0.000005						
17-α Ethinyl estradiol		mg/L								< 0.0000005[f]		
17-β Estradiol		mg/L	< 0.0000057		0.00000175					< 0.0000005[f]		
Estrone		mg/L	0.000006	0.000055		< 0.0000009				< 0.0000005[f]		
Bisphenol A		mg/L	< 0.000035	< 0.000035	< 0.000035	< 0.000035				< 0.0001[f]		
Nonylphenol (4-Nonyl phenol)		mg/L	0.00002	0.00005	0.00003					< 0.0005[f]		
Pharmaceuticals and Other Chemicals												
Acetaminophen		mg/L	0.000128	0.0008	< 0.000036					< 0.000005[f]		
Caffeine										< 0.00005[f]		< 0.0002
Carbomazapine									0.0000525[f]	0.000057[f]		
Gemfibrozil		mg/L	0.000108	0.00108	< 0.0000194				0.0000025[f]	0.0000043[f]		
Ibuprofen		mg/L	0.00036	0.00108	< 0.000009					< 0.00005[f]		
Triclosan		mg/L	0.000019	0.000021								
Diazepam						0.0000184				< 0.00001[b]		
Naproxen						0.000015				< 0.000002[f]		
Clofibric acid						0.0000016				< 0.0000005[f]		

ND Not Detected
(#) Number in parenthesis is a California Public Health Goal
(#) Number in parenthesis and bold italics is a California Notification Level or archived Action Level
(# 2nd) Indicates value is a California secondary MCL
NS No Standard. Monitoring required in California
* Ave CRW microbiological data from 1/2005-6/2009
*** No more than 5% of the samples/month may be positive
t If a repeat total coliform sample is fecal-coliform or *E. coli*-positive, the system is in violation of the MCL for total coliforms

TT Treatment technique in place of MCL
Unreg.A Unregulated. Monitoring required for all community and non- transient, non-community water systems
Unreg.B Unregulated. Monitoring required for all community and non- transient, non-community water systems if determined vulnerable
Unreg.C Unregulated. Monitoring required for all community and non- transient, non-community water systems if determined vulnerable
Unreg.D Unregulated. Monitoring may be required at State's discretion
Unreg.E Unregulated. Monitoring required unless determined not vulnerable.
DNQ Detected, but Not Quantifiable. Estimated concentration value in parenthesis
1 Beenyup only
2 Kwinana only
3 Manipulated data - $x_{ave} = (x_1n_1+x_2n_2)/(n_1+n_2)$, where x_i is the mean value for each plant and n_i is the number of samples taken to determine that mean value
**** Manipulated data - $x_{ave} = [(x1n1+x2n2)/(n1+n2)]*2.7*10^{-11}*10^{12}$, where x_i = mean value for each plant, n_i = number of samples taken to determine that mean value, $2.7*10^{-11}$ = number of Ci in 1 Bq, 10^{12} = number of pCi in 1 Ci

[a] 2006 to 2010
[b] 2010
[c] 2007 to 2010
[d] September 2002
[e] 2008 to 2010
[f] 2009 & 2010
[g] As total Kjeldahl nitrogen

Table 6. Non-carcinogenic Risk Assessment[1] for OCWD GWRS Product Water

Constituent	Mean Concentration (µg/L)	Dose[2] (mg/kg/day)	Reference Dose (mg/kg/day)	Hazard Index
	GWRS Product Water			
Metals				
Arsenic	0.07	2.0 E-06	3.0 E-04	6.7 E-03
Barium	1.0	2.9 E-05	7.0 E-02	4.1 E-04
Boron	291	8.3 E-03	9.0 E-02	9.2 E-02
Chromium	1.0	2.9 E-05	1.5 E 00	1.9 E-05
Cobalt	1.1	3.1 E-05	1.5 E 00	2.1 E-05
Manganese	1.5	4.3 E-05	1.4 E-01	3.1 E-04
Selenium	5.5	1.6 E-04	5.0 E-03	3.1 E-02
Organics				
1,4-Dichlorobenzene	0.9	2.6 E-05	1.0 E-01	2.6 E-04
Bromodichloromethane	0.3	8.6 E-06	2.0 E-02	4.3 E-04
Bromoform	0.3	8.6 E-06	2.0 E-02	4.3 E-04
Chloroform	1.1	3.1 E-05	1.0 E-02	3.1 E-03
Dibromoacetonitrile	0.1	2.9 E-06	2.0 E-02	1.4 E-04
Dichloroacetonitrile	0.2	5.7 E-06	8.0 E-03	7.1 E-04
Dibromochloromethane	0.3	8.6 E-06	2.0 E-02	4.3 E-04
Methylene Chloride	1.9	5.4 E-05	6.0 E-02	9.0 E-04
Tetrachloroethene	0.3	8.6 E-06	1.0 E-02	8.6 E-04
Total				**0.14**

[1] Based on constituents detected and listed on IRIS or OEHHA with a reference dose for toxicity

[2] Point estimate based on 2 L/day water intake

Adapted from [*19*]

Table 7. Non-carcinogenic Risk Assessment[1] for Santa Ana River and Imported Waters

Constituent	Mean Concentration (µg/L)	Dose[2] (mg/kg/day)	Reference Dose (mg/kg/day)	Hazard Index
Santa Ana River Water				
Metals				
Arsenic	4.3	1.2 E-04	3.0 E-04	4.1 E-01
Barium	40	1.1 E-03	7.0 E-02	1.6 E-02
Boron	267	7.6 E-03	9.0 E-02	8.5 E-02
Manganese	31	8.8 E-04	1.4 E-01	6.3 E-03
Nickel	2.5	7.1 E-05	2.0 E-03	3.6 E-02
Thallium	1.0	2.9 E-05	5.0 E-03	5.7 E-03
Organics				
Bis(2-ethylhexyl) phthalate	2.1	6.0 E-05	2.0 E-02	3.0 E-03
Bromodichloromethane	0.3	8.6 E-06	2.0 E-02	4.3 E-04
Bromoform	0.3	8.6 E-06	2.0 E-02	4.3 E-04
Butylbenzyl phthalate	2.1	6.0 E-05	2.0 E-01	3.0 E-04
Chloroform	0.4	1.1 E-05	1.0 E-02	1.1 E-03
Diazinon	0.2	5.7 E-06	9.0 E-05	6.3 E-02
Di-n-butylphthalate	2.1	6.0 E-05	1.0 E-01	6.0 E-04
Diuron	1.4	4.0 E-05	2.0 E-03	2.0 E-02
Formaldehyde	3.0	8.6 E-05	2.0 E-01	4.3 E-04
Methoxychlor	0.5	1.4 E-05	5.0 E-02	2.9 E-03
Propazine	0.1	2.9 E-06	2.0 E-02	1.4 E-04
Simazine	0.4	1.1 E-05	5.0 E-03	2.3 E-03
Total				**0.65**
Imported Surface Waters				
Metals				
Arsenic	2.5	7.1 E-05	3.0 E-04	2.4 E-01
Barium	118	3.4 E-03	7.0 E-02	4.8 E-02
Boron	198	5.7 E-03	9.0 E-02	6.3 E-02
Manganese	9.7	2.8 E-04	1.4 E-01	2.0 E-03
Molybdenum	16	4.4 E-04	5.0 E-03	8.9 E-02
Selinium	2.9	8.3 E-05	5.0 E-03	1.7 E-02
Strontium	998	2.9 E-02	6.0 E-01	4.8 E-02
Organics				
Bis(2-ethylhexyl) phthalate	6.5	1.8 E-04	2.0 E-02	9.2 E-03
Bromodichloromethane	0.4	1.2 E-05	2.0 E-02	5.9 E-04
Chloroform	0.4	1.0 E-05	1.0 E-02	1.0 E-03
Dibromochloromethane	0.3	9.7 E-06	2.0 E-02	4.9 E-04
Total				**0.51**

[1] Based on constituents detected and listed on IRIS or OEHHA with a reference dose for toxicity

[2] Point estimate based on 2 L/day water intake

Adapted from [*19*]

Table 8. Comparison of Carcinogenic Risk for OCWD GWRS and Santa Ana River Water

Constituent	Mean Concentration (µg/L)	Slope Factor (mg/kg/day)[1]	Risk[1,2] (prob/lifetime)
	GWRS Product Water		
Metals			
Arsenic	0.07	1.5 E-00	3.0 E-06
Organics			
1,4-Dichlorobenzene	0.9	5.4 E-03	1.4 E-07
Bromodichloromethane	0.3	6.2 E-03	5.3 E-08
Bromoform	0.3	7.9 E-03	6.8 E-08
Chloroform	1.1	6.1 E-03	1.9 E-07
Methylene Chloride	2.1	7.5 E-03	4.5 E-07
Tetrachloroethene	0.3	5.1 E-02	4.4 E-07
NDMA	0.020	5.1 E-01	2.9 E-05
			3.3 E-05
	Santa Ana River Water		
Metals			
Arsenic	4.3	1.5 E-00	1.8 E-04
Organics			
Bis(2-ethylhexyl) phthalate	2.1	1.4 E-02	8.4 E-07
Bromodichloromethane	0.3	6.2 E-02	5.3 E-08
Bromoform	0.3	7.9 E-03	6.8 E-08
Chloroform	0.4	6.1 E-03	7.0 E-08
NDMA	0.0015	5.1 E-01	2.2 E-06
Total			**1.9 E-04**

[1] Based on 95% SF, and mean concentration
[2] Point estimate based on 2 L/day water intake
Adapted from [*19*]

Table 9. Summary of Trace-Organic Compounds Removal across WBMWD's Barrier Project

Contaminant	Application	Rejection Across MF (%)	Rejection Across RO (%)	UV Oxidation (%)	Removal Across Post Treatment (decarb/ph adj./Cl_2) (%)
1,4-Dichlorobenzene (p-Dichlorobenzene)	Pharm./Personal Care Product	< 5	42	>77	ND
Dichloroacetic acid (DCAA)	Pharm./Personal Care Product	ND	> 95	ND	ND
Trichloroacetic acid (TCAA)	Pharm/Personal Care Product	ND	> 97	ND	ND
Bromodichloromethane	Trihalomethane	< 5	56	23	> 72
Bromoform	Trihalomethane	< 5	> 78	ND	ND
Chloroform	Trihalomethane	< 5	53	2	> 78
Dibromochloromethane	Trihalomethane	< 5	63	> 73	ND
Estrone	Endocrine Disruptor	NC	NC	NC	ND
Bis (2-ethylhexyl) phthalate	Plasticizer	CON	ND	ND	ND
Butylbenzyl phthalate	Plasticizer	NC	NC	NC	NC
Diethyl phthalate	Plasticizer	CON	NC	NC	NC
Di-n-butyl phthalate	Plasticizer	CON	CON	ND	NC
Dibromomethane	Solvent	< 5	< 5	27	> 66
Methylene Chloride	Solvent	< 5	< 5	6	> 68
Methyl-tert-butyl ether	Solvent	< 5	> 81	ND	ND
Tetrachloroethene	Solvent	< 5	69	> 78	ND
Toluene	Solvent	NC	> 85	ND	ND
1,4 Dioxane	Solvent	< 5	> 89	ND	ND
Bromochloromethane	Fire Ext.	< 5	< 5	10	> 72
PBDE-154	Electronics	NC	33	ND	ND
Dalapon	Herbicide	< 5	89	ND	ND
NDMA	Ind. By-product	Increase*	50	> 97	Increase*

* These treatment steps include NaOCl addition which may account for the observed increases in NDMA concentration

CON = Sample contamination suspected

NC = Data not consistent and thus rejection rates were not determined

ND = Not determined

Adapted from [*29*] using data from 2007

Table 10. Water Quality Results for Beenyup Pilot Plant in Western Australia

Parameter	Beenyup Secondary WW			Beenyup Pilot Plant Post-RO			Removal by MR/RO
	Mean	Std. Dev.	n	Mean	Std. Dev.	n	Average %
Alkalinity	108	48	12	6	2.6	12	91.8
Suspended Solids	18.3	13	12	3.1	2.2	12	70.9
Organic Nitrogen	3.2	1.2	109	No Data			
TKN	4.1	2.4	13	0.49	0.46	12	82.6
Phosphate	9.3	0.7	13	0.01	0.01	12	99.9
Total Phosphorus	10.1	1.1	13	0.06	0.08	12	99.4
Calcium	37.2	4	12	0.07	0.06	12	99.8
Potassium	22.7	2.3	12	0.34	0.09	12	98.5
Magnesium	11.5	1.1	12	< 0.1	-	12	99.6[a]
Silica	17	2.2	12	< 2.2	-	12	93.5[a]
Chem. Oxygen Demand	39.6	20.8	11	8.2	6	11	70.2
BOD_5 (Ops Data)†	5.4 Median < 5 (12.8)	6.1 (8.5)	11 (218)	< 5	-	11	80.5[a]
Total Organic Carbon	9.2	2.9	12	0.4	0.37	12	95.7
Dissolved Organic Carbon	8.1	0.6	12	0.23	0.13	12	97.2
Oil and Grease	12.6	27.3	9	No Data			
Colour (TCU)	34.6	3.6	12	< 1	-	12	98.1 (97.8)
Conductivity (µS/cm) (Ops data)[b]	1271 (1292)	128 (94.4)	14 (16702)	24.1 (28.2)	5.5 (7.0)	12 (16702)	99.6
pH - in situ[c] (Ops Data)[b]	6.94 (5.90)	0.12 (0.50)	11 (16702)	5.53	0.9	11	
Dissolved Oxygen[c]	3.8	1.2	11	5.6	2.2	11	
Chlorine[c]	0.05	0.05	12	0.87	0.78	12	
Chloramine[c]	0.05	0.05	12	0.67	0.6	12	

† Operational data used in % removal calculations

* AGWR 2008 Guideline level only

[b] Operational data were recorded every 10 minutes while RO system operational: 3/18/08 to 12/23/08

[c] Measures taken on site either with a probe or Hach chemical method

Adapted from [*36*] using data from 2006 to 2008

Table 11. Log Removal/Inactivation Credits Adopted for Beenyup Advanced Water Treatment Plant in Western Australia

Unit Process	Bacteria (*Campylobacter*)	Virus (Adenovirus)	Protozoa (*Cryptosporidium*)
Secondary Treatment	1.0	1.0	0.5
Ultrafiltration	3.0	3.0	3.0
Reverse Osmosis	3.0	3.0	3.0
UV Disinfection (200 mJ/cm^2)	4.0	4.0	4.0
Total	**11.0**	**11.0**	**10.5**
Required*	8.1	9.5	8

Adapted from [*39*]; * Per [*38*]

Table 12. Surrogates Used to Gauge Operational Stability in Western Australia

Critical Control Point	Surrogate	Measured online in real time with	Hazard for which surrogate represents removal	Monitoring locations
Feed Water Acceptance Criteria	Dissolved Oxygen	DO meters in WWTP aeration tanks	Organic chemicals, pathogens, particulates	WWTP aeration tanks
	TOC	UV Absorbance	Dissolved organic chemicals	Raw (AWTP Feed)
	Turbidity	Turbidity meter	Particulates, pathogens, chemicals	Raw (AWTP Feed)
MF Operation	Turbidity	Turbidity meters	Particulates, pathogens	Raw, Post-MF
	Turbidity	Particle counter	Particulates, pathogens	Post-MF
	Pressure Decay (Daily)	Daily test: Pressure pre and post membranes	Failure in seals, membrane degradation	Pre- and Post-MF
RO Operation	Conductivity	Conductivity meter	Inorganic chemicals, organic chemicals, pathogens	Post-MF, Post-RO
	TOC	TOC Analyzer	Organic chemicals	Post-MF, Post-RO
UV Operation	UV Transmittance	UV intensity	Microbial pathogens	UV Feed
	UV dose (fluorescence)	UV dose and flow	Microbial pathogens	UV unit
Injection Acceptance Criteria	Oxidation Reduction Potential	ORP meter	Chemical stability (affecting aquifer risks)	Treated water
	pH	pH meter	Chemical stability (affecting aquifer risks)	Treated water

Adapted from [*36*]

Table 13. Suggested Chemical Indicators to Gauge Treatment Performance in Western Australia

Chemical Indicator	Chemical Properties	Detection in Secondary Wastewater (Median Conc.)	Detection in Post-RO Effluent (Median Conc.)	Median Removal Efficiency (Min.-Max.)	Reason for Selection
Boron	• Metalloid • Small size • Charged (+ or -) • Very hydrophilic	100% (160 µg/L)	89% (75 µg/L)	Intermediate 62% (31–90%)	• Metal with lowest % rejection • Only metal with median post-RO conc. higher than groundwater
Nitrate	• Inorganic anion • Small size • Very hydrophilic	100% (3.45 mg/L)	100% (0.12 mg/L)	Intermediate 88% (85–99%)	• Commonly detected anion with intermediate rejection by RO
NDMA	• *N*-nitrosamine • Small size • Uncharged • Very hydrophilic • Very polar	96% (16 ng/L)	92% (4.5 ng/L)	Intermediate 79% (30–95%)	• Highest median concentration and high % detection in wastewater and post-RO water • Toxicological concerns
Chloroform	• DBP • Small size • Slightly hydrophilic • Non-polar • Organic	85% (0.4 µg/L)	56% (0.14 µg/L)	Intermediate 82% (-412–98%)	• Halomethanes were the most commonly detected DBP • Represents hydrophobic compounds • Potentially absorbing to membrane and partitioning into RO permeate
Bromochloromethane	• DBP • Small size • Uncharged • Hydrophilic • Non-polar organic	94% (0.22 µg/L)	100% (0.11 µg/L)	Intermediate 63% (-50–99%)	• May be better indicator than chloroform based on higher detection and lower rejection by RO

Chemical Indicator	Chemical Properties	Detection in Secondary Wastewater (Median Conc.)	Detection in Post-RO Effluent (Median Conc.)	Median Removal Efficiency (Min.-Max.)	Reason for Selection
1,4-Dichlorobenzene	• VOC • Intermediate size • Uncharged • Hydrophobic • Non-polar organic	95% (0.81 µg/L)	90% (0.2 µg/L)	Intermediate 84% (-20–95%)	• Highest VOC concentration and % detection in wastewater and post-RO water
Carbamazepine	• Pharmaceutical • Non-polar organic • Moderately large sized • Slightly hydrophobic	97% (938 ng/L)	0% (ND)	Good 99.8% (98.8–99.9%)	• Very persistent in the environment • Pharmaceutical with highest % detection and concentration in wastewater • Very well rejected by Ro membranes
EDTA	• Complexing agent • Large size • Negatively charged • Polar organic	100% (2 µg/L)	48% (0.5 µg/L)	Good 99.5% (98–99.9%)	• Detected in all wastewater samples at relatively high concentrations • Well rejected by Ro membranes
Diclofenac	• Pharmaceutical • Acidic • Large size • Slightly hydrophobic • Polar organic	100% (362 ng/L)	0% (ND)	Good 99.6% (76.7–99.8)	• Detected in all wastewater samples • Represents acidic pharmaceuticals

ND = Not detected

Adopted from [*36*]

Table 14. Chemical Indicators of Recycled Water Quality for Western Australia

Chemical Indicator	Chemical Group	Detection in Secondary Wastewater (Median Conc.)	Detection in Post-RO Effluent (Median Conc.)
Boron	• Metalloid	100% (160 µg/L)	89% (75 µg/L)
Nitrate	• Inorganic anion	100% (3.45 mg/L)	100% (0.12 mg/L)
NDMA	• *N*-nitrosamine	96% (16 ng/L)	92% (4.5 ng/L)
Chlorate	• Anion	37% (12.8 µg/L)	46% (12.7 µg/L)
1,4-Dioxane*	• Neutral organic	100% (0.52 µg/L)	28.5% (0.12 µg/L)
1,4-Dichlorobenzene	• VOC • Non-polar organic	95% (0.81 µg/L)	90% (0.2 µg/L)
Fluorene	• Polycyclic aromatic hydrocarbon	64% (0.003 µg/L)	19% (0.003 µg/L)
2,4,6-Trichlorophenol	• Phenol	64% (44.5 µg/L)	0% (ND)
Carbamazepine	• Pharmaceutical • Non-polar organic	97% (938 ng/L)	0% (ND)
Estrone	• Hormone	48% (15 ng/L)	0% (ND)
EDTA	• Complexing agent • Large, polar organic	100% (2 µg/L)	48% (0.5 µg/L)
Diclofenac	• Pharmaceutical • Acidic, polar organic	100% (362 ng/L)	0% (ND)
Trifluralin	• Pesticide	91% (16 pg/L)	0% (ND)
Octadioxin	• Dioxin	67% (16 pg/L)	18% (5 pg/L)

ND = Not detected

Adapted from [*36*]

Table 15. UOSA Permit Limits

Parameter	Limit	Unit
Flow	54	MGD
E. coli	< 2	number/100 ml
Biological Oxygen Demand$_5$	1.0	mg/L
Chemical oxygen demand	10.0	mg/L
Turbidity	0.5	NTU
Total Suspended Solids	1.0	mg/L
Total Phosphorus	0.1	mg/L
Surfactants	0.1	mg/L
MBAS	0.1	mg/L
Total Kjeldahl Nitrogen	1.0	mg/L
Dissolved Oxygen	> 5.0	mg/L
Dechlorination Chlorine Residual	Non detect	mg/L

Adapted from [*44,45*]

Table 16. Microbial Removal Assessment for Millard H. Robbins, Jr. Water Reclamation Plant

Log$_{10}$ Reduction	Microorganism	Average Product Water Concentration
4.02	*Clostridium perfringens*	0.35 CFU/100 ml
> 5.95	Fecal coliform	ND
> 5	*E. coli*	ND
> 5	Total coliform	ND
5.27	*Enterococcus*	0.45 CFU/100 ml
5.86	Coliphage	0.02 PFU/100 ml
> 4.11	Enterovirus	ND
> 4	*Cryptosporidium*	0.04 cysts/100 L (1 of 14)
3.8–4.6	*Giardia*	1.1 cysts/100 L (3 of 14)

Adapted from [*46*]

Table 17. Land use in the Occoquan Watershed based on LANDSAT satellite imagery

Land Use	Acres	Percent
Agriculture	94,754	25
Barren/Transitional	350	0
Forest	160,288	42
Grassland	41,892	11
Water	3,910	1
Residential	51,648	14
Urban/Industrial	25,900	7
Total	378,741	100

Adapted from [*49*]

Table 18. Comparison of FCWA 2005 Lorton WTP and 2010 Griffith WTP Influent and Effluent Water Quality Data

General Parameters	Units	2005 Lorton Water Treatment Plant				2010 Griffith Water Treatment Plant			
		Influent		Effluent		Influent		Effluent	
		Avg	Max	Avg	Max	Avg	Max	Avg	Max
Aggressive Index Number	Units	10	11	11	12	10	11	11	11
Ammonia as N	mg/L	0.11	0.24	0.67	1.35	< 0.2	0.36	0.56	1.14
Bromide	mg/L	0.02	0.03	< 0.01	0.02	0.03	0.04	0.01	0.02
Chloride	mg/L	23.7	51.7	35	59.9	33.2	45.1	43.8	58.3
Chlorine, Free	mg/L	-	-	1.6	4.6	-	-	0.9	3
Chlorine, Total	mg/L			4.1	5	-	-	3.1	3.7
Color	Units	58	170	3	12	51	117	1	1
Dissolved Oxygen	mg/L	6.4	10.5	7.2	13.1	6.5	13	18.3	27.5
Fluoride	mg/L	< 0.2	0.2	0.9	1.5	< 0.2	0.4	1	1.2
Hardness, Calcium	mg/L	50	67	80	109	53	70	53	71
Nitrate as N	mg/L	1.3	2.7	1.4	2.8	0.9	1.9	1	2
Nitrite as N	mg/L	0.05	0.14	< 0.01	0.02	0.04	0.22	< 0.01	0.02
pH	Units	7	7.7	7.4	8.5	7.1	7.4	7.4	7.7
Phosphate as Phosphorous	mg/L	0.01	0.04	0.52	0.64	< 0.1	< 0.1	0.42	0.66
Specific Conductivity	µmhos/cm	227	330	305	398	271	363	322	424
Sulfate	mg/L	20.5	29.4	34.2	44.8	23.4	36.4	24.4	38.6
Temperature	°C	16	26.7	17.1	26.4	15.4	25.4	18.6	24.9
Total Alkalinity	mg/L	47	65	52	74	49	67	52	71
Total Dissolved Solids	mg/L	147	208	192	250	163	205	176	229
Total Hardness	mg/L	73	94	107	140	80	95	77	93
Total Organic Carbon	mg/L	5.1	8.6	2.7	4.2	4.6	5.2	2.2	2.9

Total Suspended Solids	mg/L	9	35	< 1	1	5	14	< 1	< 1
Turbidity	NTU	15.08	55	0.56	3.1	10	42	0.08	0.15
DBPs									
Bromate	µg/L	-	-	< 10	< 10	-	-	< 5	6
Haloacetic Acids, Total	µg/L	-	-	32	80	-	-	9	16
Trihalomethanes, Total	µg/L	-	-	27	73	-	-	18	35
Taste-and-Odor Indicators									
Taste	Units	-	-	3	4	-	-	2	4
Threshold Odor Number	Units	5	11	5	11	13	39	4	8

Adapted from [*52*]

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APPENDIX C

WATER QUALITY PARAMETERS, ANALYTICAL METHODS, AND TARGET CONCENTRATIONS

This appendix describes the analysis methods for each of the water quality parameters measured in this project. EPA or Standard Methods (abbreviated as "SM" throughout this report, and published by the American Public Health Association) were used for most compounds. The hormones, endocrine disrupting compounds, and the pharmaceuticals and personal care products (PPCPs) do not currently have standardized methods. Most of these compounds were analyzed according to Nelson *et al*. (2011). However, a different method was used for the alkylphenol ethoxylate samples taken throughout the study, as well as for the steroid and alkylphenol samples taken during 2012; Section C1 describes the analytical method used in 2012 for these three classes of compounds. Section C2 provides tables that list the methods used for the routine water quality samples and the AOP samples. Section C3 provides tables that list the methods, minimum required reporting levels, the regulatory limits that drove the analysis, and the analyzing laboratory.

C.1 ANALYTICAL METHOD FOR STEROIDS, ALKYLPHENOLS, AND ALKYLPHENOL ETHOXYLATES

During 2010 and 2011, the steroids and alkylphenols were analyzed according to Nelson *et al*. (2011). In 2010, the EPA released a new method (539) for analyzing steroids in drinking water and source water. However, this method was not appropriate for wastewater matrices. Consequently, the method described below was used for samples taken in 2012; this method provided lower reporting limits than the previously-used method and applied to a wider range of compounds. The new method added estriol, equilin, testosterone and androstenedione, and removed progesterone, which had never been detected in any Districts' samples over the three-year period that it was sampled. This method was also used for all alkylphenol ethoxylate samples taken throughout the study (2010-2012).

The AP and APEO analysis at SJCWQL used a Shimadzu HPLC system equipped with two LC 10AD-vp metering pumps, a DGU-14A degassing unit, and a SIL-HTc autosampler unit. The mass spectrometer was an Applied Biosystems API 5000 tandem mass spectrometer with an electrospray ionization (ESI) probe, which was operated in both positive (APEO) and negative (AP) ESI modes. Two HPLC columns were used: a Thermo Aquasil C18 HPLC column (50 x 2.1mm, 3 μm particle size) was used for APs, and a Phenomenex Gemini® C18 HPLC column (50 x 2.1 mm, 3 μm particle size) was used for APEOs.

The Steroid analysis used a Dionex HPLC system equipped with two Ultimate 3000 ternary pumps, an Ultimate 3000 degassing unit, an Ultimate 3000 HPLC column compartment, and an Ultimate 3000 autosampler unit. The mass spectrometer was an AB Sciex 5500 QTrap tandem mass spectrometer with an electrospray ionization (ESI) probe, which was operated in both positive and negative ESI modes simultaneously. A Phenomenex Kinetix® XB-C18 HPLC column (50 x 2.1mm, 2.6 μm particle size) was used.

The first phase of the sample preparation was SPE, which used Phenomenex Strata™-X cartridges (500 mg resin/6 cm^3) with a Caliper Life Sciences Autotrace™ programmable SPE workstation. The SPE system was first cleaned by flushing with a sequence of rinses: 15 mL each of methanol, dichloromethane, and methanol, followed by a final 40 mL flush with reagent water and 3 min of air-drying. The cartridges were then conditioned with a progression of rinses: 7 mL of methanol, and then 10 mL of reagent water.

Prior to extraction, a mixture of isotope labeled analog compounds was added to the effluent samples to facilitate isotope dilution quantitation. Samples (500 mL) were passed through the SPE cartridges, which were then washed with 5 mL of reagent water, followed by 7.0 mL of a 65% methanol solution (in reagent water) to remove polar interferences, dried with compressed air for 25 min, and eluted with 11 mL of methanol. The eluent volume was reduced to dryness by a stream of dry air in an Organomation Associates N-Evap™ 111 nitrogen evaporator, and the final volume was brought up to 1 mL using methanol/water (50:50).
Three separate analyses were conducted on the same sample. The AP analysis used 3.0 µL of sample, and compounds were separated using gradient program with two solvents at a combined flow rate of 0.4 mL/min. Solvent A was 40 mg/L of ammonium acetate, and solvent B was methanol. APEO analysis used 2.0 µL of sample with two solvents at a combined flow rate of 0.4 mL/min. Solvent for APEO analysis were the same as for AP analysis. Steroid analysis used 12 µL of sample, and compounds were separated using gradient program with two solvents at a combined flow rate of 0.55 mL/min. Solvent A was reagent water, and solvent B was acetonitrile. Additionally, the steroid analysis used a post-HPLC column infusion of NH_4OH (2.0% in reagent water) to improve the chemical ionization (0.05 mL/ min). Table B1 provides the gradient profile used for each mode.

Table C-1. LC Gradient Profiles

Alkylphenols		Alkylphenol Ethoxylates		Steroids	
Time (min)	**% of Solvent B in the Mobile Phase**	**Time (min)**	**% of Solvent B in the Mobile Phase**	**Time (min)**	**% of Solvent B in the Mobile Phase**
0.0	65	0.0	50	0.0	15
2.0	85	1.0	50	1.0	20
3.5	95	4.5	95	7.3	60
7.0	95	8.0	95	8.0	80
7.1	65	8.1	50	9.5	80
10	End	13.0	End	9.6	15
				14.0	End

For the MS, AP analysis used an ionization energy of -4500V and a temperature of 600ºC, whereas APEO analysis used an ionization energy of 4500V and a temperature of 300ºC. Steroid analysis used an ionization energy that rapidly alternated between 4500 V and -4500V, and a temperature of 500ºC. The probe height was 5 mm. Other conditions on the instrument were as follows: gas 1 at 40 psi, gas 2 at 55 psi, curtain gas at 27, and collision gas at a setting of 6. Nitrogen was used as the curtain, heater, and collision gas. Multiple reaction monitoring (MRM) transitions were used to identify each of the compounds as shown in Table B2. Chromatographically resolved analytes were quantified by peak area to internal standard area ratios for each specific parent/daughter mass transition as measured by tandem mass spectrometry and calculated by Analyst® software.

Table C-2. MRM Transitions

Compound	ESI Mode	Quantitation Transition
4-Nonylphenol	Negative	219→133
4-*tert* octylphenol	Negative	205→133
4- Nonylphenol monoethoxylate	Positive	282→127
4- Nonylphenol diethoxylate	Positive	326→183
4- Octylphenol monoethoxylate	Positive	268→113
4- Octylphenol diethoxylate	Positive	312→183
Estrone (E1)	Negative	269→145
17 Estradiol (E2)	Negative	271→145
17 Ethinylestradiol (EE2)	Negative	295→145
Equilin (EQ)	Negative	267→143
Estriol (E3)	Negative	287→145
Testorsterone	Positive	289→97
Androstenedione	Positive	287→97

C.2 ANALYTICAL METHOD FOR ROUTINE WATER QUALITY SAMPLES AND AOP SAMPLES

The tables in this section list the parameters measured by the Districts' laboratories during routine water quality sampling, as well as during AOP testing. For each parameter, the method and reporting limit are provided. Tables C-3 through C-5 list the analytical methods and reporting limits for endocrine disrupting compounds (EDCs) and pharmaceuticals and personal care products (PPCPs), which were only measured in the AOP experiments; the nitrosamines and 1,4-dioxane; and the general water quality parameters.

Table C-3. EDCs and PPCPs Analyzed in AOP Experiments

Parameters	Method	Reporting Limit (ng/L)
17-Alpha Ethinylestradiol	See Section C1	0.5-2.0
17-Beta Estradiol	See Section C1	0.5-2.0
4-Nonylphenol (tech mix)	See Section C1	25
4-tert Octylphenol	See Section C1	5.0
Acetaminophen	Nelson *et al*. (2011)	10
Androstenedione	See Section C1	0.5
Azithromycin	Nelson *et al*. (2011)	10
Bisphenol A	Nelson *et al*. (2011)	10
Caffeine	Nelson *et al*. (2011)	10
DEET	Nelson *et al*. (2011)	10
Dilantin (Phenytoin)	Nelson *et al*. (2011)	10
Equilin	See Section C1	0.5
Estriol	See Section C1	0.5
Estrone	See Section C1	0.5-2.0
Gemfibrozil	Nelson *et al*. (2011)	10
Ibuprofen	Nelson *et al*. (2011)	10
Iopromide	Nelson *et al*. (2011)	30
Meprobamate	Nelson *et al*. (2011)	10
Nonylphenol diethoxylate	See Section C1	25
Nonylphenol monoethoxylate	See Section C1	25
Octylphenol diethoxylate	See Section C1	25
Octylphenol monoethoxylate	See Section C1	25
Progesterone	See Section C1	1.0
Sucralose	Nelson *et al*. (2011)	40
Sulfamethoxazole	Nelson *et al*. (2011)	10
TCEP	Nelson *et al*. (2011)	10
Testosterone	See Section C1	0.5
Triclosan	Nelson *et al*. (2011)	10

Table C-4. Nitrosamines and 1,4-Dioxane Analyzed in Routine and AOP Samples

Parameter	Method	Units	Reporting Limits				
			Secondary, UF	MBR	RO Permeate	RO Concentrate	AOP
1,4-Dioxane	EPA 3535/8270C	µg/L	0.4	0.4	0.4	*	0.4
NDMA	EPA 1625	ng/L	2.0-4.0	2.0-2.2	1.0-4.0	*	2.0-4.9
NDEA	EPA 1625	ng/L	2.0-2.2	2.0-2.2	2.0-2.2	*	2.0-4.9
NDPA	EPA 1625	ng/L	2.0-2.2	2.0-2.2	2.0-2.2	*	2.0-4.9
NDBA	EPA 1625	ng/L	2.0-2.2	2.0-2.2	2.0-2.2	*	2.0-4.9
NMEA	EPA 1625	ng/L	2.0-2.2	2.0-2.2	2.0-2.2	*	2.0-4.9
NPIP	EPA 1625	ng/L	2.0-2.2	2.0-2.2	2.0-2.2	*	2.0-4.9
NPYR	EPA 1625	ng/L	2.0-2.2	2.0-2.2	2.0-2.2	*	2.0-4.9

*Not measured.

Table C-5. Analytical Methods for Routine Water Quality Samples

Parameters	Method	Units	Reporting Limits				
			Secondary, UF	MBR	RO Permeate	RO Concentrate	AOP
Alkalinity	SM 2320B (Low)	mg/L	3-5	3-5	3-5	3-5	3-5
Aluminum	EPA 200.8	µg/L	10	10	10	10	*
Ammonia	SM 4500 NH3 C	mg/L	4	1	1	16	1
Barium	EPA 200.8	µg/L	0.5	0.5	0.5	0.5-10	*
Boron	EPA 200.8	mg/L	0.02	0.02	0.02	0.02-1.0	*
Calcium	EPA 200.8	mg/L	0.20-0.40	0.20-0.40	0.02	0.4-2.0	*
Chloride	EPA 300.0	mg/L	10-50	10-20	2	100-200	*
COD	SM 5220C (SMicro)	mg/L	10	10	10	10-100	10
Fluoride	SM 4500 F C	mg/L	0.1	0.1	0.1	0.1-0.6	*
Iron	EPA 200.8	mg/L	0.02	0.02	0.02	0.02	*
Magnesium	EPA 200.8	mg/L	0.02	0.02-0.40	0.02	0.1-2.0	*
Nitrate	SM 4500 NO3 E	mg/L	0.100-0.125	0.1-1.0	0.1	0.1	0.1
Nitrite	SM 4500 NO2 B	mg/L	0.01-0.02	0.01-0.05	0.01	0.025-0.100	0.01-0.02
Orthophosphate	SM4500P-E	mg/L	0.10-0.77	0.13-0.51	0.12-0.38	0.1-1.5	*
pH	SM 4500 H+ B	pH units	*	*	*	*	*
Potassium	EPA 200.8	mg/L	0.2-4.0	0.2-4.0	0.2	1-20	*
sCOD	SM 5220C (SMicro)	mg/L	10	*	*	*	*
Silica	EPA 200.8	mg/L	0.04-0.80	0.80	0.04	2-8	*
Sodium	EPA 200.8	mg/L	2-20	2-20	0.2	10-40	*
Strontium	EPA 200.8	µg/L	4	4	0.2	4-2,000	*
Sulfate	EPA 300.0	mg/L	2.5-12.5	2.5-10.0	0.5	20-50	*
TDS	SM 2540C	mg/L	25-54	25-53	12.5-33.3	156-250	*
TKN	SM 4500 NH3 C	mg/L	4	1	1	1-16	1
TOC	SM 5310B	mg/L	0.5-5.0	0.5	0.5	0.5-10	0.5
TSS	SM 2540D	mg/L	3.1-12.6	*	*	*	*
Turbidity	SM 2130B	NTU	0.10-0.12	0.10-0.12	*	*	*

*Not measured.

C.3 ANALYTICAL METHODS FOR TITLE 22+ SAMPLES

The tables in this section list the analyzing laboratory, the method, the reporting limits, the target concentration for this project, and limits or other levels considered in setting the target concentration. Compounds were analyzed by one of three laboratories: MWD, the Districts (referred to as CSD in the tables below), or Eurofins Eaton Analytical (referred to as EEA in the tables below). It should be noted that the original contract for analysis was with MWH Laboratories, which were acquired by Eurofins Scientific partway through the project. The laboratory facility was the same for all samples, but the name of the laboratory changed to Eurofins Eaton Analytical.

Targets for water quality were based on requirements for groundwater recharge, and were set to the lowest of the following values for each parameter:

- EPA primary maximium contaminant levels (MCLs) and secondary MCLs for drinking water,
- CDPH primary and secondary MCLs, and notification levels (NLs) for drinking water,
- CDPH DGRR levels for total nitrogen, TOC, and turbidity,
- local basin plan objectives for Western Sub-basin of the Main San Gabriel Basin,
- SWRCB monitoring trigger levels for chemicals of emerging concern (note that these levels are guidelines, not regulatory requirements).

In addition to these limits, removal requirements for N-nitrosodimethylamine (NDMA) and 1,4-dioxane from the 2008 CDPH DGRR were applied to the AOP portion of the study; the 2011 DGRR (released partway through this project) eliminated the NDMA requirement, but it was kept for this project.

In the following tables, BPO refers to a basin plan objective, MTL refers to a monitoring trigger level from the 2010 SWRCB report, NL refers to a notification level, PMCL refers to a primary maximum contaminant level, RL refers to a reporting level, and SMCL refers to a secondary maximum contaminant level. Note that some of the criteria overlap; for example, all CDPH MCLs apply to the basin plan objectives. For simplicity, these only the unique values are included in the tables in this appendix.

Table C-6. Inorganic Samples (General Physical and Mineral)

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	CDPH BPO	CDPH MTL	Target Conc
Alkalinity, Total	EEA	SM 2320B	mg/L	2									NA
Ammonia as N	EEA	EPA 350.1	mg N/L	0.05									NA
Asbestos	EEA	EPA 100.1	MFL	0.2-6.4	7		7						7
Boron	EEA	EPA 200.7	mg/L	0.05					1		0.5		0.5
Bromide	EEA	EPA 300.0	ug/L	5									NA
Calcium	EEA	EPA 200.7	mg/L	1									NA
Chloride	EEA	EPA 300.0	mg/L	1		250					100		100
Color	EEA	SM 2120B	ACU	3		15		15					15
Conductivity	EEA	SM 2510B	umho/cm	2									NA
Cyanide	EEA	SM 4500CN-	mg/L	0.01-0.03	200								200
Fluoride	EEA	SM 4500F-C	mg/L	0.05	4	2	2				2		2
Foaming Agents	EEA	SM 5540C	mg/L	0.05		0.5		0.5					1
Hardness, Total	EEA	SM 2340B	mg/L	3									NA
Magnesium	EEA	EPA 200.7	mg/L	0.1									NA
Nitrate	EEA	EPA 300.0	mg N/L	0.05-0.1	10						10		10
Nitrate + Nitrite**	EEA	EPA 300.0	mg N/L	0.1			10						10
Nitrite	EEA	EPA 300.0	mg N/L	0.01-0.05	1		1				1		1
Odor	EEA	SM 2150B	TON	1		3		3			3		3
Organic nitrogen	CSD	SM 4500 NH3	mg N/L	1									NA
Perchlorate	EEA	EPA 314	ug/L	2			6				6		6
pH	EEA	SM 2330B	Units	0.1		6.5-8.5							6.5-8.5
Potassium	EEA	EPA 200.7	mg/L	1									NA
Sodium	EEA	EPA 200.7	mg/L	1									NA
Sulfate	EEA	EPA 300.0	mg/L	0.5		250					100		100
TDS	EEA	EPA 160.1	mg/L	10									NA
Total Organic Carbon	CSD	SM 5310C	mg/L	0.5						0.5			0.5
Total Phosphorus	EEA	SM 4500P-E	mg/L	0.02									NA
Turbidity	EEA	EPA 180.1	NTU	0.05				5		2			2
UVT, 254 nm	CSD	SM 5910	%	0									NA

*Samples with detections of cyanide were analyzed with manual distillation, which had a lower reporting limit (0.005 mg/L) than SM 4500CN-F.

**CDPH DGRR also has a limit of 10 mg N/L for total nitrogen.

Table C-7. Inorganic Samples (Trace Metals)

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DRGG	BPO	MTL	Target Conc
Aluminum	EEA	EPA 200.8	µg/L	20		50-200	1,000	200			200		50
Antimony	EEA	EPA 200.8	µg/L	1	6		6				6		6
Arsenic	EEA	EPA 200.8	µg/L	1	10		10				10		10
Barium	EEA	EPA 200.8	µg/L	2	2,000		1,000				1,000		1,000
Beryllium	EEA	EPA 200.8	µg/L	1	4		4						4
Cadmium	EEA	EPA 200.8	µg/L	0.5	5		5				5		5
Chromium (Total)	EEA	EPA 200.8	µg/L	1	100		50				50		50
Hexavalent Chromium	EEA	EPA 218.6	µg/L	0.02-0.05			-						NA
Copper	EEA	EPA 200.8	µg/L	2	1,300	1,000	1,300	1,000			1,000		130
Iron	EEA	EPA 200.7	mg/L	0.02		0.3		0.3			0.3		0.3
Lead	EEA	EPA 200.8	µg/L	0.5	15		15				15		15
Manganese	EEA	EPA 200.8	µg/L	2		50			500				50
Mercury	EEA	EPA 245.1	µg/L	0.2	2		2						2
Nickel	EEA	EPA 200.8	µg/L	5			100				100		100
Selenium	EEA	EPA 200.8	µg/L	5	50		50				50		50
Silver	EEA	EPA 200.8	µg/L	0.5		100		100			100		100
Thallium	EEA	EPA 200.8	µg/L	1	2		2						2
Vanadium	EEA	EPA 200.8	µg/L	3					50		50		50
Zinc	EEA	EPA 200.8	µg/L	20		5,000		5,000			5,000		5,000

Table C-8. Radiological Samples

	Test				EPA		CDPH						Target
Constituent	**Lab**	**Method**	**Units**	**RL**	**PMCL**	**SMCL**	**PMCL**	**SMCL**	**NL**	**DRGG**	**BPO**	**MTL**	**Conc**
Gross Alpha	EEA	EPA 900.0	pCi/L	1.61-3	15		15				15		15
Gross Beta	EEA	EPA 900.0	pCi/L	1.7-3.39	4 mrem/yr		4 mrem/yr				50		50
Radium 226	EEA	EPA 903.1	pCi/L	0.21-0.77			-						NA
Radium 228	EEA	EPA 904.0	pCi/L	0.87-0.97			-						NA
Combined Radium 226, 228	EEA	EPA 903.0	pCi/L		5		5				5		5
Radon	EEA	SM 7500RN	pCi/L	50									NA
Strontium-90	EEA	EPA 905.0	pCi/L	0.35-0.88			8				8		8
Tritium	EEA	EPA 906.0	pCi/L	194-231			20,000				20,000		20,000
Uranium	EEA	EPA 200.8	pCi/L	0.7	30		20				20		20

Table C-9a. Semi-volatile Organic Compounds

Constituent	Lab	Test Method	Units	RL	EPA		CDPH				BPO	MTL	Target Conc
					PMCL	SMCL	PMCL	SMCL	NL	DGRR			
Benzo (A) Pyrene	EEA	EPA 525.2	µg/L	0.02	0.2		0.2						0.2
Di (2-Ethylhexyl) Adipate	EEA	EPA 525.2	µg/L	0.6	400		400						400
Di (2-Ethylhexyl) Phthalate	EEA	EPA 525.2	µg/L	0.6	6		4						4
2,4,6-Trichlorophenol	CSD	EPA 625	µg/L	10									NA
P-Chloro-m-Cresol	CSD	EPA 625	µg/L	0.2									NA
2-Chlorophenol	CSD	EPA 625	µg/L	5									NA
2,4-Dichlorophenol	CSD	EPA 625	µg/L	5									NA
2-Nitrophenol	CSD	EPA 625	µg/L	10									NA
4-Nitrophenol	CSD	EPA 625	µg/L	10									NA
2,4-Dinitrophenol	CSD	EPA 625	µg/L	5									NA
4,6-Dinitro-o-Cresol	CSD	EPA 625	µg/L	2.5									NA
Benzidine	CSD	EPA 625	µg/L	5									NA
Hexachloroethane	CSD	EPA 625	µg/L	1									NA
Bis (2-chloroethyl) ether	CSD	EPA 625	µg/L	2									NA
2-chloronaphthalene	CSD	EPA 625	µg/L	10									NA
3,3'-dichlorobenzidine	CSD	EPA 625	µg/L	5									NA
2,4-dinitrotoluene	EEA	EPA 525.2	µg/L	0.1									NA
2,6-dinitrotoluene	EEA	EPA 525.2	µg/L	0.1									NA
1,2-diphenylhydrazine	CSD	EPA 625	µg/L	1									NA
4-chlorophenyl phenyl ether	CSD	EPA 625	µg/L	5									NA

Table C-9b. Semi-volatile Organic Compounds (Continued)

Constituent	Lab	Test Method	Units	RL	EPA		CDPH				BPO	MTL	Target Conc
					PMCL	SMCL	PMCL	SMCL	NL	DGRR			
4-bromophenyl phenyl ether	CSD	EPA 625	µg/L	5									NA
Bis (2-chloroisopropyl) ether	CSD	EPA 625	µg/L	2									NA
Bis (2-chloroethoxy) methane	CSD	EPA 625	µg/L	5									NA
Isophorone	EEA	EPA 525.2	µg/L	0.5									NA
Nitrobenzene	CSD	EPA 625	µg/L	1									NA
Bis (2-ethylhexyl) phthalate	EEA	EPA 525.2	µg/L	0.6									NA
Butyl benzyl phthalate	EEA	EPA 525.2	µg/L	0.5									NA
Di-n-butyl phthalate	EEA	EPA 525.2	µg/L	1									NA
Di-n-octyl phthalate	EEA	EPA 525.2	µg/L	0.1									NA
Diethyl phthalate	EEA	EPA 525.2	µg/L	0.5									NA
Dimethyl phthalate	EEA	EPA 525.2	µg/L	0.5									NA

Table C-10a. Volatile Organic Compounds

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
Benzene	EEA	EPA 524.2	µg/L	0.5	5		1						1
Bromobenzene	EEA	EPA 524.2	µg/L	0.5									NA
Bromochloromethane	EEA	EPA 524.2	µg/L	0.5									NA
Bromodichloromethane	EEA	EPA 524.2	µg/L	0.5									NA
Bromoform	EEA	EPA 524.2	µg/L	0.5									NA
Bromomethane (Methyl bromide)	EEA	EPA 524.2	µg/L	0.5									NA
sec-Butylbenzene	EEA	EPA 524.2	µg/L	0.5					260				260
n-Butylbenzene	EEA	EPA 524.2	µg/L	0.5					260				260
tert-Butylbenzene	EEA	EPA 524.2	µg/L	0.5					260				260
Carbon Tetrachloride	EEA	EPA 524.2	µg/L	0.5	5		0.5						1
Chlorobenzene	EEA	EPA 524.2	µg/L	0.5	100		70						70
Chlorodibromomethane	EEA	EPA 524.2	µg/L	0.5									NA
Chloroethane	EEA	EPA 524.2	µg/L	0.5									NA
Chloroform	EEA	EPA 524.2	µg/L	0.5									NA
Chloromethane (methyl chloride)	EEA	EPA 524.2	µg/L	0.5									NA
2-Chlorotoluene or o-Chlorotoluene	EEA	EPA 524.2	µg/L	0.5					140				140
4-Chlorotoluene or p-Chlorotoluene	EEA	EPA 524.2	µg/L	0.5					140				140
Dibromomethane	EEA	EPA 524.2	µg/L	0.5									NA
1,2-Dichlorobenzene	EEA	EPA 524.2	µg/L	0.5	600		600						600
1,3-Dichlorobenzene	EEA	EPA 524.2	µg/L	0.5	75								75

Table C-10b. Volatile Organic Compounds (Continued)

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
1,4-Dichlorobenzene	EEA	EPA 524.2	µg/L	0.5			5						5
1,2-Dichloroethane	EEA	EPA 524.2	µg/L	0.5	5		0.5				0.5		0.5
1,1-Dichloroethane	EEA	EPA 524.2	µg/L	0.5			5						5
1,1-Dichloroethene	EEA	EPA 524.2	µg/L	0.5	7		6				6		6
cis-1,2-Dichloroethene	EEA	EPA 524.2	µg/L	0.5	7		6				6		6
trans-1,2-Dichloroethene	EEA	EPA 524.2	µg/L	0.5	100		10						10
Dichlorodifluoromethane (Freon12)	EEA	EPA 524.2	µg/L	0.5					1,000				1,000
1,2-Dichloropropane	EEA	EPA 524.2	µg/L	0.5	5		5						5
1,3-Dichloropropane	EEA	EPA 524.2	µg/L	0.5									NA
2,2-Dichloropropane	EEA	EPA 524.2	µg/L	0.5									NA
1,1-Dichloropropene	EEA	EPA 524.2	µg/L	0.5									NA
1,3-Dichloropropene	EEA	EPA 524.2	µg/L	0.5			0.5						0.5
cis-1,3-Dichloropropene	EEA	EPA 524.2	µg/L	0.5									NA
trans-1,3-Dichloropropene	EEA	EPA 524.2	µg/L	0.5									NA
ETBE (Ethyl tertiary butyl ether)	EEA	EPA 524.2	µg/L	3									NA
Ethylbenzene	EEA	EPA 524.2	µg/L	0.5	700		300						300
Hexachlorobutadiene	EEA	EPA 524.2	µg/L	0.5									NA
Isopropylbenzene	EEA	EPA 524.2	µg/L	0.5									NA
p-Isopropyltoluene	EEA	EPA 524.2	µg/L	0.5									NA
Methylene Chloride (dichloromethane)	EEA	EPA 524.2	µg/L	0.5	5		5				5		5
MTBE	EEA	EPA 524.2	µg/L	0.5			13	5			5		5
Naphthalene	EEA	EPA 524.2	µg/L	0.5					17				17
n-Propylbenzene	EEA	EPA 524.2	µg/L	0.5					260				260
Styrene	EEA	EPA 524.2	µg/L	0.5	100		100						100

Table C-10c. Volatile Organic Compounds (Continued)

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
TAME (Tertiary amyl methyl ether)	EEA	EPA 524.2	µg/L	3									NA
1,1,1,2-Tetrachloroethane	EEA	EPA 524.2	µg/L	0.5									NA
1,1,2,2-Tetrachloroethane	EEA	EPA 524.2	µg/L	0.5			1						1
Tetrachloroethene	EEA	EPA 524.2	µg/L	0.5	5		5				5		5
Toluene	EEA	EPA 524.2	µg/L	0.5	1,000		150				150		150
1,2,3-Trichlorobenzene	EEA	EPA 524.2	µg/L	0.5									NA
1,2,4-Trichlorobenzene	EEA	EPA 524.2	µg/L	0.5	70		5						5
1,1,1-Trichloroethane	EEA	EPA 524.2	µg/L	0.5	200		200						200
1,1,2-Trichloroethane	EEA	EPA 524.2	µg/L	0.5	5		5						5
Trichloroethene	EEA	EPA 524.2	µg/L	0.5	5		5				5		5
Trichlorofluoromethane	EEA	EPA 524.2	µg/L	0.5			150						150
1,2,3-Trichloropropane	EEA	EPA 524.2m	µg/L	0.005			-		0.005			0.005	0.005
1,1,2-Trichloro-1,2,2-trifluoroethane (Freon 113)	EEA	EPA 524.2	µg/L	0.5			1,200				1,200		1,200
1,3,5-Trimethylbenzene	EEA	EPA 524.2	µg/L	0.5					330				330
1,2,4-Trimethylbenzene	EEA	EPA 524.2	µg/L	0.5					330				330
Vinyl Chloride	EEA	EPA 524.2	µg/L	0.3	2		0.5						0.5
Xylenes	EEA	EPA 524.2	µg/L	1	10,000		1,750						1,750
TOTAL THMs	EEA	EPA 524.2	µg/L	0.5	80		80				80		80
Acrolein	CSD	EPA 624	µg/L	2									NA
Acrylonitrile	CSD	EPA 624	µg/L	2									NA
2-chloroethyl vinyl ether	EEA	EPA 524.2	µg/L	0.5									NA

Table C-11a. Organochlorine Pesticides

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
Alachlor	EEA	EPA 525.2	µg/L	0.05	2		2					0.4	2
Aldrin	EEA	EPA 525.2	µg/L	0.05									NA
Chlordane	EEA	EPA 505	µg/L	0.1	2		0.1						0.1
Chlorothanlonil	EEA	EPA 525.2	µg/L	0.1									NA
Dieldrin	EEA	EPA 525.2	µg/L	0.2									NA
Endrin	EEA	EPA 525.2	µg/L	0.2	2		2						2
Heptachlor	EEA	EPA 505	µg/L	0.01	0.4		0.01						0.01
Heptachlor Epoxide	EEA	EPA 505	µg/L	0.01	0.2		0.01						0.01
Hexachlorobenzene	EEA	EPA 525.2	µg/L	0.05	1		1						1
Hexachlorocyclopentadiene	EEA	EPA 525.2	µg/L	0.05	50		50						50
Lindane	EEA	EPA 525.2	µg/L	0.04	0.2		0.2				0.2		0.2
Methoxychlor	EEA	EPA 525.2	µg/L	0.1	40		30						30
Polychlorinated Biphenyls	EEA	EPA 505	µg/L	0.08	0.5		0.5						0.5
Aroclor-1016 (PCB-1016)	EEA	EPA 505	µg/L	0.1									NA
Aroclor-1221 (PCB-1221)	EEA	EPA 505	µg/L	0.1									NA
Aroclor-1232 (PCB-1232)	EEA	EPA 505	µg/L	0.1									NA
Aroclor-1242 (PCB-1242)	EEA	EPA 505	µg/L	0.1									NA
Aroclor-1248 (PCB-1248)	EEA	EPA 505	µg/L	0.1									NA
Aroclor-1254 (PCB-1254)	EEA	EPA 505	µg/L	0.1									NA
Aroclor-1260 (PCB-1260)	EEA	EPA 505	µg/L	0.1									NA

Table C-11b. Organochlorine Pesticides (Continued)

					EPA		CDPH						Target
Constituent	**Lab**	**Test Method**	**Units**	**RL**	**PMCL**	**SMCL**	**PMCL**	**SMCL**	**NL**	**DGRR**	**BPO**	**MTL**	**Conc**
Propachlor	EEA	EPA 525.2	µg/L	0.05					90				90
Toxaphene	EEA	EPA 505	µg/L	0.5	3		3						3
4,4'-DDT	EEA	EPA 525.2	µg/L	0.1									NA
4,4'-DDE	EEA	EPA 525.2	µg/L	0.1									NA
4,4'-DDD	EEA	EPA 525.2	µg/L	0.1									NA
Alpha-endosulfan	EEA	EPA 525.2	µg/L	0.1									NA
Beta-endosulfan	EEA	EPA 525.2	µg/L	0.1									NA
Endosulfan sulfate	EEA	EPA 525.2	µg/L	0.1									NA
Endrin aldehyde	EEA	EPA 525.2	µg/L	0.1									NA
Delta-BHC	EEA	EPA 525.2	µg/L	0.1									NA

Table C-12. Organochlorine Herbicides

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
Bentazon (Basagran)	EEA	EPA 515.4	µg/L	0.5			18						18
2,4-D	EEA	EPA 515.4	µg/L	0.1	70		70						70
Dalapon	EEA	EPA 515.4	µg/L	1	200		200						200
Dicamba	EEA	EPA 515.4	µg/L	0.1									NA
Dinoseb	EEA	EPA 515.4	µg/L	0.2	7		7						7
Pentachlorophenol	EEA	EPA 515.4	µg/L	0.04	1		1						1
Pichloram	EEA	EPA 515.4	µg/L	0.1	500		500						500
Silvex (2,4,5-TP)	EEA	EPA 515.4	µg/L	0.2	50		50						50

Table C-13. Fumigants

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
Ethylene dibromide (EDB)	EEA	EPA 504.1	µg/L	0.01	0.05		0.05						0.05
Dibromochloropropane (DBCP)	EEA	EPA 504.1	µg/L	0.01	0.2		0.2						0.2

Table C-14. Carbamate Pesticides

Constituent	Lab	Test Method	Units	RL	EPA		CDPH				BPO	MTL	Target Conc
					PMCL	SMCL	PMCL	SMCL	NL	DGRR			
Diuron	EEA	EPA 532	µg/L	1									NA
Aldicarb	EEA	EPA 531.2	µg/L	0.5									NA
Aldicarb sulfone	EEA	EPA 531.2	µg/L	0.5									NA
Aldicarb sulfoxide	EEA	EPA 531.2	µg/L	0.5									NA
Baygon (Propoxur)	EEA	EPA 531.2	µg/L	0.5									NA
Carbofuran	EEA	EPA 531.2	µg/L	0.5	40		18						18
Carbaryl	EEA	EPA 531.2	µg/L	0.5									NA
3-hydroxycarbofuran	EEA	EPA 531.2	µg/L	0.5								0.42	NA
Methomyl	EEA	EPA 531.2	µg/L	0.5									NA
Oxamyl	EEA	EPA 531.2	µg/L	0.5	200		50						50

Table C-15. Miscellaneous Samples

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
Diquat	EEA	EPA 547	µg/L	0.4	20		20						20
Endothall	EEA	EPA 548.1	µg/L	5	100		100						100
Glyphosate	EEA	EPA 549.2	µg/L	6	700		700						700
Paraquat	EEA	EPA 547	µg/L	2									NA
Polynuclear Aromatic Hydrocarbons	EEA	EPA 525.2											NA
Acenaphthene	EEA	EPA 525.2	µg/L	0.1									NA
Fluoranthene	EEA	EPA 525.2	µg/L	0.1									NA
Benzo (a) anthracene	EEA	EPA 525.2	µg/L	0.05									NA
Benzo (b) fluoranthene	EEA	EPA 525.2	µg/L	0.02									NA
Benzo (k) fluoranthene	EEA	EPA 525.2	µg/L	0.02									NA
Chrysene	EEA	EPA 525.2	µg/L	0.02									NA
Acenaphthylene	EEA	EPA 525.2	µg/L	0.1									NA
Anthracene	EEA	EPA 525.2	µg/L	0.02									NA
1,12-benzoperylene	EEA	EPA 525.2	µg/L	0.05									NA
Fluorene	EEA	EPA 525.2	µg/L	0.05									NA
Phenanthrene	EEA	EPA 525.2	µg/L	0.04									NA
1,2,5,6-dibenzanthracene	EEA	EPA 525.2	µg/L	0.05									NA
Indeno (1,2,3-cd) pyrene	EEA	EPA 525.2	µg/L	0.05									NA
Pyrene	EEA	EPA 525.2	µg/L	0.05									NA
2,3,7,8-TCDD Dioxin	EEA	EPA 1613	pg/L	5	30		30						30

Table C-16. Nitrogen/Phosphorus Pesticides

Constituent	Lab	Test Method	Units	RL	EPA		CDPH				BPO	MTL	Target Conc
					PMCL	SMCL	PMCL	SMCL	NL	DGRR			
Atrazine	EEA	EPA 525.2	µg/L	0.05	3		1						1
Bromacil	EEA	EPA 525.2	µg/L	0.2									NA
Butachlor	EEA	EPA 525.2	µg/L	0.05									NA
Diazinon	EEA	EPA 525.2	µg/L	0.1					1.2				1.2
Dimethoate	EEA	EPA 525.2	µg/L	0.1									NA
Malathion	EEA	EPA 525.2	µg/L	0.1									NA
Metolachlor	EEA	EPA 525.2	µg/L	0.05									NA
Metribuzin	EEA	EPA 525.2	µg/L	0.05									NA
Molinate	EEA	EPA 525.2	µg/L	0.1			20						20
Prometryn	EEA	EPA 525.2	µg/L	0.05									NA
Simazine	EEA	EPA 525.2	µg/L	0.05	4		4						4
Thiobencarb (Bolero)	EEA	EPA 525.2	µg/L	0.2			70	1					1

Table C-17. Other Chemicals

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
a-Benzene Hexachloride (a-BHC)	EEA	EPA 525.2	µg/L	0.1									NA
b-Benzene Hexachloride (b-BHC)	EEA	EPA 525.2	µg/L	0.1									NA
2,4-Dimethylphenol	EEA	EPA 528	µg/L	0.2									NA
1,4-Dioxane	CSD	EPA 8270M	µg/L	0.4					1				1
Diphenamide	EEA	EPA 8140	µg/L	0.5									NA
Ethion	EEA	EPA 8140	µg/L	0.5									NA
Formaldehyde	EEA	EPA 556	µg/L	5					100				100
Isopropyl N (3-Chlorophenyl) Carbamate (CIPC)	EEA	EPA 8321	µg/L	2									NA
Methyl Isobutyl Ketone (MIBK)	EEA	EPA 524.2	µg/L	5					120				120
Methyl Parathion	EEA	EPA 525.2	µg/L	0.5									NA
Parathion	EEA	EPA 525.2	µg/L	0.1									NA
Pentachloronitro-benzene	EEA	EPA 8081	µg/L	0.05									NA
Phenol	EEA	EPA 420.4	µg/L	0.2									NA
Trithion	EEA	EPA 525.2	µg/L	0.05									NA
Captan	EEA	EPA 525.2	µg/L	0.05									NA
Chloropicrin	EEA	EPA 551.1	µg/L	0.5									NA
Tert butyl alcohol	EEA	EPA 524.2m	µg/L	2					12				12
Carbon disulfide	EEA	EPA 524.2	µg/L	0.5					160				160
Chlorate	EEA	EPA 300.1	µg/L	10					800				800
Ethylene glycol	EEA	GC-MS	µg/L	40					14,000				14,000
HMX	EEA	EPA 529	µg/L	0.1					350				350
Isopropyl benzene	EEA	EPA 524.2	µg/L	0.5					770				770
RDX	EEA	LC-MS-MS	µg/L	0.1					0.3			0.3	0.3
2,4,6-Trinitrotoluene (TNT)	EEA	EPA 529	µg/L	0.1					1				1
N-Nitrosodiphenylamine	CSD	EPA 625	µg/L	1									NA

Table C-18. Microbiology

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
Heterotrophic Plate Counts	EEA	SM 9215B	CFU/ml	1									NA
Total Coliforms	EEA	SM 9221B*	MPN/100 mL	1.1									NA
Fecal Coliforms	EEA	SM 9221B*	MPN/100 mL	1.1									NA
E. coli	EEA	SM 9221B*	MPN/100 mL	2									NA
Cryptosporidium	MWD	EPA 1623	Oocysts/10L	0.1									NA
Giardia	MWD	EPA 1623	Cysts/10L	0.1									NA
Enteric Viruses (Total Culturable Virus)	MWD	ICR 5-96	MPN/100 L	0.001-0.01									NA

*SM 9223B was used for total and fecal coliform samples taken on May 15, 2012, and for E. coli samples taken on May 15 and 22, 2012.

Table C-19. Hormones and Industrial Endocrine Disrupting Compounds

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
17β -Estradiol	CSD	*	ng/L	0.5-1.2								0.9	0.9
Bisphenol A	CSD	*	ng/L	10								350,000	350,000
Nonylphenol	CSD	*	ng/L	25								500,000	500,000
Nonylphenol Polyethoxalates	CSD	*	ng/L	25									NA
Octylphenol	CSD	*	ng/L	25								50,000	500,000
Octylphenol Polyethoxalates	CSD	*	ng/L	25									NA
Polybrominated Diphenyl Ethers	EEA	EPA 527	ug/L	0.3-0.9									NA

*There is no EPA or Standard Method for hormones and alkylphenols. Bisphenol A, nonylphenol, and octylphenol were analyzed according to Nelson *et al*. (2011). The alkylphenol ethoxylates and 17b-estradiol were analyzed according to the method described at the beginning of this appendix.

Table C-20. Pharmaceuticals, Personal Care Products, and Other Wastewater Indicators

					EPA		CDPH						Target
Constituent	**Lab**	**Test Method**	**Units**	**RL**	**PMCL**	**SMCL**	**PMCL**	**SMCL**	**NL**	**DGRR**	**BPO**	**MTL**	**Conc**
Acetaminophen	CSD	*	ng/L	10								350,000	350,000
Azithromycin	CSD	*	ng/L	10								3,900	3,900
Carbamazepine	CSD	*	ng/L	10								1,000	1,000
Dilantin	CSD	*	ng/L	25								N/A	NA
Gemfibrozil	CSD	*	ng/L	10								45,000	45,000
Ibuprofen	CSD	*	ng/L	10								34,000	34,000
Meprobamate	CSD	*	ng/L	10								260,000	260,000
Sulfamethoxazole	CSD	*	ng/L	10								35,000	35,000
Triclosan	CSD	*	ng/L	25								350	350
DEET	CSD	*	ng/L	10								2,500	2,500
Caffeine	CSD	*	ng/L	10								350	350
Iopromide	CSD	*	ng/L	30								750,000	750,000
TCEP	CSD	*	ng/L	10								2,500	2,500
Sucralose	CSD	*	ng/L	40								N/A	NA

*There is no EPA or Standard Method for these compounds, which were analyzed according to Nelson *et al*. (2011).

Table C-21. SWRCB Surrogate Parameters

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
DOC	CSD	SM 5310B	mg/L	0.5									NA
Chlorine residual	CSD	SM 4500 Cl G	mg/L	0.05									NA

Table C-22. DBPs and Nitrosamines

Constituent	Lab	Test Method	Units	RL	EPA PMCL	EPA SMCL	CDPH PMCL	CDPH SMCL	CDPH NL	CDPH DGRR	BPO	MTL	Target Conc
HAA5	MWD	SM 6251B	µg/L		60		60						60
N-Nitrosodimethylamine (NDMA)	CSD	EPA 1625	ng/L	2			-		10			10	10
N-Nitrosodiethylamine (NDEA)	CSD	EPA 1625	ng/L	2					10				10
N-Nitrosodi-n-propylamine (NDPA)	CSD	EPA 1625	ng/L	2					10				10
N-Nitrosopyrollidine (NPYR)	CSD	EPA 1625	ng/L	2								20	NA
N-Nitrosomethylethylamine (NMEA)	CSD	EPA 1625	ng/L	2									NA
N-Nitrosopiperidine (NPIP)	CSD	EPA 1625	ng/L	2									NA
N-Nitroso-n-butylamine (NDBA)	CSD	EPA 1625	ng/L	2									NA

APPENDIX D

MEMBRANE AUTOPSY REPORTS

Membrane Autopsy Report

Prepared for:

Sanitation Districts of Los Angeles County

Envirosoft WO # 04042011-1
LACSD PO # 1110075
May 18, 2011

Rev. 1

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Synopsis

Los Angeles County Sanitation Districts (LACSD) provided four sets of Hydranautics ESPA2-4040 (Low Pressure RO) membrane elements to Envirosoft for analysis. Two of the elements were the lead (SN 6008011642) and tail (SN 6008011004) RO elements from LACSD pilot UF-RO system, while the remaining two were the lead (SN 6008011637) and tail (SN 6008011167) RO elements from LACSD pilot MBR-RO system.

Examinations of the submitted RO membrane elements revealed no visually-observable evidence of physical damage. Fiberglass wraps, end caps, brine seals, and permeate tubes appeared to be in good condition. Feed and permeate spacers and glue lines were also in satisfactory mechanical condition. Performance testing of full RO elements and membrane sample coupons revealed lower than normal membrane productivities. For the UF-RO system, the tail RO element had 50% less productivity than the lead element. For the MBR-RO system, the lead element had slightly lower (17%) productivity than the tail element. Productivity performance of the RO membrane elements were all well below manufacturer specifications by 33% or more, particularly the tail RO element of the UF-RO system (66% below manufacturer specifications). Water permeability values were mostly below manufacturer specifications, with the membrane sample coupon from the UF-RO system tail RO element having the lowest water permeability (43% below manufacturer specifications).

Internal visual examinations, optical imaging, light microscope analysis, FTIR analysis, and SEM-EDS analysis indicated the presence of a thin layer of brown foulant material on the membrane surfaces of all membrane elements, with the tail RO element from the UF-RO system appearing to be most fouled. The foulant layers were composed of both organic and inorganic materials (with silicon, calcium, iron, and possibly sulfur as primary inorganic constituents). Biological examination revealed trace gram-positive bacteria in the lead RO element of the UF-RO system and possible fungi in the lead RO element of the MBR-RO system.

Results of performance testing of membrane elements and membrane sample coupons revealed lower than normal levels of salt rejection (0.2-0.7 percentage points below the RO element manufacturer specification). Fujiwara test was positive for samples taken from all of the RO membrane elements, except for those from the UF-RO system tail RO element. Positive Fujiwara test results were indicative of membrane halogenation due to membrane exposure to halogens (i.e., chlorine). It is noted that extended membrane exposure to chloramine (NH_2Cl) may lead to enhanced membrane halogenation when in the presence of Fe(II) ions[1].

Preliminary assessments of membrane cleaning suggest that foulant materials can be removed to recover RO membrane permeability to within or above manufacturer's specifications. Upon membrane cleaning, however, salt passage (i.e., salt transport coefficient) was significantly elevated (by up to 527-741% and 148-601% above manufacturer specifications for the membrane samples from the UF-RO and MBR-RO systems, respectively), suggesting that halogenated membrane areas were exposed upon the removal of foulant materials.

[1] C.J. Gabelich, J.C. Frankin, F.W.Gerringer, K.P. Ishida, I.H. Suffet, Enhanced oxidation of polyamide membranes using monochloramine and ferrous iron, J. Membr. Sci. 258 (2005) 64.

Contents

1. Work Statement

Los Angeles County Sanitation Districts (LACSD) and Metropolitan Water District of Southern California (MWDSC) have been evaluating advanced treatment of the effluent from the Joint Water Pollution Control Plant (JWPCP). Two different treatment processes were pilot tested in parallel, utilizing an UF-RO pilot system (UF: 0.04 μm, PVDF, Memcor, Siemens) and an MBR-RO pilot system (MBR: 0.04 μm, PVDF, ZeeWeed 500C, GE). Each pilot system employed an RO unit with a total of 21 RO membrane elements (Hydranautics ESPA2-4040), arranged in 2:1 array configuration with 7 elements per series per stage. In each RO unit, antiscalant treatment (King Lee PreTreat Plus 0100) and RO feed water pH adjustment (to pH ~6.5 with sulfuric acid) were employed to mitigate membrane mineral scaling. Chloroamine residual (3-4 ppm) was maintained in the RO feed streams in order to control biofouling. Each RO unit was operated at a target water recovery level of 85%.

Envirosoft was retained by LACSD to manage the autopsy of four RO elements from the pilot systems. Both the MF-RO and the MBR-RO pilot systems were shut down on April 4, 2011. Two representative RO membrane elements (a lead element from the 1st RO unit stage and the tail element from the 2nd RO unit stage) from each pilot system were removed and provided to Envirosoft. This report summarizes the membrane autopsy results.

2.Summary of Results & Analysis

2.1. Membrane Autopsy Results

The pilot UF-RO and MBR-RO systems were shut down in the morning of April 4, 2011. From the RO unit of each system, a lead RO membrane element in the 1st RO unit stage and the tail membrane element in the 2nd RO unit stage were removed from the RO pressure vessels and submitted for autopsy. The RO elements were all Hydranautics ESPA2-4040 (Size: 4" x 40").

Table 1. Submitted RO membrane elements.

No	System	RO Element Position	Serial No. (SN)
1	UF-RO	Lead	6008011642
2	UF-RO	Tail	6008011004
3	MBR-RO	Lead	6008011637
4	MBR-RO	Tail	6008011167

2.1.1. External visual examination

Element weight

The RO elements were weighed prior to the autopsy given that RO element weight is often indicative of the degree of fouling. The lead (SN 6008011642) and tail (SN 6008011004) RO elements from the UF-RO system were of 9 pounds weight each. The lead (SN 6008011637) and tail (SN 6008011167) RO elements from the MBR-RO system were of weights 9 and 8 pounds, respectively. New RO elements of this type typically weigh 7-9 pounds.

Fiberglass wrap

The outer fiberglass casing of the membrane elements appeared to be in good condition, with no apparent sign of physical damage. They appeared to be relatively clean (**Fig. 1**), except for the tail RO element from the UF-RO system (**Fig. 2**).

Brine seal

The brine seals were inspected on site. They were in good condition and showed no signs of damage that could allow bypass of the NF/RO concentrate water around the spiral wound membrane scrolls.

End-caps / Anti-telescoping device (ATD)

ATDs are designed to prevent telescoping of element leaves at normal differential pressures. There were no visible signs of physical damage (**Fig. 3**).

Permeate tube

There was no visible physical damage on the ends of the permeate tubes that could allow by-pass of feed water (**Fig. 3**).

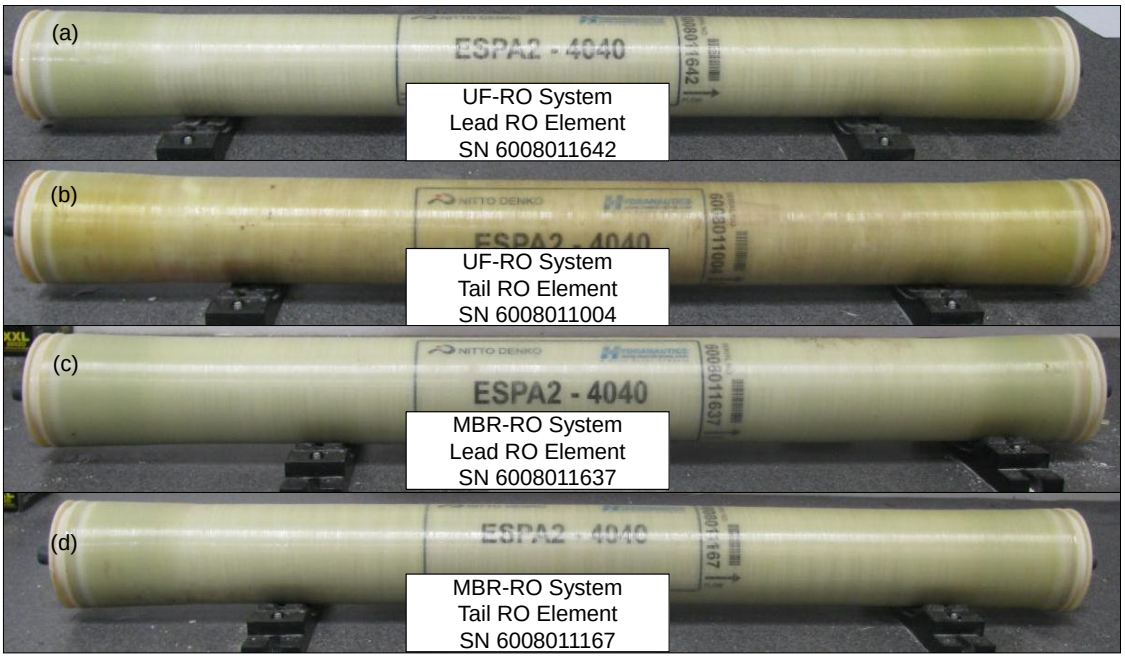


Figure 1. Photograph of submitted RO membrane elements.

Figure 2. Photograph (taken on site) of the tail RO element from the UF-RO system.

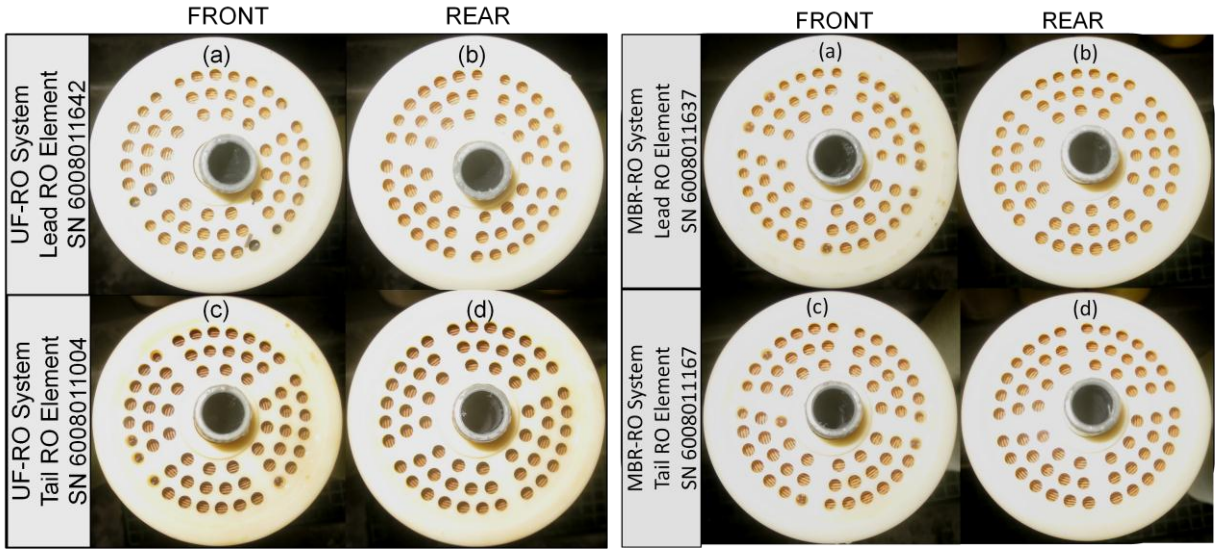


Figure 3. Photographs of the front and rear ends of the lead and tail RO elements.

2.1.2. Membrane element performance

Performance the RO elements was tested at 15% water recovery and net driving pressure of 133.5 psig, employing de-chlorinated city water (~1000 μS). The normalized permeate flow and salt rejection of the membrane element represents the overall (average) performance of the entire membrane element, including the membrane sheets, the effect of channel spacers, as well as the integrity of internal element flow connections and fluid channels.

The results below (**Table 2**) indicated that the normalized permeate flows of all of the membrane elements were significantly below manufacturer's specifications by 33%-66%; the tail RO element from the UF-RO system had the lowest normalized permeate flow. The normalized salt rejection levels were slightly below manufacturer's specifications (by 0.2%-0.7%). The differential pressure drop levels were in the normal range of 3-5 psid, indicating that there was no significant blockage of the RO retentate channels.

Table 2. Results of RO membrane element performance testing

Element	System	Permeate Flow, gpm	Salt Rejection, %	Differential Pressure Drop, psid
Lead SN 6008011642	UF-RO	0.74	99.2	3
Tail SN 6008011004	UF-RO	0.37	98.7	3
Lead, SN 6008011637	MBR-RO	0.49	98.7	3
Tail, SN 6008011167	MBR-RO	0.59	99.0	3
Manufacturer's Specifications		**1.1-1.3**	**99.4-99.6**	**3-5**

Internal visual examination

The membrane elements were dissected and unrolled. Direct visual examination (**Figs. 4-5**) revealed that exposed RO membrane surfaces had brown stains that were indicative of thin membrane fouling layers. The brown stains were darker on the tail RO elements, especially the tested element from the UF-RO system (**Fig. 4**).

Feed spacers

Feed spacers are plastic net material (Vexar) designed to separate membrane leaves to form a thin channel for feed flow. Feed spacers in all of the membrane elements were clean without visual traces of foreign material.

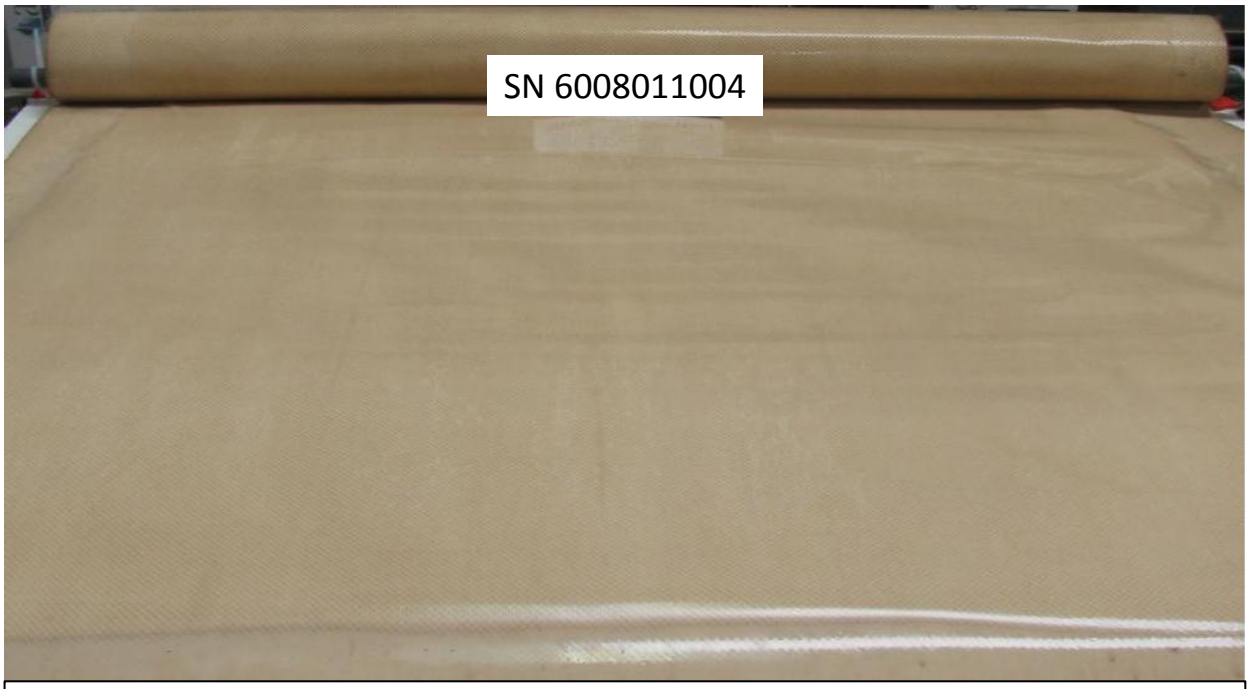
Permeate spacers

Permeate spacers are typically made of Tricot material and provide a porous channel for permeate flow into a central permeate collection tube. Damage of tricot material can increase permeate-side pressure losses. Tricot material was found to be in good condition in all membrane elements.

Glue lines

For all of the membrane elements, the glue lines at the edges of membrane leaves, which separated feed and permeate channels, were in good condition and showed no signs of pouching or delamination.

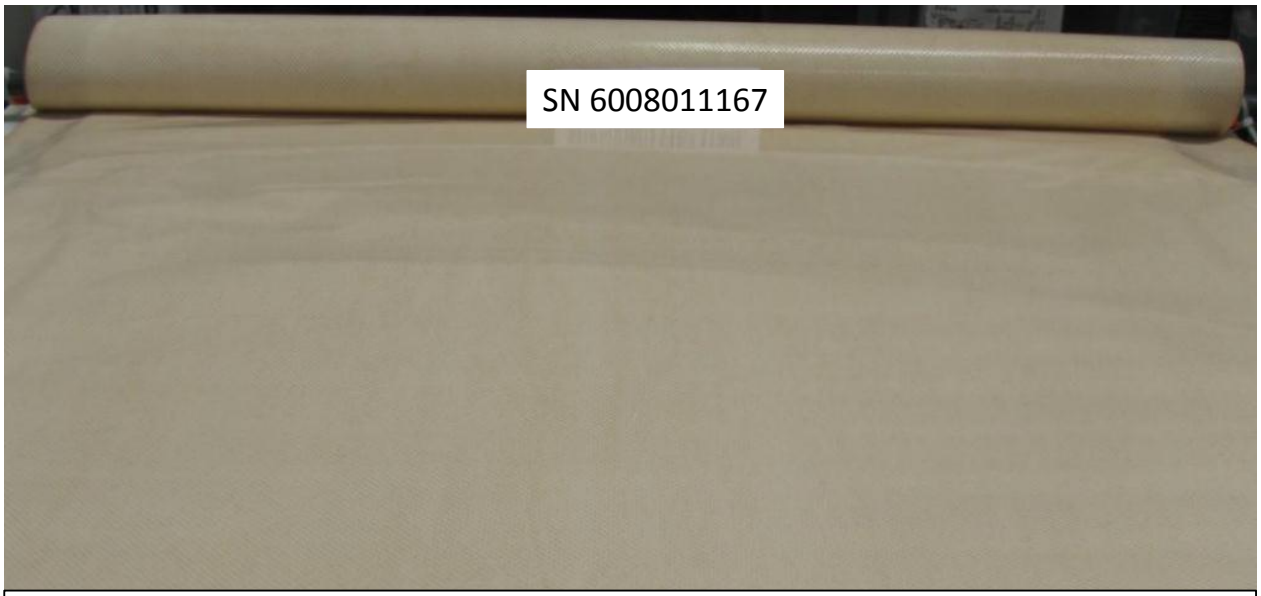
UF-RO System, Lead RO Element



UF-RO System, Tail RO Element

Figure 4. Internal view of the lead and tail RO elements from the UF-RO system.

MBR-RO System, Lead RO Element



MBR-RO System, Tail RO Element

Figure 5. Internal view of the lead and tail RO elements from the MBR-RO system.

2.1.3. Membrane coupon sampling and storage

For each membrane element, membrane coupons were sampled from several locations as indicated in the example shown in **Fig. 6**. The membranes were stored in sealed plastic bags and kept refrigerated before subsequent testing.

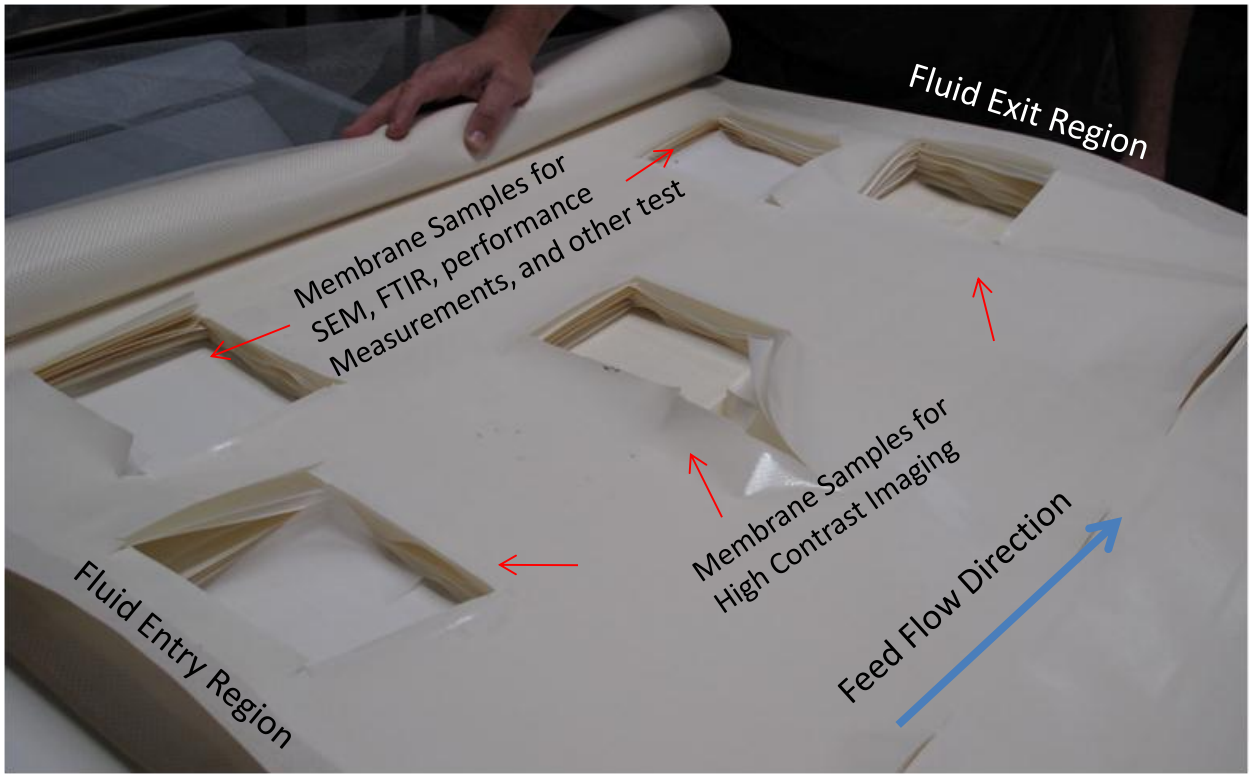


Figure 6. Example locations of membrane coupon sampling.

2.1.4. Optical Imaging

The surfaces of membrane samples taken near the fluid entrance (front), midsection (middle), and exit (rear) regions of each membrane element (see **Fig. 6**) were imaged optically. Color images were taken under white LED lighting. High-contrast, grayscale images were taken utilizing a special imaging method in order to enhance the contrast of difficult-to-see membrane surface features.

Optical images of membrane samples from the UF-RO systems are shown in **Figs 7-8**. Color images reveal membrane surface discolorations, particularly the surfaces of membrane samples taken from the tail RO element (**Fig. 7**); these discolorations could be due to organic fouling. Toward the rear end of the tail RO element, trace level presence of powdery material was apparent from high contrast images (**Fig. 8**). For all membrane samples taken from the UF-RO system, embossed patterns resembling that of the permeate carrier material were apparent, suggesting the occurrence of membrane compaction – the deformation of the membrane and

membrane backing material under pressure. Embossing of the membrane backing into the permeate (Tricot) carrier material can result in increased pressure losses on the permeate side of the elements.

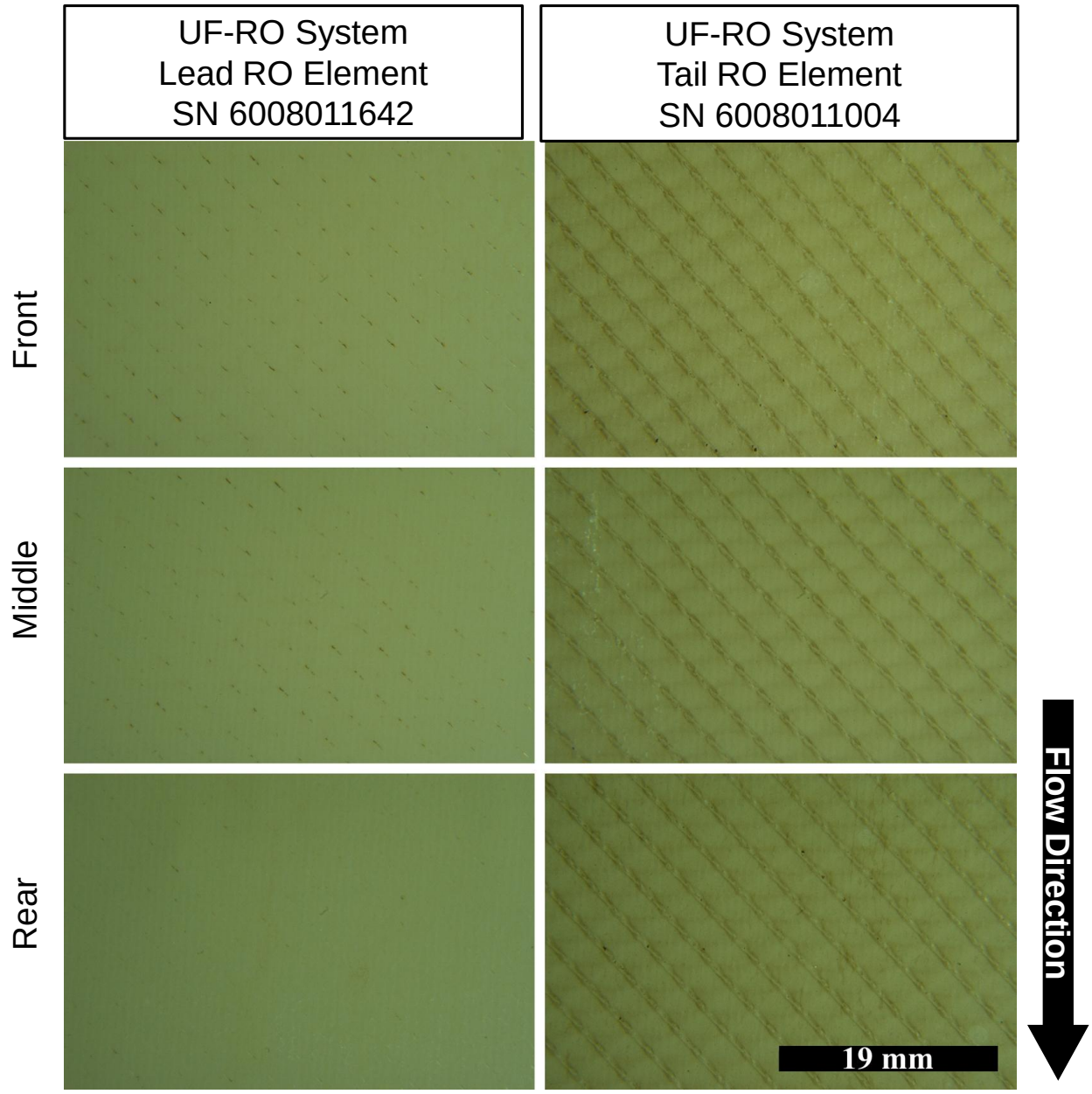


Figure 7. Color surface images of membrane samples taken from various locations in the lead and tail RO membrane elements from the UF-RO system.

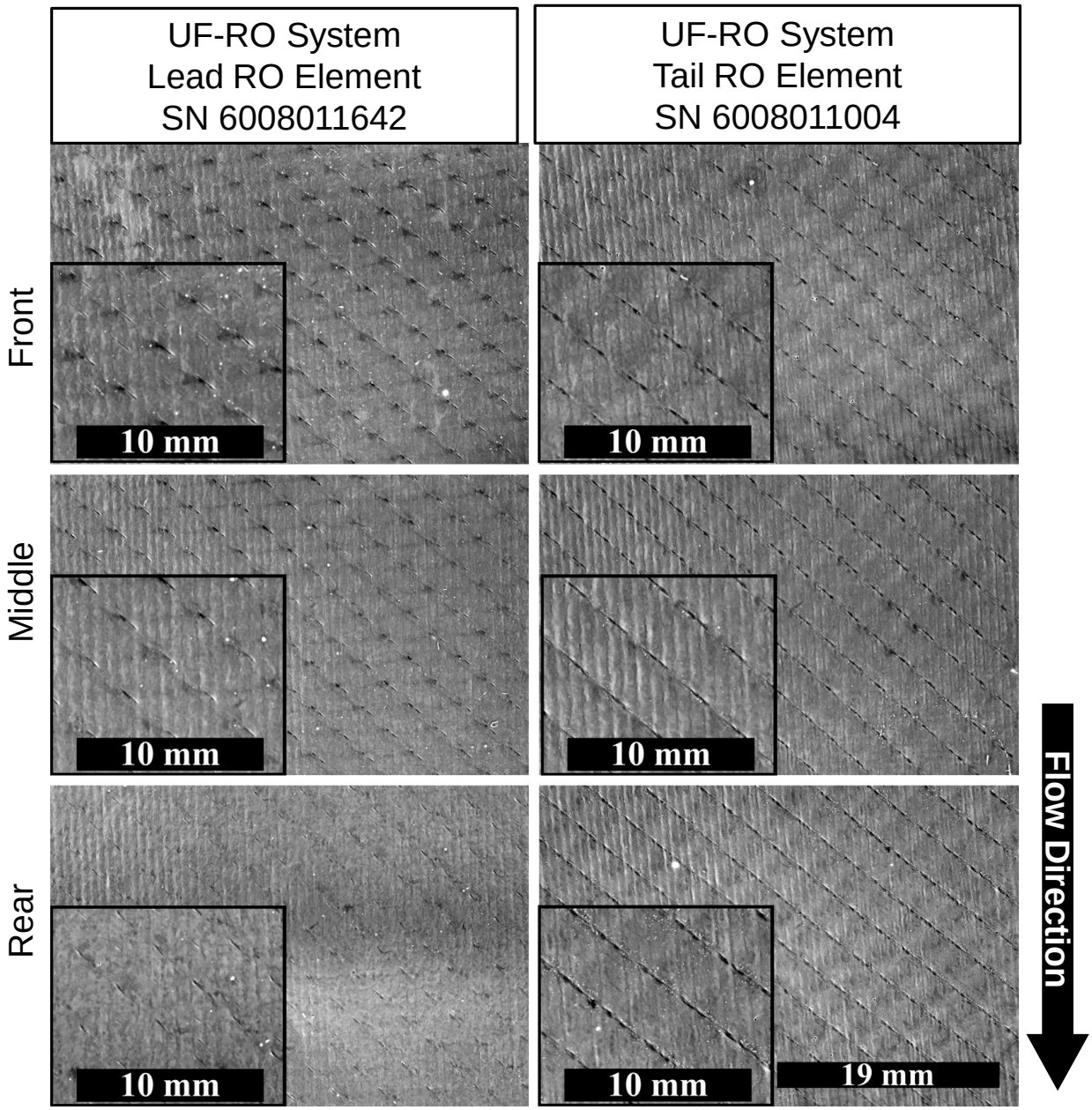


Figure 8. High-contrast surface images of membrane samples taken from various locations in the lead and tail RO membrane elements from the UF-RO system.

Optical images of membrane samples from the MBR-RO systems are shown in **Figs 9-10**. Membrane surface discolorations were apparent and were most pronounced on samples taken from the tail RO element. High contrast images also revealed trace level of powdery materials toward the rear end of the tail RO element (**Fig. 10**). Embossed patterns on the surfaces of the membrane samples suggest significant occurrence of membrane compaction (**Fig. 10**).

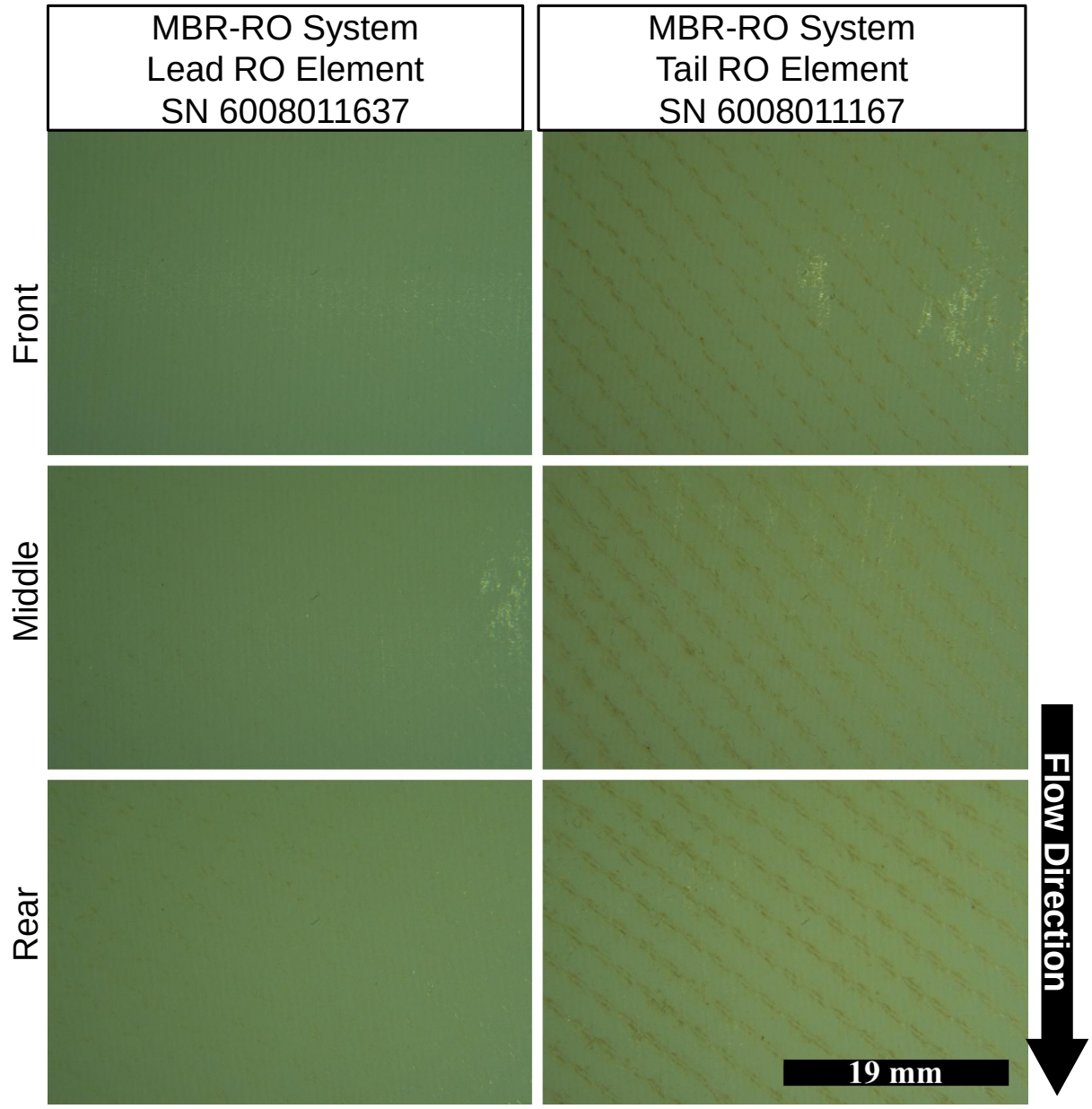


Figure 9. Color surface images of membrane samples taken from various locations in the lead and tail RO membrane elements from the MBR-RO system.

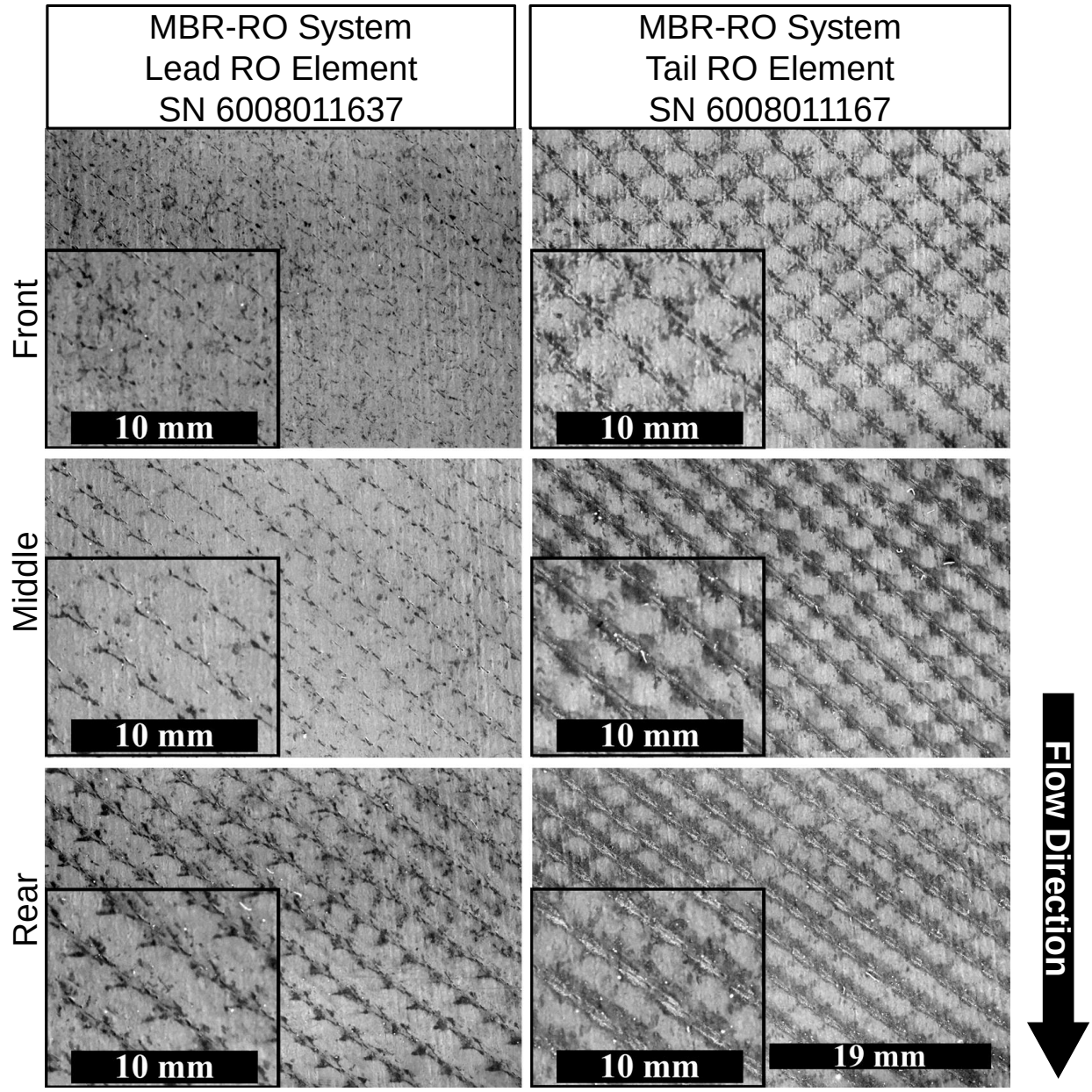


Figure 10. High-contrast surface images of membrane samples taken from various locations in the lead and tail RO membrane elements from the MBR-RO system.

2.1.5. Fujiwara test

The Fujiwara test is a qualitative test that detects the presence of chemically bound halogen compounds on the membrane surface. The Fujiwara test results were positive for all membrane samples, *except* for the sample taken from the tail RO element of the UF-RO system. Halogenated membrane surface is indicative of chemical transformation occurring at the membrane surface due to exposure to chemical oxidants (e.g., free chlorine), which may affect membrane salt-rejection performance. It is noted that polyamide membranes have low tolerance

to free chlorine (about 1000 ppm-h). Polyamide membranes tolerance to chloramine can be significantly higher (about 300,000 ppm-h); however, membrane exposure to chloramine may lead to enhanced membrane halogenation in the presence of certain ions (e.g., Fe(II))[2]. Finally, one should note that a positive Fujiwara test does not quantify the extent of membrane damage, but merely suggests the occurrence of membrane surface halogenation.

Table 3. Fujiwara test results.

Element	System	Fujiwara Test Result
Lead (SN 6008011642)	UF-RO	Positive (+)
Tail (SN 6008011004)	UF-RO	Negative (-)
Lead (SN 6008011637)	MBR-RO	Positive (+)
Tail (SN 6008011167)	MBR-RO	Positive (+)

2.1.6. FTIR analysis

FTIR analysis was conducted using a Perkin Elemer 1600 FT-IR system with a HATR (ZnSe crystal) attachment. FTIR analysis (**Fig. 11-12**) showed peaks associated with O-H, N-H, C=O, amides, C-O, C-N groups. These groups are consistent with the polyamide active layer of the RO membranes. It is noted that the C=O and C-O stretches are also expected if polysaccharides, organic proteins, and carbohydrates from organic foulants are on the membrane surface.

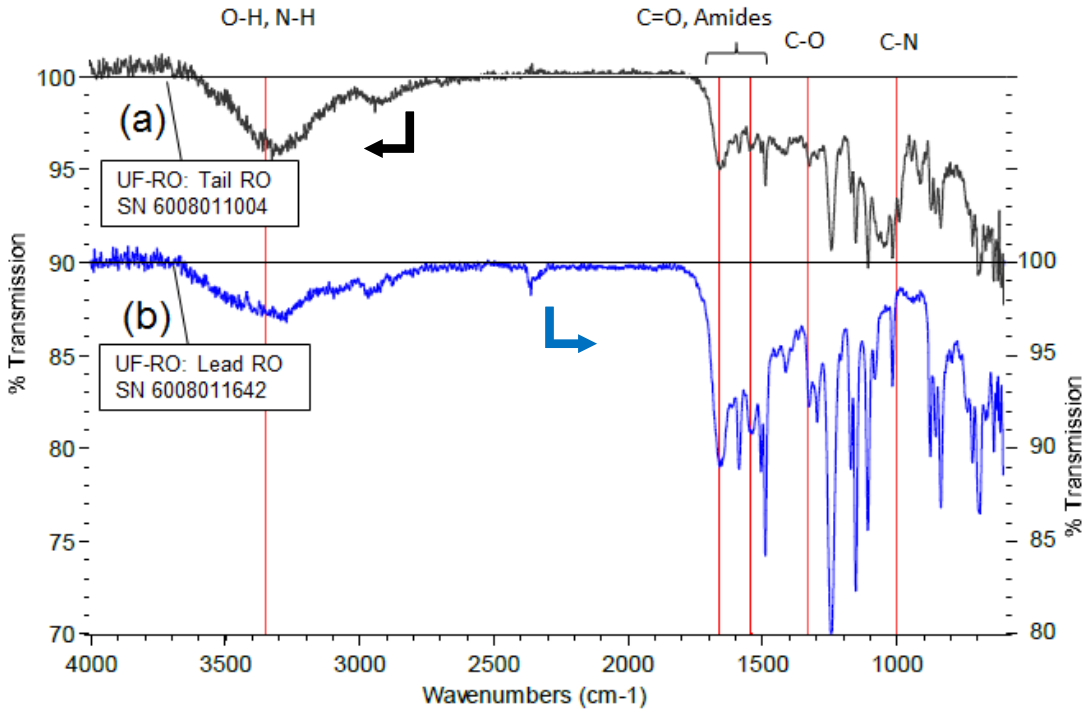


Figure 11. FT-IR spectral image of membrane surface samples from the UF-RO system.

[2] C.J. Gabelich, J.C. Frankin, F.W.Gerringer, K.P. Ishida, I.H. Suffet, Enhanced oxidation of polyamide membranes using monochloramine and ferrous iron, J. Membr. Sci. 258 (2005) 64.

There appears to be a noticeable difference between the FTIR spectra of membrane samples taken from the lead and the tail RO elements of the UF-RO system (**Fig. 11**). Specifically, IR peaks for the tail RO element membrane samples appeared to be pronounced, relative to those of the lead RO element membrane samples, at wavenumbers in the range of 950-1170 cm^{-1}, while reduced at other wavenumber range. Given that the membrane surfaces of the tail RO element membrane samples were most stained (**Fig. 7**), the pronounced IR peaks may be indicative of organic fouling, possibly polysaccharides and/or polysaccharide-like substances. However, FTIR analysis alone is insufficient to provide a definitive chemical identification.

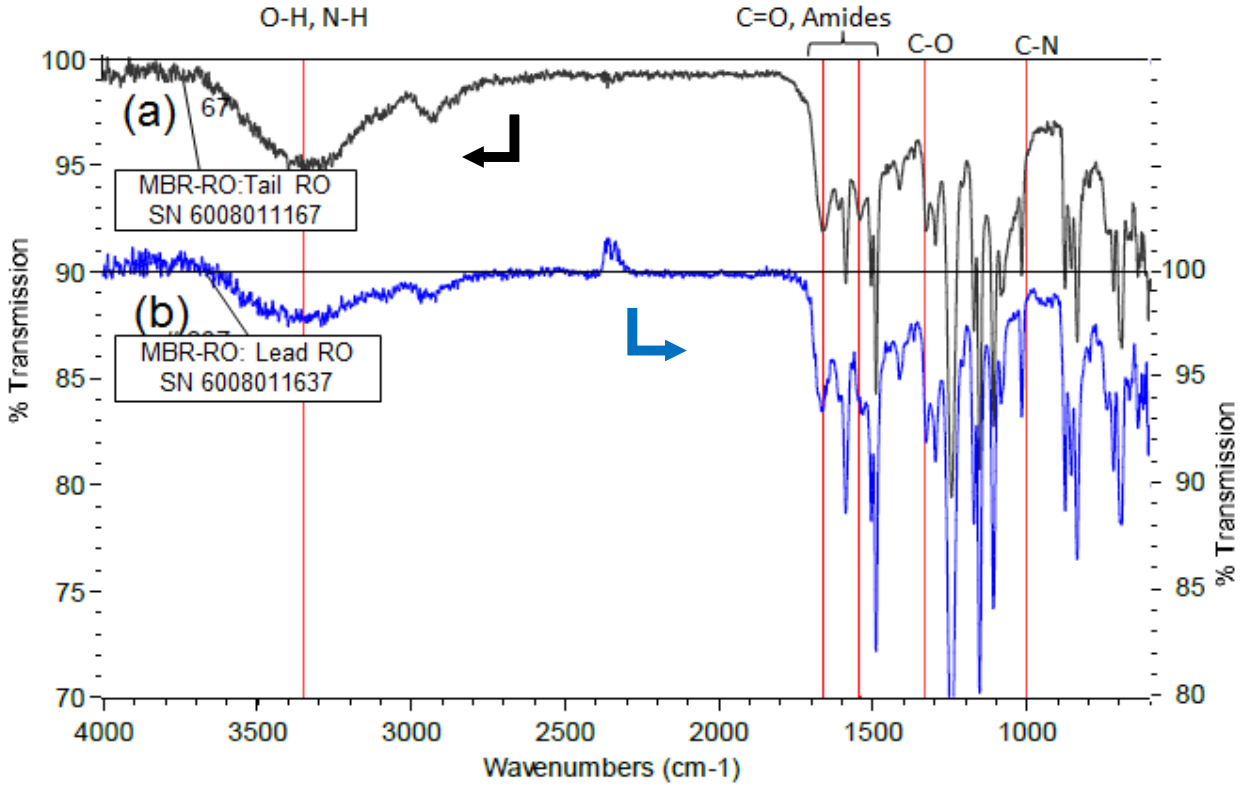


Figure 12. FT-IR spectral image of membrane surface samples from the MBR-RO system.

2.1.7. Light Microscope Analysis and Bacteria Gram Staining Test

Foulant samples were collected, stained, and examined with a light microscope. Gram positive bacteria are stained blue while Gram negative bacteria are stained red. For the UF-RO system, Gram Positive bacteria were visible for the lead RO element membrane sample (**Fig. 13a**). In the tail RO element, the foulant material appeared amorphous; there was no definitive indication of bacterial presence in the tail RO element membrane samples (**Fig. 13b**).

For the MBR-RO system, the image of **Fig. 14a** indicated possible presence of fungi in the lead RO element membrane samples. In the tail RO element, foulant materials appeared amorphous; there was no definitive indication of bacterial presence in the tail RO element membrane samples (**Fig. 14b**) .

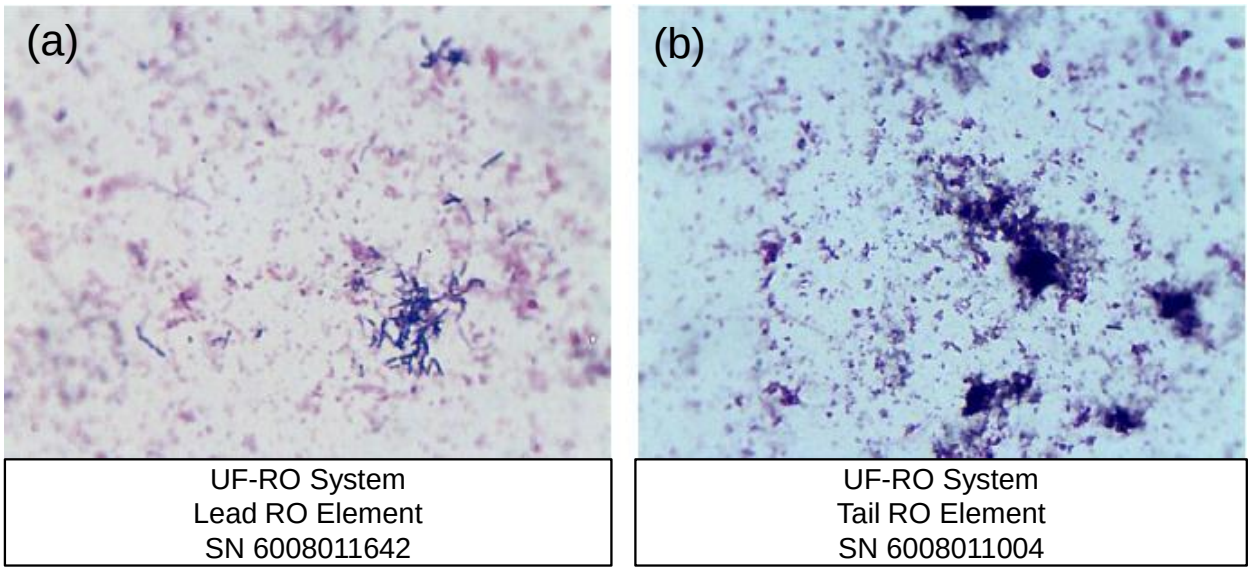


Fig. 13. Light microscope image (1000X) of gram-stained foulant samples from the (a) lead and (b) tail RO elements of the MBR-RO system.

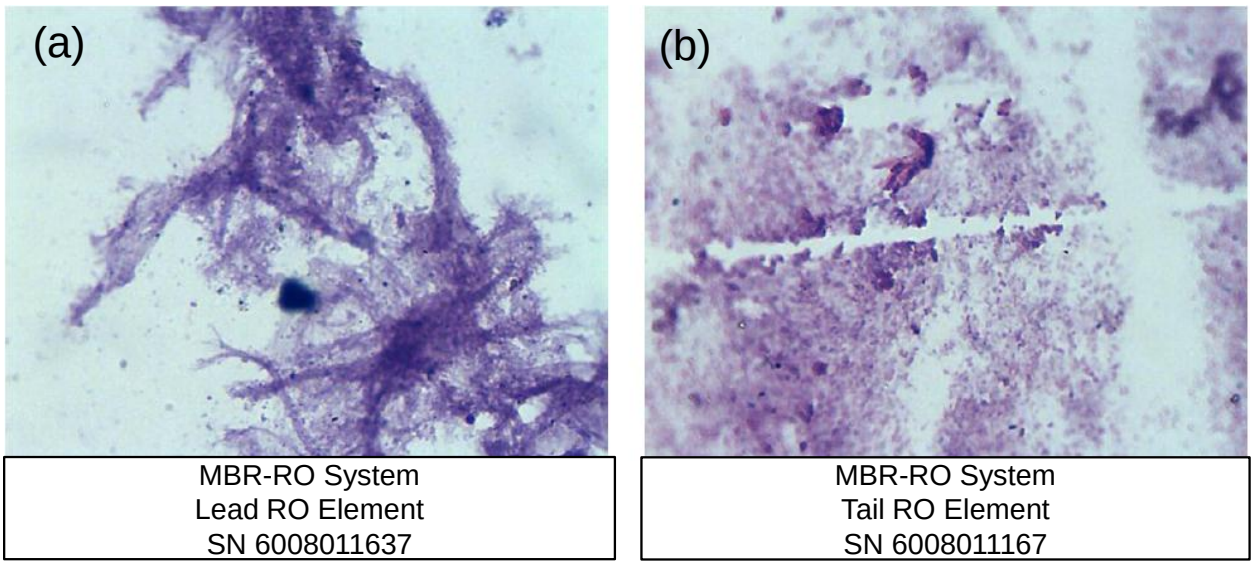


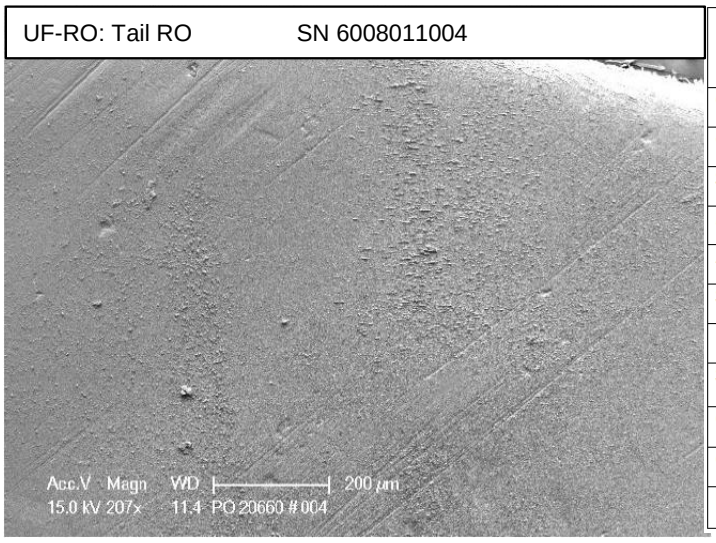
Fig. 14. Light microscope image (1000X) of gram-stained foulant samples from the (a) lead and (b) tail RO elements of the MBR-RO system.

2.1.8. SEM-EDS analysis

SEM/EDS analysis was conducted using Philips XL30 FEG Field Emission Microscope with an EDAX attachment for elemental analysis via energy dispersive X-ray spectroscopy (EDS). SEM images of the membrane samples are shown in **Figs. 15-16** for membrane samples from the UF-RO system and in **Figs. 17-18** for membrane samples from the MBR-RO system. SEM images suggest thin foulant layer on the membrane surfaces (**Fig. 15** and **Fig. 18**), as well as some powdery materials (**Figs. 16-17**). EDS analysis suggest that inorganic foulant constituents were primarily silicon, iron, and calcium. Sulfur also appeared as a major constituent, but may also originate from the sulfur content of the RO membrane polysulfone support layer. At the level of EDS sensitivity, it is likely that the detected carbon and oxygen were due to interferences from the RO membrane (i.e., polyamide active layer on top of polysulfone and polyester backing).

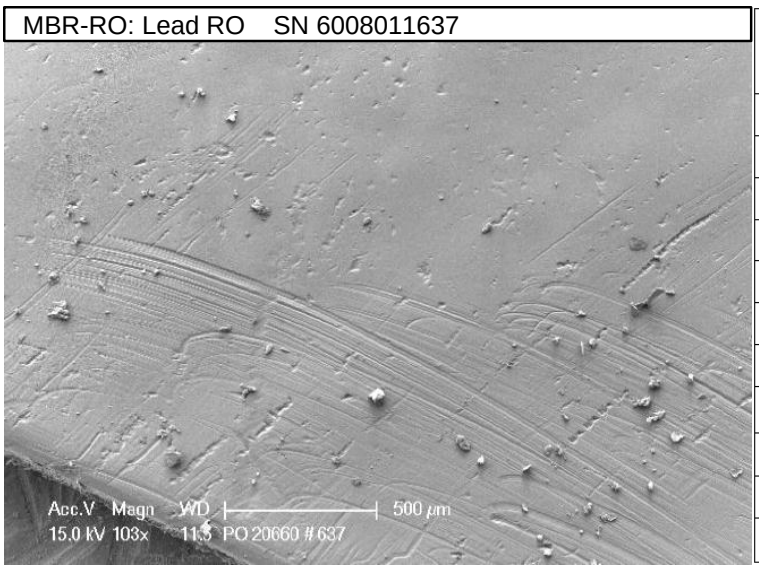
Elements (wt. %)	Lead Element SN# 6008011642
Carbon	59.5
Oxygen	25.1
Sodium	0.4
Magnesium	0.5
Aluminum	<0.2
Silicon	1.8
Phosphorous	<0.2
Sulfur	9.0
Chlorine	2.2
Calcium	0.7
Iron	1.0

Figure 15. SEM image and EDS microanalysis of membrane surface from the lead RO element membrane samples of the UF-RO system.



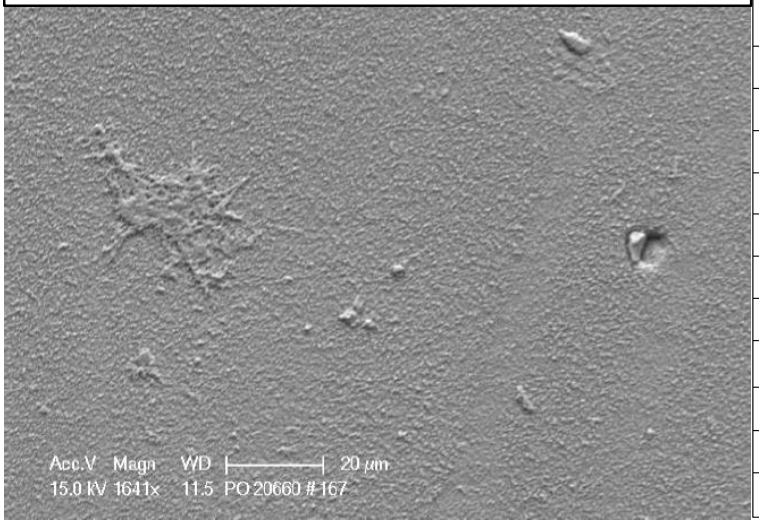
Elements (wt. %)	Tail Element SN# 6008011004
Carbon	63.0
Oxygen	23.5
Sodium	0.3
Magnesium	0.4
Aluminum	<0.2
Silicon	1.5
Phosphorous	<0.2
Sulfur	9.5
Chlorine	1.5
Calcium	0.4
Iron	0.7

Figure 16. SEM image and EDS microanalysis of membrane surface from the tail RO element membrane samples of the UF-RO system.



Elements (wt. %)	Lead Element SN# 6008011637
Carbon	62.0
Oxygen	26.1
Sodium	0.3
Magnesium	0.4
Aluminum	<0.2
Silicon	1.0
Phosphorous	<0.2
Sulfur	7.8
Chlorine	1.2
Calcium	0.5
Iron	0.5

Figure 17. SEM image and EDS microanalysis of membrane surface from the lead RO element membrane samples of the MBR-RO system.



Elements (wt. %)	Tail Element SN# 6008011167
Carbon	65.0
Oxygen	23.5
Sodium	0.3
Magnesium	0.4
Aluminum	<0.2
Silicon	1.1
Phosphorous	<0.2
Sulfur	8.5
Chlorine	1.3
Calcium	0.3
Iron	0.4

Figure 18. SEM image and EDS microanalysis of membrane surface from the tail RO element membrane samples of the MBR-RO system.

2.1.9. Membrane sample coupons performance

Membrane performance (water permeability and salt transport coefficient) using membrane sample coupons from the RO elements was evaluated using dechlorinated tap water (~1000 µS), before and after membrane cleaning. Cleaning of membrane sample coupons were conducted for initial assessments of membrane cleaning feasibility. Membrane cleaning involved a sequence of low pH (2.5-3.5) and high pH cleaning (10.5-11.5) for 60 minutes in each step.

Except for the sample from the UF-RO system lead RO element, water permeability for all membrane samples prior to cleaning were well below manufacturer's specifications (by 43% for the tail element sample from the UF-RO system and 19-31% for the samples from the MBR-RO system). Salt transport coefficient values prior to cleaning were either slightly below (UF-RO system tail element), within (MBR-RO lead element), or above specifications (UF-RO lead element and MBR-RO tail element). Upon membrane cleaning, water permeability was recovered for all membrane sample coupons to within or above manufacturer's specifications. Salt transport coefficient values, however, were elevated significantly above the manufacturer specifications after membrane cleaning (by up to 527-741% for the samples from the UF-RO system and 150-501% for the samples from the MBR-RO system). Elevated salt transport coefficient may suggest that damaged areas of the membranes were exposed once the foulant layer was removed by cleaning.

Table 4. Performance of membrane sample coupons before and after membrane cleaning.

Source of Membrane Sample		**Water Permeability (10^{-8} m/s/kPa)**	**Salt Transport Coeff. (10^{-8} m/s)**
UF-RO System: Lead RO Element	Pre-Clean	1.04	11.6
SN 6008011642	Post-Clean	2.04	41.3
UF-RO System: Tail RO Element	Pre-Clean	0.58	2.97
SN 6008011004	Post-Clean	1.46	30.8
MBR-RO System: Lead RO Element	Pre-Clean	0.70	4.04
SN 6008011637	Post-Clean	1.39	34.4
MBR-RO System: Tail RO Element	Pre-Clean	0.82	7.59
SN 6008011167	Post-Clean	1.49	12.2
Manufacturer's specifications		**1.01-1.36**	**3.63-4.91**

In comparing the results of membrane sample coupon testing with membrane element testing (**Section 2.1.2**), one should note that membrane sample coupon testing is a more sensitive test for quantifying membrane sheet performance. The results of membrane sample coupon testing only represents membrane performance in specific sections of the membrane element (see **Fig. 6**). However, membrane sample coupon testing excludes the impact of flow channel integrity of the membrane element, as well as the effect of flow channel spacers. Therefore, testing of small membrane area (from membrane sample coupons) should not be taken as representative of the whole membrane element test. Tests with small sections of the membrane serve as indicators of potential performance problems that may develop over time and thus are useful for evaluation and optimization of process conditions.

2.1.10. Other tests

The following tests could not be conducted due to insufficient foulant material on the surfaces of the membrane samples: (a) Loss on ignition, and (b) Ion analysis on digested sample coupons.

2.2. Membrane Scaling Tendency

Membrane autopsy results, as described in **Section 2.1**, indicated the presence of organic fouling, as well as some inorganic constituents (silicon, iron, calcium, and possibly sulfur). In order to evaluate the relevance of the membrane autopsy results, water quality data of the pilot RO systems' feed streams (obtained from LACSD; **Table A1**) were employed to assess the membrane scaling tendency.

Typically, membrane scaling tendency (for the majority of sparingly soluble mineral salts) is assessed in terms of a thermodynamic saturation index, $SI_x = IAP/K_{sp,x}$, where *IAP* is the ion activity product and $K_{sp,x}$ is the solubility product for a mineral salt *x*. If the stream in the RO retentate fluid channel is supersaturated with respect to one or more mineral scalants (i.e., $SI_x>1$), mineral scale may form and block RO membrane surfaces, which would lead to permeate flux decline and eventually shortening of membrane useful life. In the present analysis, RO concentrate saturation indices were estimated based on the average, minimum, and maximum concentration levels of ionic species in the feed UF filtrate and MBR permeate of the UF-RO and MBR-RO systems (**Table A1**; see **Appendix A**), multiplied by the ion concentration factor (CF) of the RO concentrate streams (CF=6.39 at RO recovery level of 85% and nominal salt rejection of 97%). For the purpose of these calculations, pH levels in the RO concentrate were estimated to be at pH ~7.5. Dissolved sulfide (HS^-) concentration in the RO feed streams, per information provided by LACSD, was estimated to be at the limit of detection. (0.1 mg/L). One should note that membrane scaling tendency assessment based on SI_x does not take into account the kinetics of scale formation. In other words, supersaturation (SI_x >1) is a necessary but not a sufficient condition for scale formation. Antiscalant treatment, for example, can effectively retard mineral scale formation (by affecting the kinetics of crystal nucleation and growth), thereby allowing the RO process to operate under supersaturated conditions (SI_x>1). Antiscalant treatment, however, is only effective up to limited supersaturation levels (SI_x), depending on the mineral scalant type, antiscalant type and dose, and RO operating conditions.

The calculation results (**Tables 5-6**) confirmed that the RO concentrate streams of the UF-RO and MBR-RO systems were supersaturated (SI_x >1) with respect SiO_2, $Fe(OH)_3$, FeS, consistent with the results of EDS microanalysis which indicated the presence of silicon, iron, and sulfur on the surfaces of the membrane samples (**Figs. 15-18**). The presence of trace calcium on the surfaces of the membrane samples (**Figs. 15-18**) may be due to $CaCO_3$, consistent with the slight supersaturation of the RO concentrate streams with respect to $CaCO_3$ (**Tables 5-6**). The presence of sulfur (**Figs. 15-18**) would be unlikely to originate from gypsum scaling ($CaSO_4 \cdot 2H_2O$; **Tables 5-6**) as the RO concentrate was consistently below saturation with respect to gypsum.

Table 5. Mineral salt saturation indices of RO concentrate, estimated based on water quality data of UF filtrate in the pilot UF-RO system (**Table A1**). RO Concentrate pH was estimated at 7.5.

Ion concentration level	Average	Minimum	Maximum
Mineral Salt	**Saturation Index**		
$Fe(OH)_3$[(a)]	458	380	650
FeS[(b)]	120	103	176
$CaCO_3$	54	53	52
$BaSO_4$	34	31	28
CaF_2	13	4.6	65
SiO_2	1.3	1.1	1.5
$Ca_3(PO4)_2$	-	-	132
$Al(OH)_3$	-	-	75
$CaSO_4 \cdot 2H_2O$	0.26	0.20	0.31

(a) when dissolved iron is primarily in the form of Fe^{+3}.
(b) when dissolved iron is primarily in the form of Fe^{+2} and RO feed dissolved sulfide concentration is at the detection limit of 0.1 mg/L.

Table 6. Mineral salt saturation indices of RO concentrate, estimated based on water quality data of MBR permeate in the MBR-RO system (**Table A1**). RO Concentrate pH was estimated at 7.5.

Ion concentration level	Average	Minimum	Maximum
Mineral Salt	**Saturation Index**		
$Fe(OH)_3$[(a)]	382	266	536
FeS[(b)]	167	126	230
$CaCO_3$	14	14	12
$BaSO_4$	39	36	31
CaF_2	19	6	92
SiO_2	1.3	1.2	1.4
$Ca_3(PO4)_2$	-	-	32
$Al(OH)_3$	-	-	139
$CaSO_4 \cdot 2H_2O$	0.31	0.26	0.35

(a) when dissolved iron is primarily in the form of Fe^{+3}.
(b) when dissolved iron is primarily in the form of Fe^{+2} and RO feed dissolved sulfide concentration is at the detection limit of 0.1 mg/L.

3. Conclusions

a) Examinations of the submitted RO membrane elements did not reveal visually-observable evidence of physical damage (e.g., glue line failure or delamination).

b) Lower than normal membrane productivities were evident based on performance testing of full RO elements and membrane sample coupons. For the UF-RO system, the tail RO element had 50% lower productivity than the lead element. For the MBR-RO system, the lead element had slightly lower (17%) productivity than the tail element. Performance of the RO membrane elements was well below manufacturer specifications (for all elements) by 33% or more, particularly the tail RO element of the UF-RO system (66% below specifications). Water permeabilities were mostly below manufacturer's specifications, with the membrane sample coupon from the UF-RO system tail RO element having the lowest water permeability (43% below manufacturer specifications).

c) Internal visual examinations, optical imaging, light microscope analysis, FTIR analysis, and SEM-EDS analysis of the membrane surfaces indicated the presence of thin layer of brown foulant materials on the membrane surfaces of all membrane elements, with the tail RO element from the UF-RO system appearing to be most fouled. The foulant layers appeared to be composed of both organic and inorganic materials (with silicon, calcium, iron, and possibly sulfur as primary inorganic constituents). Biological examination revealed trace gram-positive bacteria in the lead RO element of the UF-RO system and possible fungi in the lead RO element of the MBR-RO system.

d) Results of performance testing of membrane elements and membrane sample coupons revealed lower than normal levels of salt rejection (0.2%-0.7% below the RO element manufacturer's specification). Fujiwara test was positive for the presence of halogen (i.e., chlorine) on the membranes samples from all of the RO membrane elements, except for those taken from the UF-RO system tail RO element.

e) Preliminary assessment of membrane cleaning suggest that foulant materials can be removed to recover RO membrane permeability to within or above manufacturer's specifications. However, cleaning resulted in elevation of the salt passage (i.e., salt transport coefficient) by up to 527-741% and 148-601% above manufacturer specifications for the membrane samples from the UF-RO and MBR-RO systems, respectively, suggesting that halogenated membrane areas were exposed upon removal of foulant materials.

4. Appendix

4.1. Water quality data

Table A1. Water quality data of UF filtrate and MBR permeate (i.e., RO feed streams) from LACSD UF-RO and MBR-RO pilot systems, respectively.

Parameter	Unit	UF Filtrate			MBR Permeate		
		Avg.	Min	Max	Avg.	Min	Max
Field pH	--	7.32	7.14	7.45	7.14	6.7	8.24
Turbidity	NTU	--	<0.12	1.35	--	<0.12	0.22
TSS	mg/L	--	--	--	--	<2.5	<3.0
COD	mg/L	--	--	--	34.13	21	76
Sol COD	mg/L	--	--	--	--	--	--
TOC	mg/L	12.73	10.6	22.3	9.67	7.65	11.4
NH_3	mg N/L	35.03	24.9	38.2	--	<1	6.62
TKN	mg N/L	36.56	25.5	40.2	--	<1	4.26
NO_3	mg N/L	--	<0.1	<0.1	35.59	1.22	44.6
NO_2	mg N/L	--	<0.01	0.069	--	<0.01	7.46
o-PO4	mg P/L	--	<0.125	0.431	--	<0.125	0.229
Calcium	mg/L	71.3	62.5	79.5	68.94	63.4	75.8
Magnesium	mg/L	23.1	19.9	26.1	22.28	20.7	23.6
Sodium	mg/L	403.57	345	447	391.73	335	432
Potassium	mg/L	20.89	19.1	22.4	20.84	18.8	22.7
Total Alkalinity	mg/L $CaCO_3$	364.47	334	384	96.1	84	112
Sulfate	mg/L	217.82	182	247	223.5	180	247
Chloride	mg/L	458.82	414	487	457	405	495
TDS	mg/L	1350.53	1210	1420	1440	1310	1520
Barium	µg/L	100.92	74.4	123	98.31	76.9	120
Strontium	µg/L	719.21	635	786	698.18	636	755
Fluoride	mg/L	1.42	0.9	3.07	1.619	0.935	3.47
Iron	mg/L	0.12	0.1	0.17	0.1	0.07	0.14
Aluminum	µg/L	--	<10	11.9	--	<10	22.8
Boron	mg/L	0.83	0.74	0.89	0.84	0.72	0.94
SiO_2	mg/L	25.13	21.5	28.4	23.9	22.2	25.6
Diss. Sulfide	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Membrane Autopsy Report

Prepared for:

Sanitation Districts of Los Angeles County

August 15, 2012

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Synopsis

Los Angeles County Sanitation Districts (LACSD) provided four sets of Hydranautics ESPA2-4040 (Low Pressure RO) membrane elements to Envirosoft for analysis. Two of the elements were the lead (SN 10464039) and tail (SN 10463998) RO elements from LACSD pilot UF-RO system, while the remaining two were the lead (SN 10463976) and tail (SN 10464235) RO elements from LACSD pilot MBR-RO system.

Examinations of the submitted RO membrane elements revealed no visually-observable evidence of physical damage. Fiberglass wraps, end caps, brine seals, and permeate tubes appeared to be in good condition. Feed and permeate spacers and glue lines were also in satisfactory mechanical condition.

Performance testing of full RO elements and membrane sample coupons revealed lower than normal membrane productivities. The productivities of the lead RO elements from the UF-RO and MBR-RO systems were slightly lower than normal by 8% and 15%, respectively. However, performance testing of the lead element membrane sample coupons revealed normal water productivity level, suggesting that fouling in the lead elements were localized and in its early stage. Tail element productivities were significantly below normal for both the UF-RO (by 41%) and MBR-RO (by 25%) systems. The lower-than-normal performance levels of the tail elements were consistent with results from sample coupon performance testing, with the UF-RO tail element having the lowest level of productivity. Performance testing also revealed normal or near normal levels of salt rejection (i.e., within 0.1% of expected normal performance). Fujiwara test was positive for the presence of halogen (i.e., chlorine) only for the membranes samples from the MBR-RO system.

Internal visual examinations, optical imaging, light microscope analysis, FTIR analysis, and SEM-EDS, CEI analysis of the membrane surfaces indicated the presence of brownish foulant materials on the membrane surfaces of all membrane elements, with the tail RO element from the UF-RO system appearing to be most fouled. The foulant layers appeared to be composed primarily of metal silicates (calcium silicates), clay, and iron-bearing granular material, as well as gram negative bacteria and amorphous organic material. Preliminary assessments of membrane cleaning suggest that the foulant materials can be removed to recover RO membrane permeability to within manufacturer's specifications. Cleaning resulted in slight elevation of the salt passage (i.e., salt transport coefficient) that remained within manufacturer specifications. The above autopsy results suggest that there is merit in exploring process performance improvements in order to mitigate fouling by metal silicates, iron-bearing material, and organics, as well as in having periodic testing of UF/MBR membrane integrity.

Contents

1. Work Statement

Los Angeles County Sanitation Districts (LACSD) and Metropolitan Water District of Southern California (MWDSC) have been evaluating advanced treatment of the effluent from the Joint Water Pollution Control Plant (JWPCP). Two different treatment processes were pilot tested in parallel, utilizing an UF-RO pilot system (UF: 0.04 μm, PVDF, Memcor, Siemens) and an MBR-RO pilot system (MBR: 0.04 μm, PVDF, ZeeWeed 500C, GE). Each pilot system employed an RO unit with a total of 21 RO membrane elements (Hydranautics ESPA2-4040), arranged in 2:1 array configuration with 7 elements per series per stage. In each RO unit, antiscalant treatment (King Lee PreTreat Plus 0100) and RO feedwater pH adjustment (to pH ~6.5 with sulfuric acid) were employed to mitigate membrane mineral scaling. Chloroamine residual (3-4 ppm) was maintained in the RO feed streams in order to control biofouling. Each RO unit was operated at a target water recovery level of 85%.

Envirosoft was retained by LACSD to assess (via membrane autopsy) the performance of four RO elements from the pilot systems. Both the MF-RO and the MBR-RO pilot systems were shut down on June 21, 2012. Two representative RO membrane elements (a lead element from the 1st RO unit stage and the tail element from the 2nd RO unit stage) from each pilot system were removed and provided to Envirosoft. This report summarizes the membrane autopsy results.

2.Summary of Results & Analysis

2.1. Membrane Autopsy Results

The pilot UF-RO and MBR-RO systems were shut down in the morning of June 21, 2012. From the RO unit of each system, a lead RO membrane element in the 1st RO unit stage and the tail membrane element in the 2nd RO unit stage were removed from the RO pressure vessels and submitted for autopsy. The RO elements were all Hydranautics ESPA2-4040 (Size: 4" x 40").

Table 1. Submitted RO membrane elements.

No	System	RO Element Position	Serial No. (SN)
1	UF-RO	Lead	10464039
2	UF-RO	Tail	10463998
3	MBR-RO	Lead	10463976
4	MBR-RO	Tail	10464235

2.1.1. External visual examination

Element weight

The RO elements were weighed prior to autopsy given that RO element weight is often indicative of the degree of fouling. The lead (SN 10464039) and tail (SN 10463998) RO elements from the UF-RO system weighed 8 lbs each. The lead (SN 10463976) and tail (SN 10464235) RO elements from the MBR-RO system weighed 9 lbs each. New RO elements of this type typically weigh 7-9 lbs.

Fiberglass wrap

The fiberglass wrapping protects the element from external differential pressure, provides compressive strength to prevent telescoping and to ensure that the various membrane components are held in their correct position for optimum performance. Damage to the fiberglass wrap can be an indication of rough handling or damage from excessive differential pressure across the membrane surface. The outer fiberglass casing of the membrane elements appeared to be in good condition, with no apparent visible signs of physical damage (**Fig. 1**).

Brine seal

The brine seals were in good condition and showed no visible signs of physical damage that could allow bypass of the NF/RO concentrate water around the spiral wound membrane scrolls (**Figs. 1-3**).

End-caps / Anti-telescoping device (ATD)

ATDs are designed to prevent telescoping of element leaves at normal differential pressures. There was no visible sign of physical damage (**Figs. 2-3**).

Permeate tube

There was no visible sign of physical damage on the ends of the permeate tubes that could allow by-pass of feed water (**Figs. 2-3**).

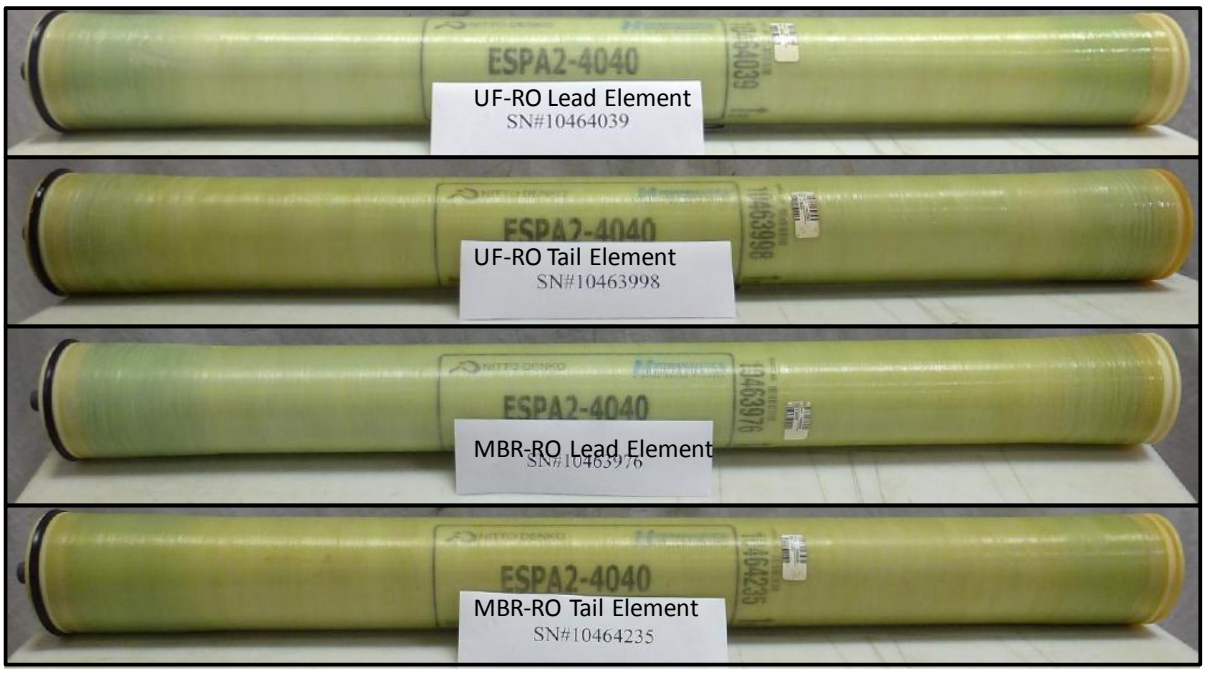


Figure 1. Photograph of submitted RO membrane elements.

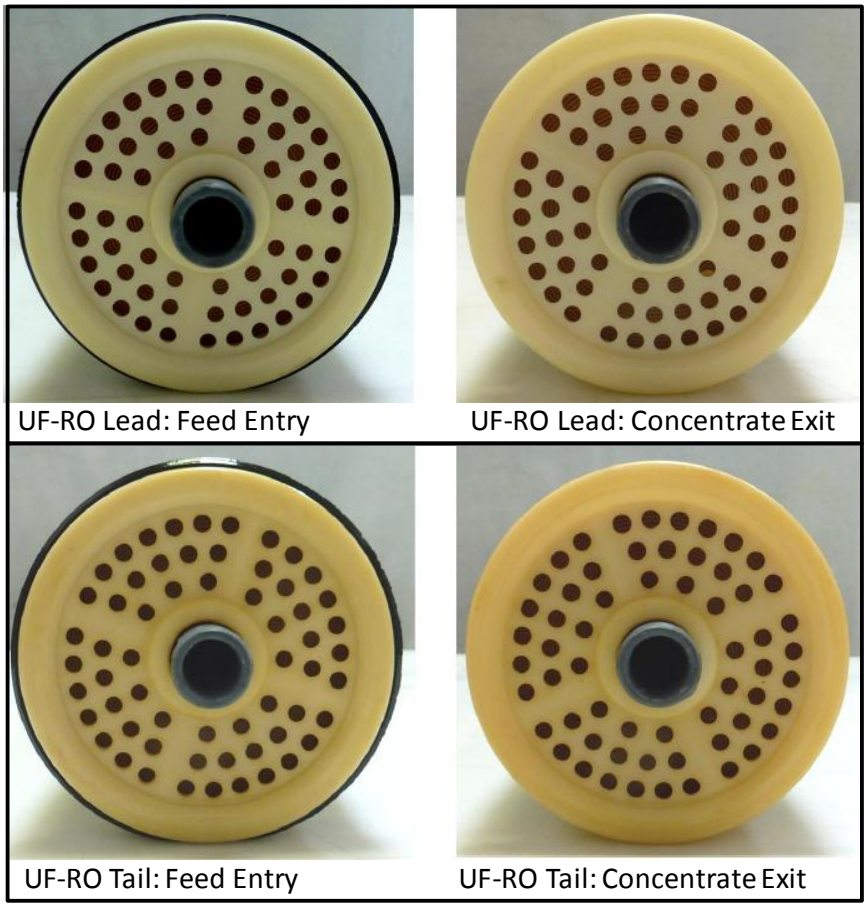


Figure 2. Photographs of the front (feed entry) and rear (concentrate exit) ends of the lead and tail RO elements from the UF-RO system.

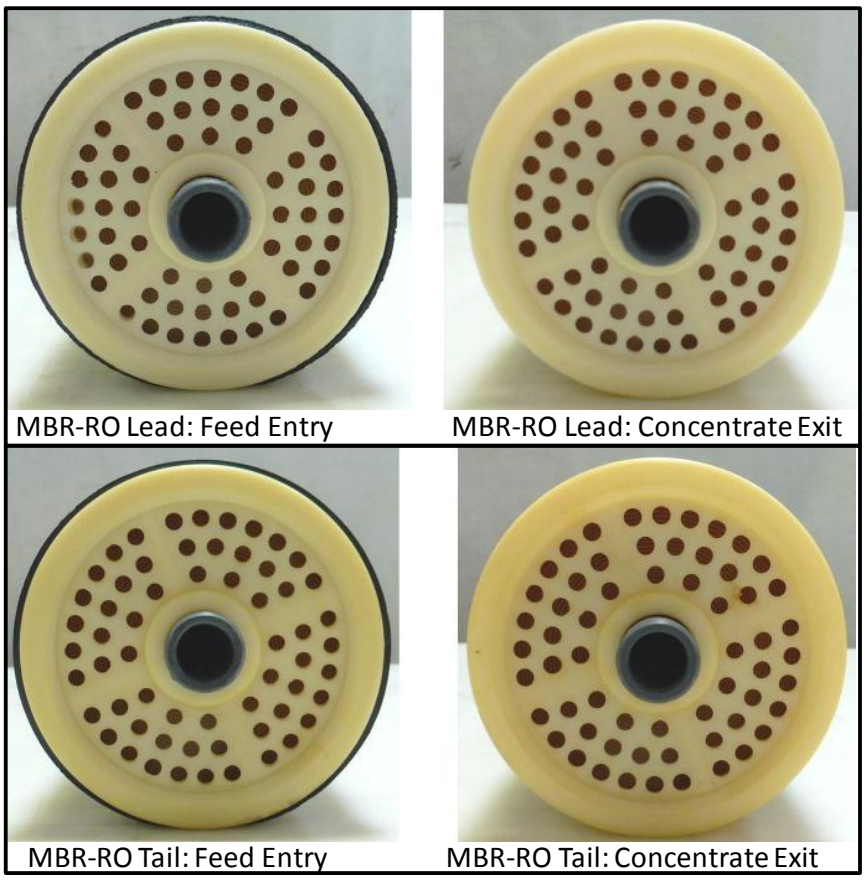


Figure 3. Photographs of the front (feed entry) and rear (concentrate exit) ends of the lead and tail RO elements from the MBR-RO system.

2.1.2. Membrane element performance

The performance the RO elements was tested at 15% water recovery and net driving pressure of 131 psig, employing de-chlorinated city water (~1000 μS). The normalized permeate flow and salt rejection of the membrane element represents the overall (average) performance of the entire membrane element, including the membrane sheets, the effect of channel spacers, as well as the integrity of internal element flow connections and fluid channels.

The results below (**Table 2**) indicated that the normalized permeate flows of the lead RO elements from both the UF-RO and MBR-RO systems were below manufacturer's specifications by 8%-15%. The tail RO elements from both systems were significantly below manufacturer's specifications by 25-41%. The tail RO elements from the UF-RO system had the lowest normalized permeate flow. Normalized salt rejection levels were all within manufacturer specifications except for the tail RO element from the UF-RO system, which was just slightly below manufacturer's specifications (by 0.1%). The differential pressure drop levels were in the normal range of 3-5 psid, indicating that there was no significant blockage of the RO retentate channels.

Table 2. Results of RO membrane element performance testing

Element	System	Permeate Flow, gpm	Salt Rejection, %	Differential Pressure Drop, psid
Lead (SN 10464039)	UF-RO	1.0	99.5	3
Tail (SN 10463998)	UF-RO	0.7	99.3	3
Lead (SN 10463976)	MBR-RO	0.9	99.5	3
Tail (SN 10464235)	MBR-RO	0.8	99.5	3
Manufacturer's Specifications		**1.1-1.3**	**99.4-99.6**	**3-5**

2.1.3. Internal Visual Examination

Scroll end examination

ATD were removed for examination of the scroll ends of the membrane leaves for the presences of fouling, feed spacer extrusion, and membrane gapping. Each scroll end was also examined for signs of membrane telescoping damage. The scroll ends of the lead RO element from the UF-RO systems were relatively free from debris, although a clear orange stain was apparent (**Fig.4**). The scroll ends for the other three elements were stained with an orange colored foulant material (**Figs. 4, 8, 12, 16**) that resembled clay. In each of these elements, the foulant material was concentrated around the areas surrounding the permeate tube, possibly trapped by the ATD.

Internal visual examination

The membrane elements were dissected and unrolled. Direct visual examination (**Figs. 4-5**) revealed that exposed RO membrane surfaces had brown stains that were indicative of thin membrane fouling layers (**Figs. 5-6, 9-10, 13-14, 17-18**). The brown stains were darker on the tail RO elements from the UF-RO (**Fig. 9-10**) and MBR-RO systems (**Fig. 17-18**).

Feed spacers

Feed spacers are plastic net material (Vexar) designed to separate membrane leaves to form a thin channel for feed flow. Feed spacers in all of the membrane elements appeared to be without significant visual traces of foreign material (**Figs. 7, 11, 15, 19**).

Permeate spacers

Permeate spacers are typically made of Tricot material and provide a porous channel for permeate flow into a central permeate collection tube. Damage of tricot material can increase permeate-side pressure losses. Tricot material was found to be in good condition in all membrane elements.

Glue lines

For all of the membrane elements, the glue lines at the edges of membrane leaves, which separated feed and permeate channels, were in good condition and showed no signs of pouching or delamination.

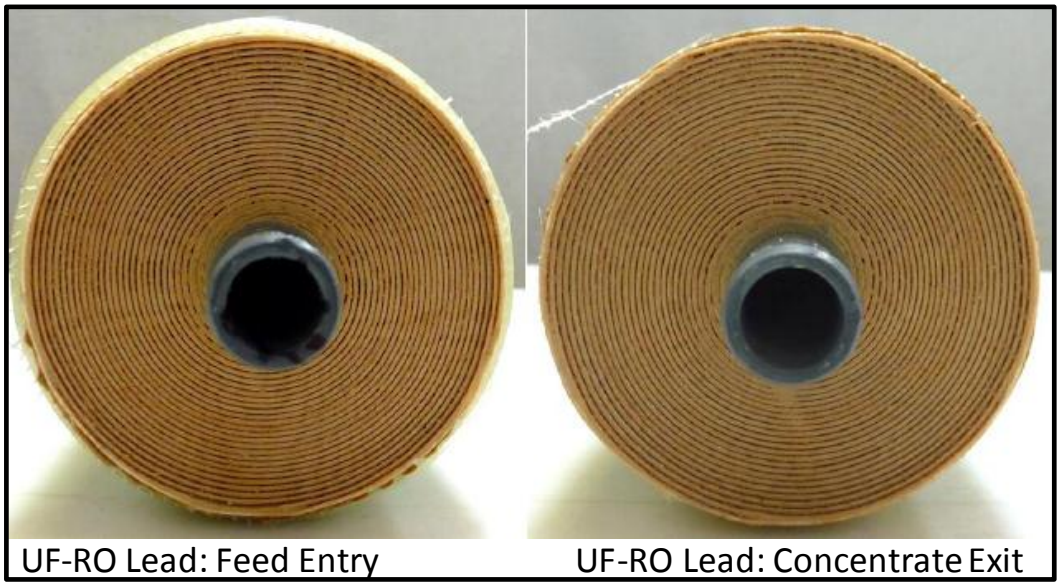


Figure 4. Photographs of the front (feed entry) and rear (concentrate exit) ends of the lead RO element from the UF-RO system.

Figure 5. Photograph of the membrane surface of the lead RO element from the UF-RO system.

Figure 6. Photograph of the membrane surface of the lead RO element from the UF-RO system.

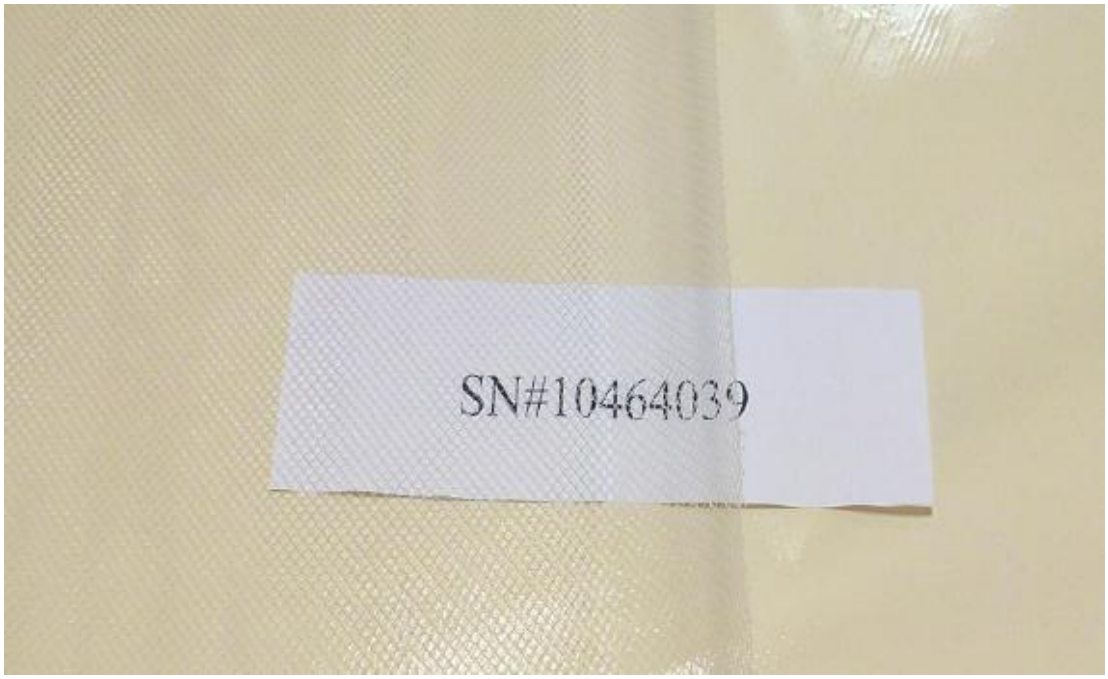


Figure 7. Image of the feed spacer of the lead RO element from the UF-RO system.

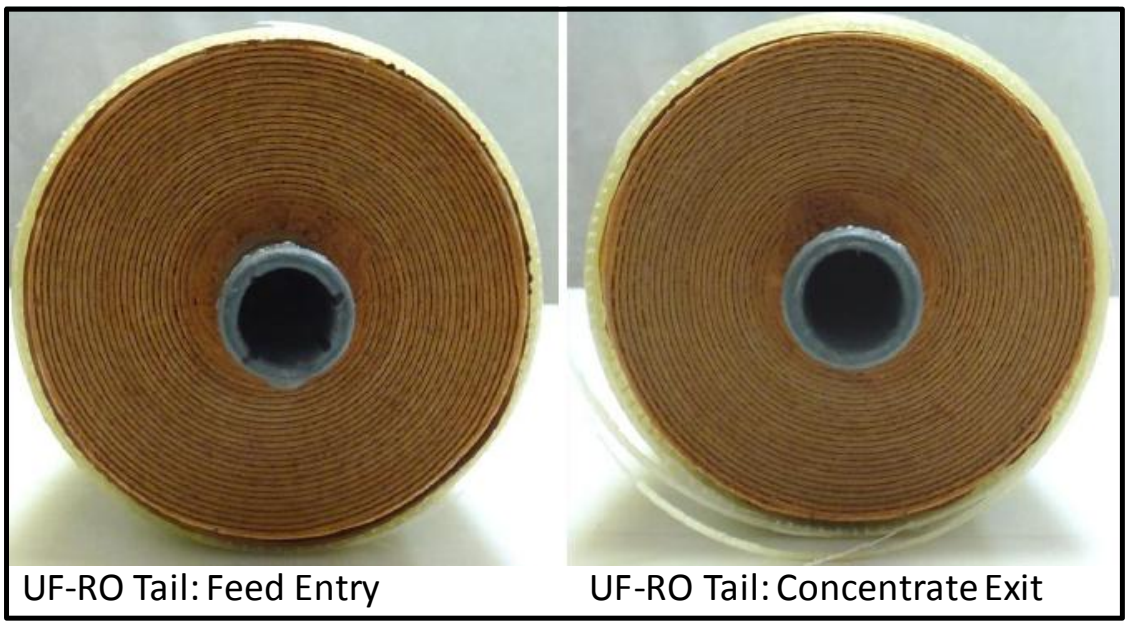


Figure 8. Photographs of the front (feed entry) and rear (concentrate exit) ends of the tail RO element from the UF-RO system.

Figure 9. Photograph of the membrane surface of the tail RO element from the UF-RO system.

Figure 10. Photograph of the membrane surface of the tail RO element from the UF-RO system.

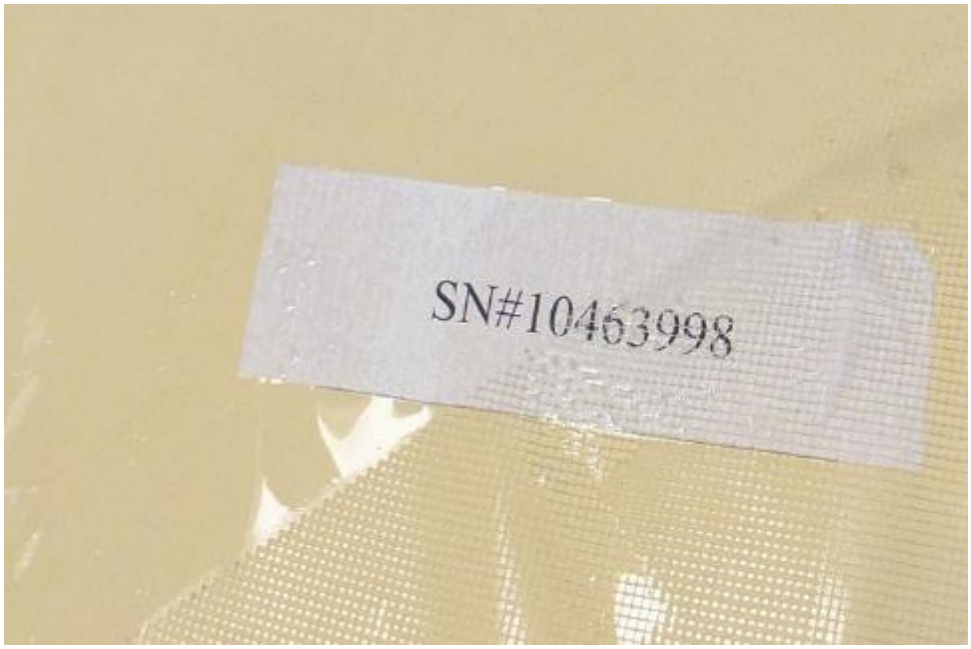


Figure 11. Image of the feed spacer of the tail RO element from the UF-RO system.

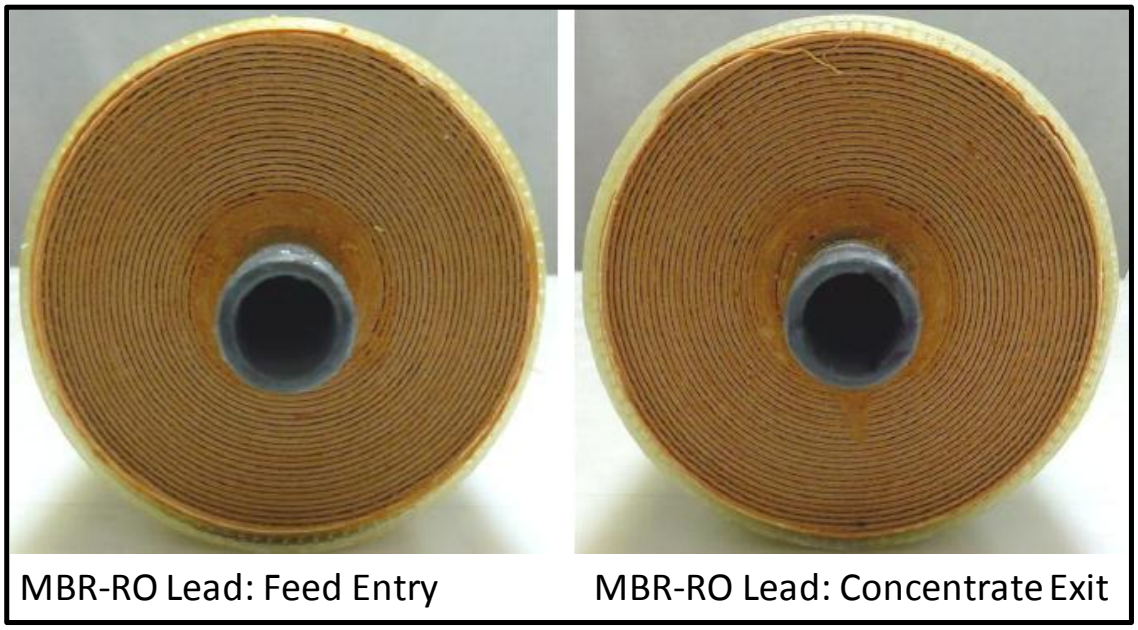


Figure 12. Photographs of the front (feed entry) and rear (concentrate exit) ends of the lead RO element from the MBR-RO system.

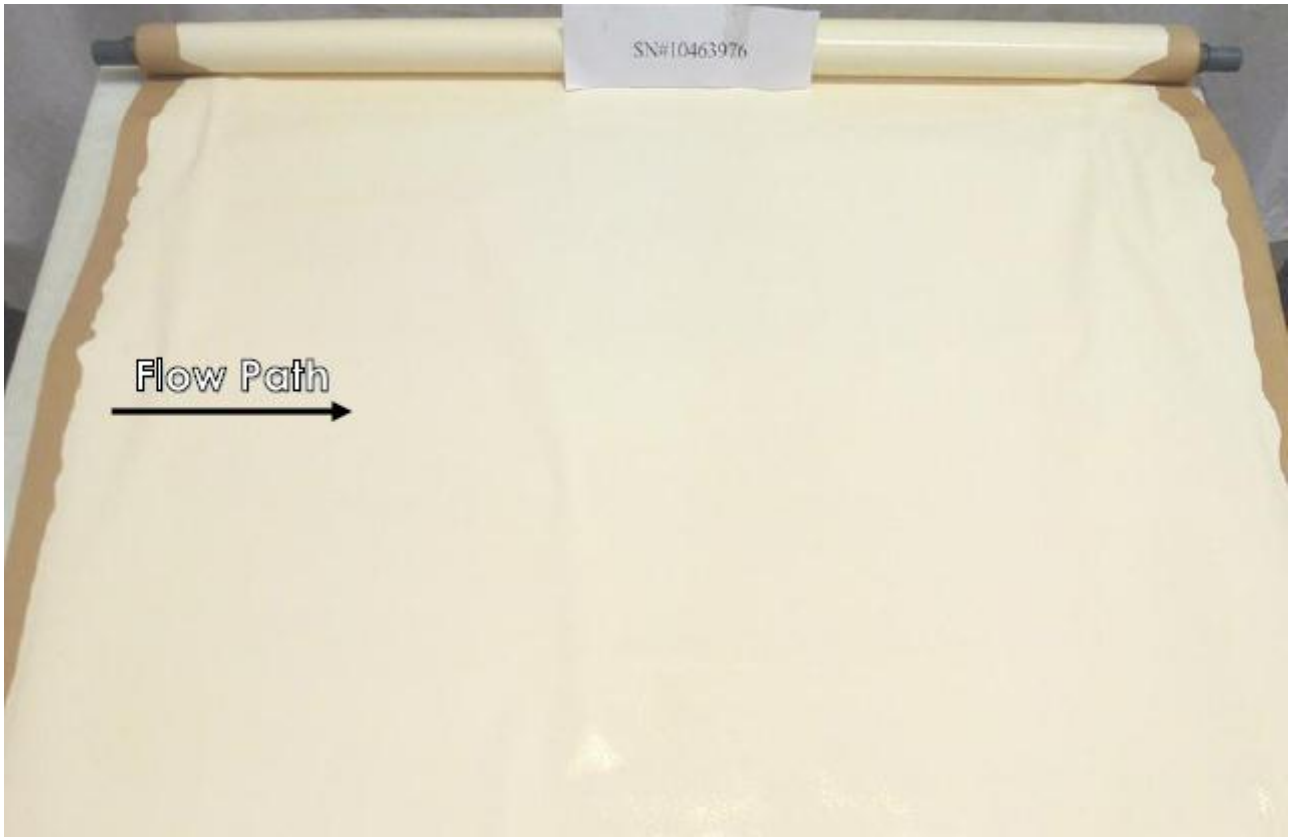


Figure 13. Photograph of the membrane surface of the lead RO element from the MBR-RO system.

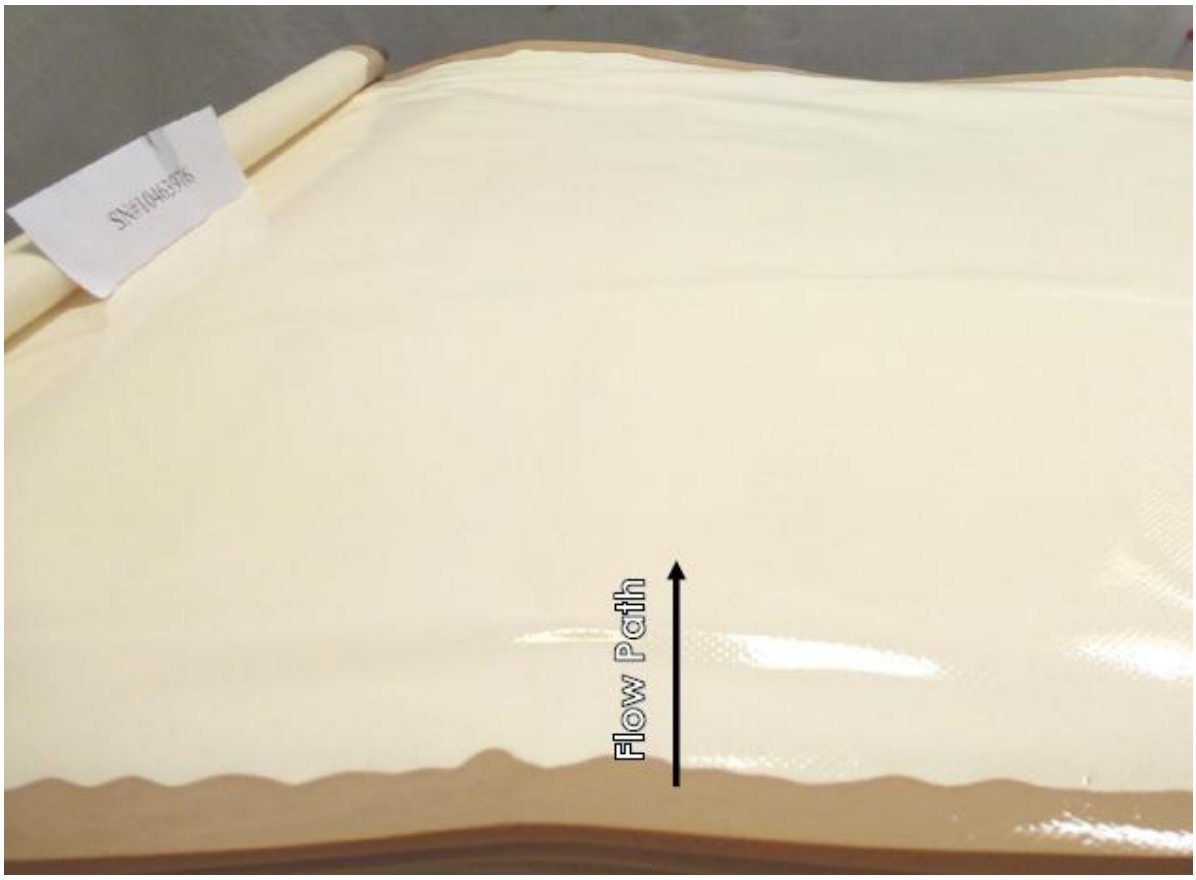


Figure 14. Photograph of the membrane surface of the lead RO element from the MBR-RO system.

Figure 15. Image of the feed spacer of the lead RO element from the MBR-RO system.

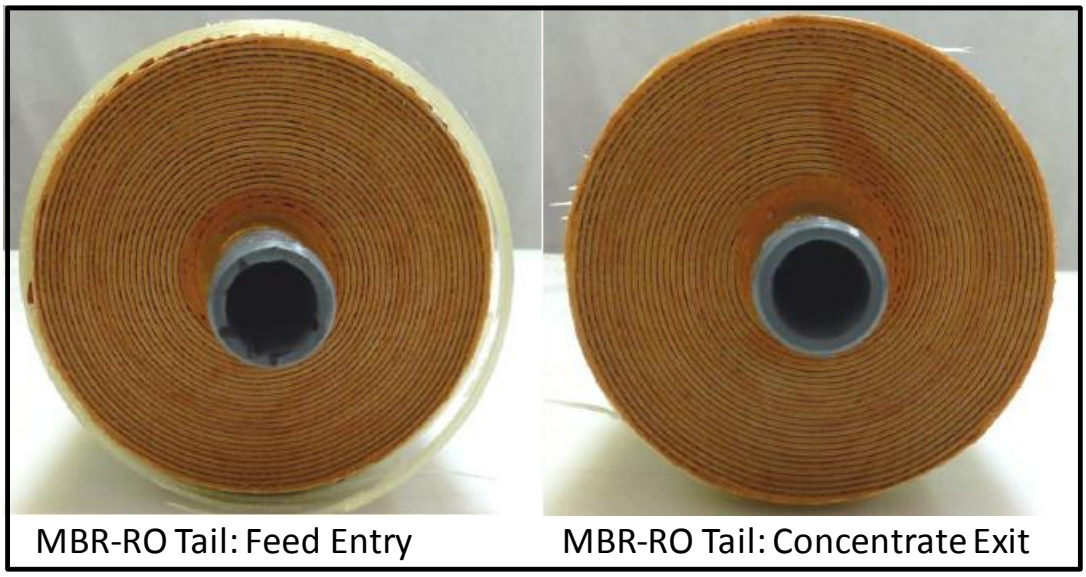


Figure 16. Photographs of the front (feed entry) and rear (concentrate exit) ends of the tail RO element from the MBR-RO system.

Figure 17. Photograph of the membrane surface of the tail RO element from the MBR-RO system.

Figure 18. Photograph of the membrane surface of the tail RO element from the MBR-RO system.

Figure 19. Image of the feed spacer of the tail RO element from the MBR-RO system

2.1.4. Membrane coupon sampling and storage

For each membrane element, membrane coupons were sampled at the midsection of the membrane element. The membranes were stored in sealed plastic bags and kept refrigerated before subsequent testing described in **Sections 2.1.5-2.1.9**.

2.1.5. Fujiwara test

The Fujiwara test is a qualitative test that detects the presence of chemically bound halogen compounds on the membrane surface. The Fujiwara test results were negative for membrane samples taken from the lead and tail RO elements of the UF-RO system, but were positive for membrane samples taken from the lead and tail RO elements of the MBR-RO system. Halogenated membrane surface is indicative of chemical transformation occurring at the membrane surface due to exposure to chemical oxidants, which may affect membrane salt-rejection performance. One should note that a positive Fujiwara test does not quantify the extent of membrane damage, but merely suggests the occurrence of membrane surface halogenation.

Table 3. Fujiwara test results.

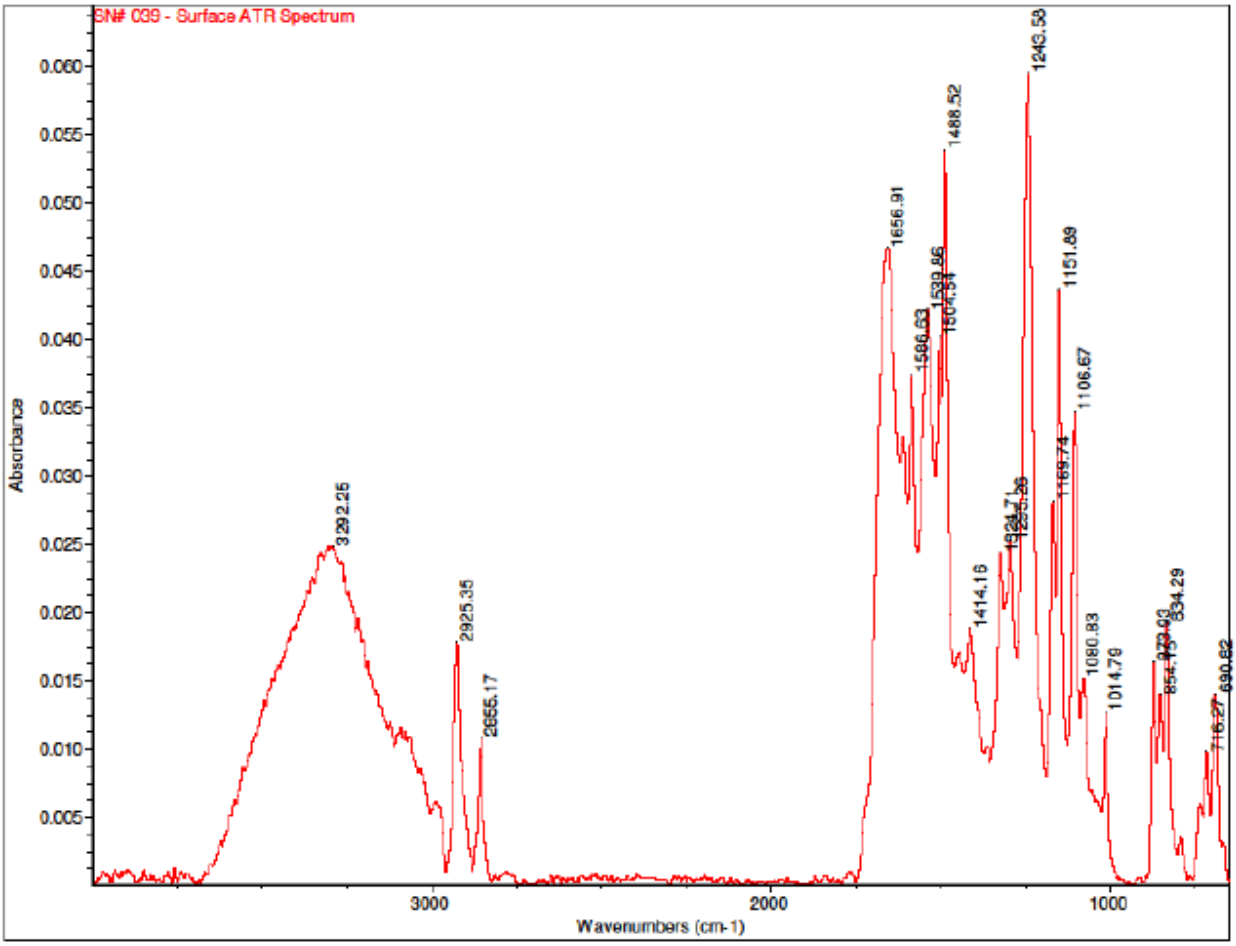
Element	System	Fujiwara Test Result
Lead (SN 10464039)	UF-RO	Negative (-)
Tail (SN 10463998)	UF-RO	Negative (-)
Lead (SN 10463976)	MBR-RO	Positive (+)
Tail (SN 10464235)	MBR-RO	Positive (+)

2.1.6. Acid testing

Several drops of dilute hydrochloric acid were placed on the fouled areas of all membrane samples. No bubbling was visually detected indicating that minimal presence of fouling by carbonates in all of the samples tested.

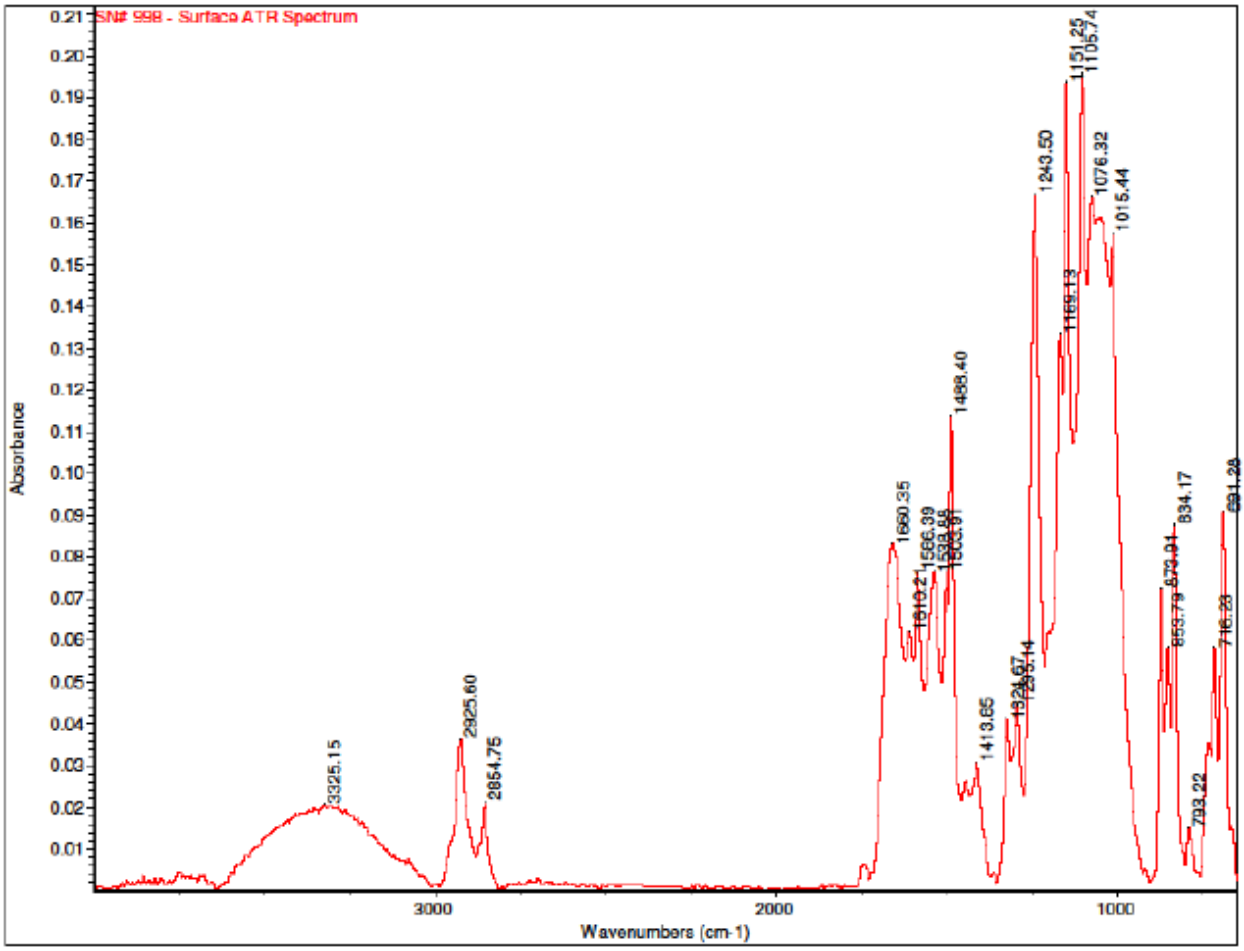
2.1.7. FTIR analysis

FTIR analysis was conducted using a Perkin Elmer 1600 FT-IR system with a HATR (ZnSe crystal) attachment. FTIR analysis (**Figs. 20-23**) showed peaks that indicated C-H, C-N, N-H, C-C, C=C, N-H-C=O, and N-C=O peaks for all membrane samples. These groups are consistent with the polyamide active layer of the RO membranes. It is noted that weak H-C-OH peaks (**Figs. 20-23**) were also apparent for all membrane samples, which would be expected if polysaccharides, organic proteins, and carbohydrates from organic foulants were on the membrane surfaces.



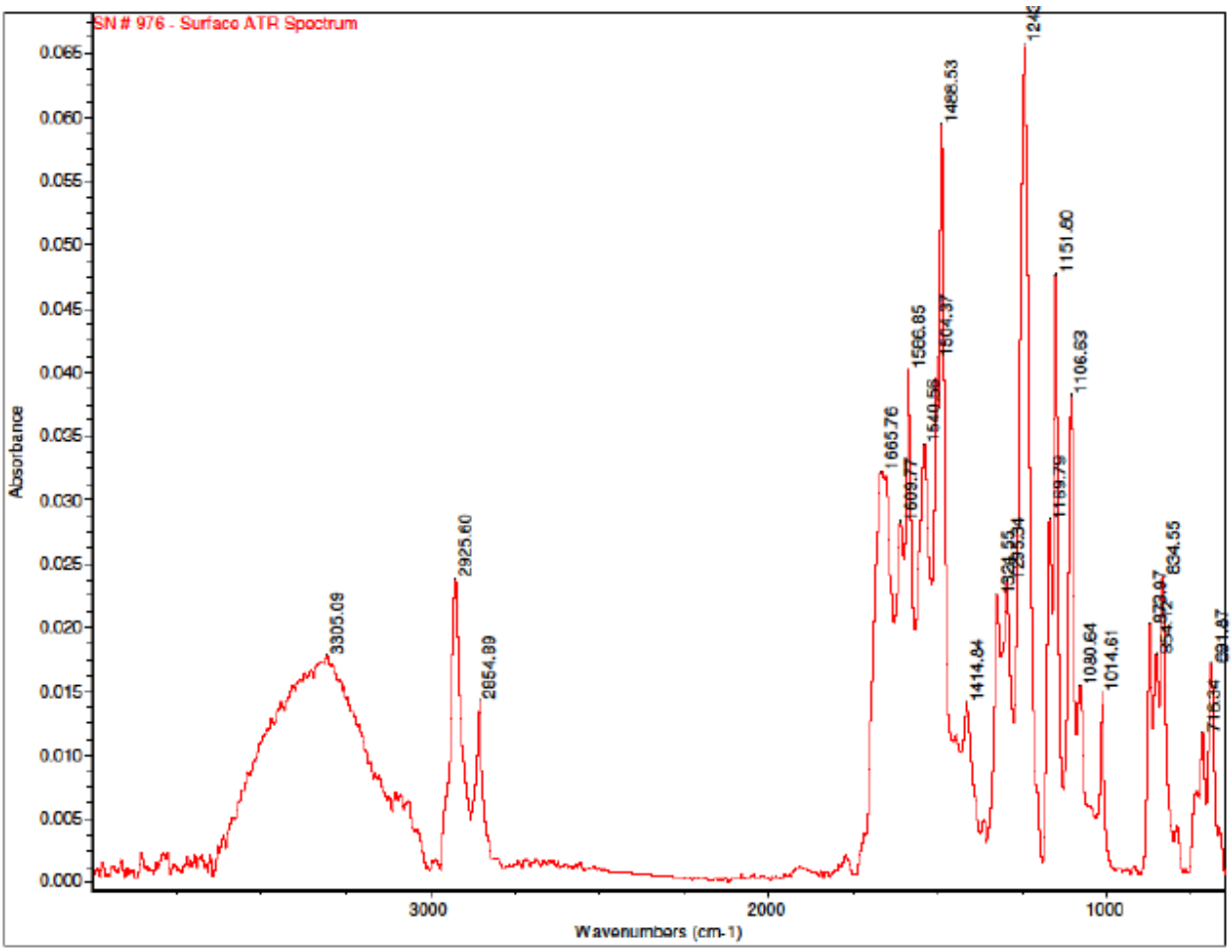
Peaks	Yes	No	Weak
C-H	X		
C-N	X		
N-H	X		
C-C	X		
C=C	X		
H-C-OH			X
N-H-C=O			X
N-C=O	X		

Figure 20. FT-IR spectral image of membrane surface samples from the lead RO element of the UF-RO system.



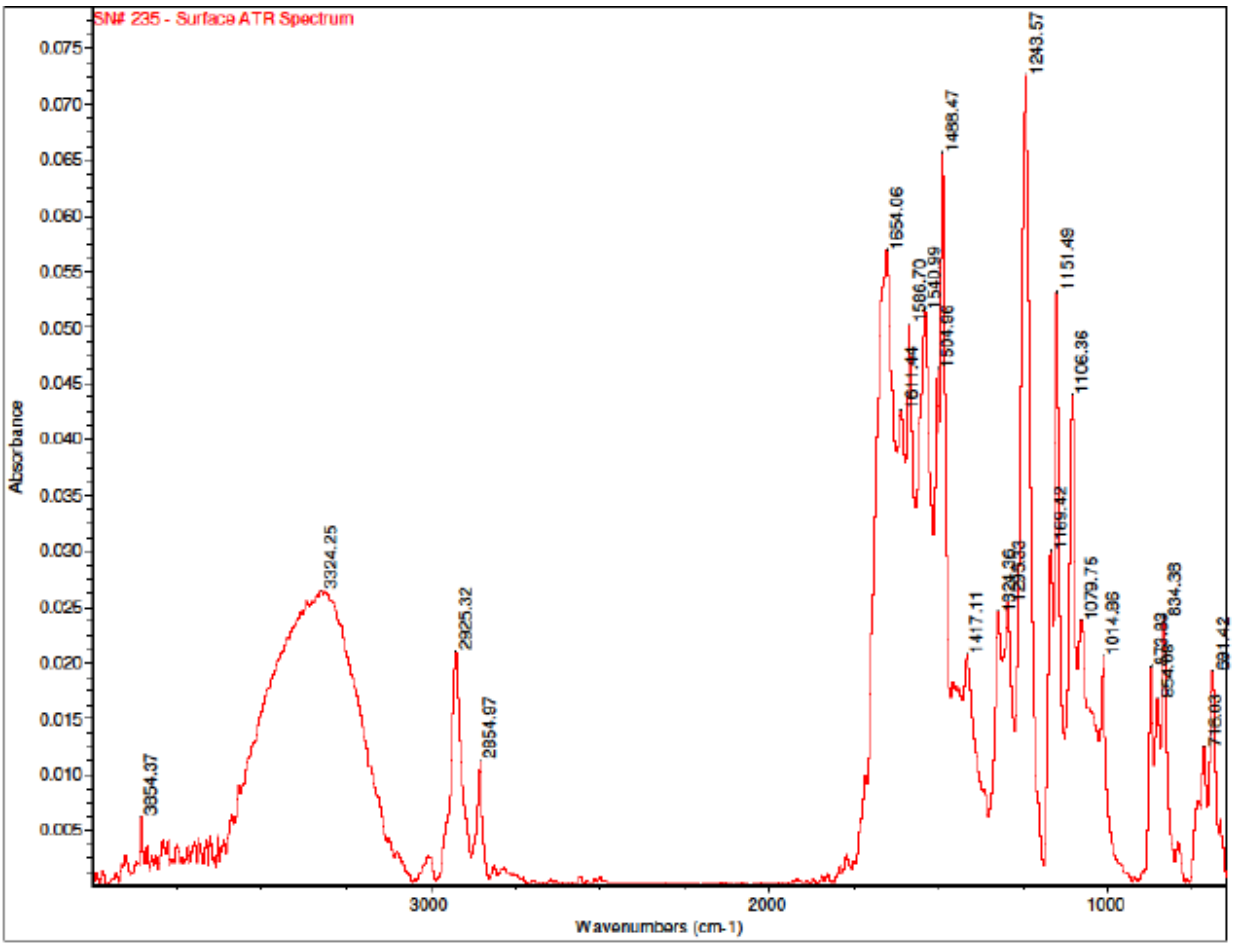
Peaks	Yes	No	Weak
C-H	X		
C-N	X		
N-H	X		
C-C	X		
Aromatic			X
C=C	X		
H-C-OH			X
N-H-C=O	X		
N-C=O	X		

Figure 21. FT-IR spectral image of membrane surface samples from the tail RO element of the UF-RO system.



Peaks	Yes	No	Weak
C-H	X		
C-N	X		
N-H	X		
C-C			X
C=C			X
H-C-OH			X
N-H-C=O	X		
N-C=O	X		

Figure 22. FT-IR spectral image of membrane surface samples from the lead RO element of the MBR-RO system.



Peaks	Yes	No	Weak
C-H			X
C-N	X		
N-H	X		
C-C	X		
C=C	X		
H-C-OH			X
N-H-C=O			X
N-C=O	X		

Figure 23. FT-IR spectral image of membrane surface samples from the tail RO element of the MBR-RO system.

2.1.8. Light Microscope Analysis and Bacteria Gram Staining Test

Foulant samples were collected, stained, and examined with a light microscope. Gram positive bacteria are stained blue while Gram negative bacteria are stained red. Gram negative bacteria were visible for all the membrane samples tested (**Figs. 24-25**) and most apparent in the tail element of the MBR-RO system (**Fig. 25b**). There were some indications of gram positive bacteria in the tail element of the UF-RO system (**Figs. 24b**). Amorphous organic material and fungi were also observed, particularly in the lead element of the UF-RO system (**Fig. 24a**).

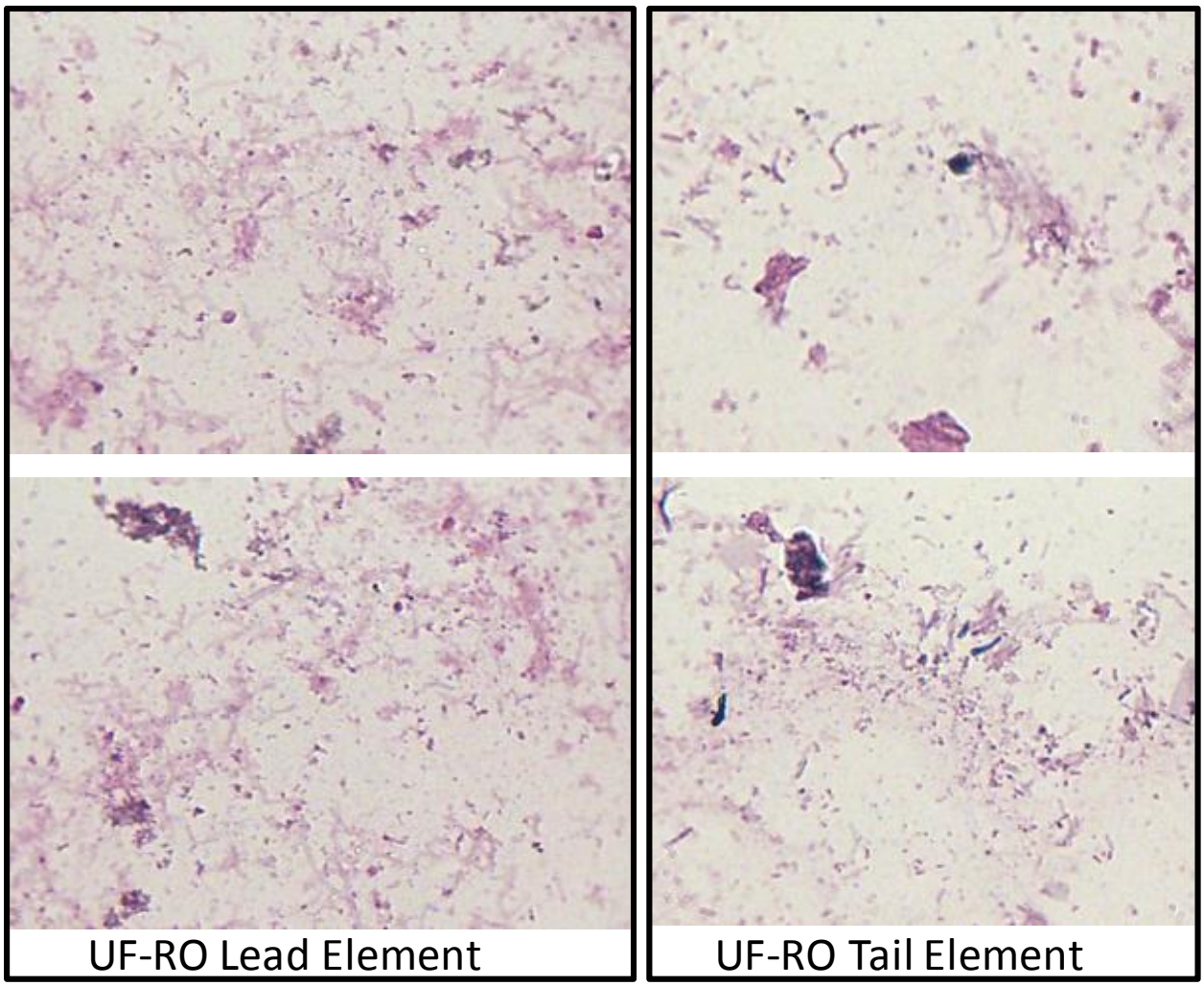


Fig. 24. Light microscope image (1000X) of gram-stained foulant samples from the (a) lead and (b) tail RO elements of the UF-RO system.

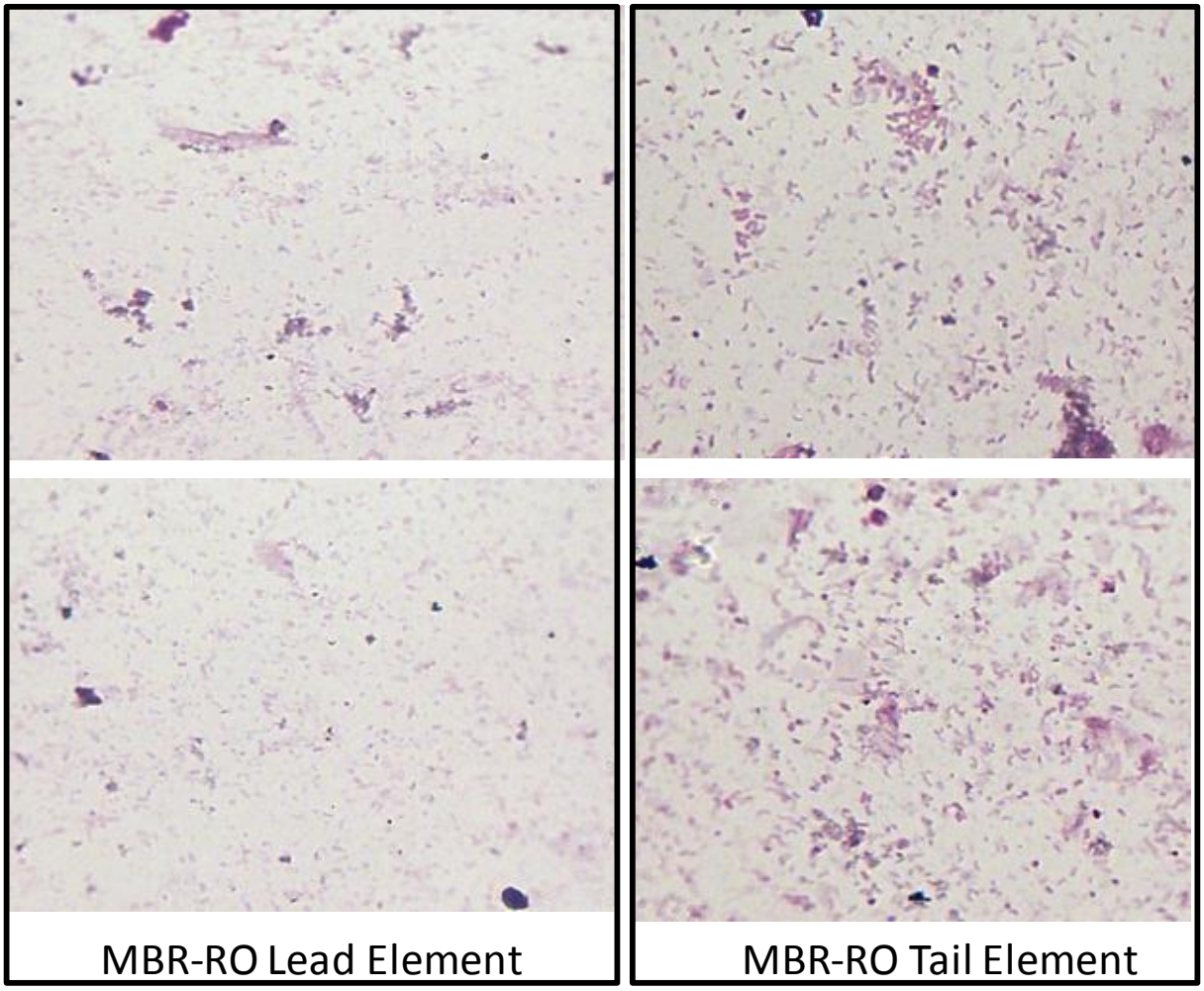


Fig. 25. Light microscope images (1000X) of gram-stained foulant samples from the (a) lead and (b) tail RO elements of the MBR-RO system.

2.1.9. SEM-EDS analysis

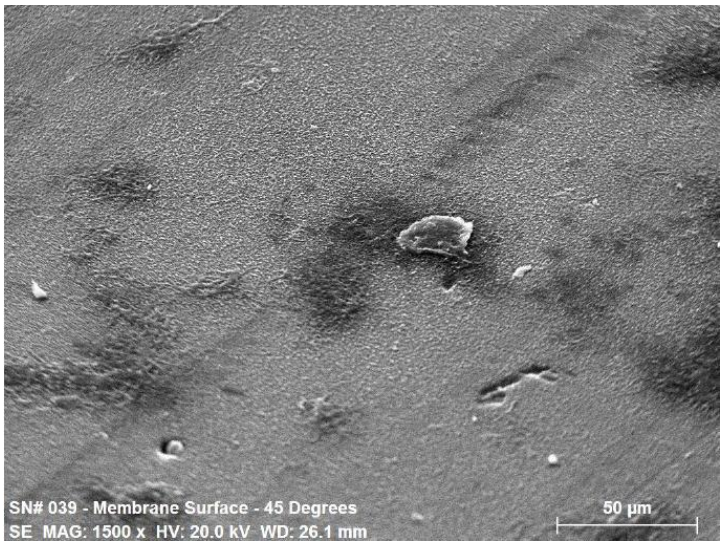
SEM/EDS analysis was conducted using Philips XL30 FEG Field Emission Microscope with an EDAX attachment for elemental analysis via energy dispersive X-ray spectroscopy (EDS). SEM images of the membrane samples and the associated EDS results are shown in **Figs. 26-27** for membrane samples from the UF-RO system and in **Figs. 28-29** for membrane samples from the MBR-RO system.

SEM images of the lead and tail element membrane samples from the UF-RO system indicate granular foulant materials on the membrane surfaces (**Fig. 26-27**). The extent of fouling appeared to be more significant on the surface of membrane sample from the tail element (**Fig. 27**) than that of the lead element (**Fig. 26)**. EDS detected silicon, iron, calcium on both the lead and tail element membrane samples (**Figs. 26-27)**, suggesting fouling by metal silicates (e.g.,

calcium silicates) and iron-bearing materials. Aluminum and phosphorus was also detected in the lead element membrane sample (**Fig. 26**).

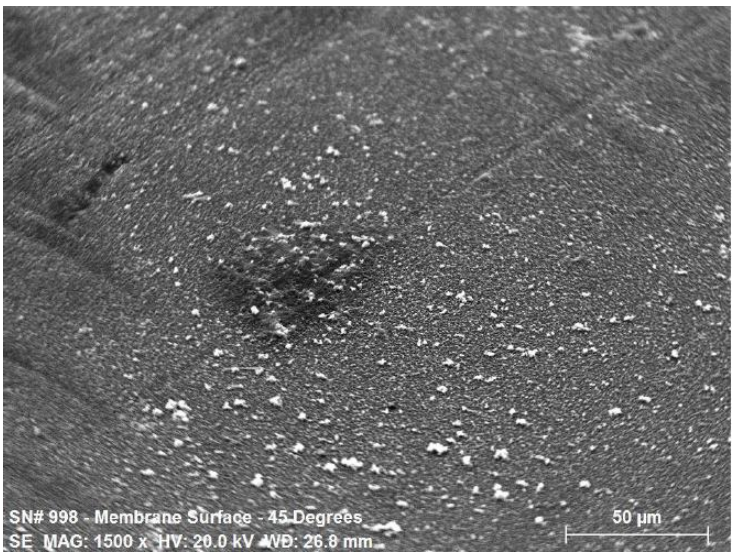
Fine granular foulant materials were observed on the surfaces of the membrane samples from the MBR-RO system, with the tail element sample (**Fig. 29**) appeared to be more fouled than the lead element (**Fig. 28**). EDS analysis (**Fig. 28**) of the lead element sample indicated that the foulant materials were composed of primarily calcium, aluminum, and iron. The tail element sample (**Fig. 29**) was composed of primarily iron, calcium, aluminum, and silicon, suggesting fouling by metal silicates (e.g., clay, calcium silicates) and iron-bearing material. Trace amounts of phosphorus and iodine were also detected in the tail element membrane sample (**Fig. 29**).

It is noted that sulfur also appeared as a major constituent in the EDS analysis of the above membrane samples, which could have originated from the sulfur content of the RO membrane polysulfone support layer. At the level of EDS sensitivity, it is likely that the detected carbon and oxygen were due to interferences from the RO membrane (i.e., polyamide active layer on top of polysulfone and polyester backing).



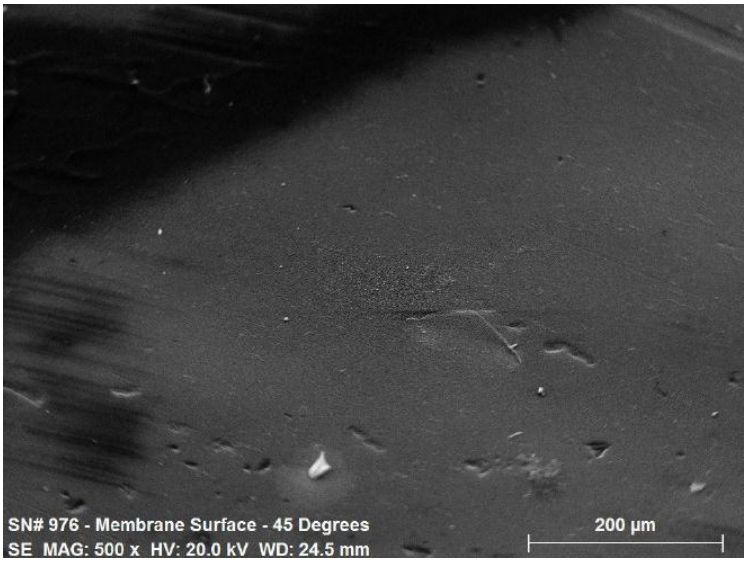
Elements (wt. %)	SN#10464039
Carbon	61.53
Silicon	0.22
Sulfur	8.03
Oxygen	28.68
Calcium	0.61
Phosphorous	0.23
Iron	0.52
Aluminum	0.18

Figure 26. SEM image and EDS microanalysis of membrane surface from the lead RO element membrane samples of the UF-RO system.



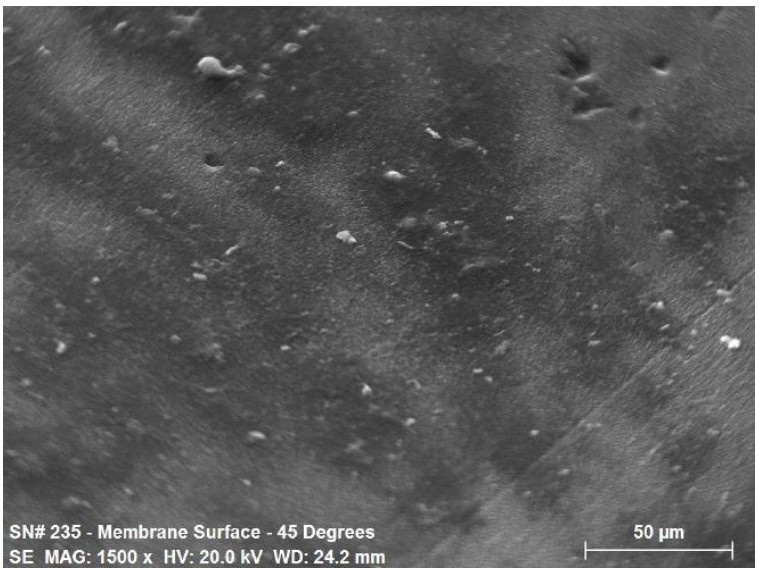
Elements (wt. %)	SN#10463998
Carbon	54.16
Silicon	0.63
Sulfur	3.84
Oxygen	39.60
Calcium	0.93
Iron	0.84

Figure 27. SEM image and EDS microanalysis of membrane surface from the tail RO element membrane samples of the UF-RO system.



Elements (wt. %)	SN#10463976
Carbon	72.36
Aluminum	0.12
Sulfur	8.08
Oxygen	18.83
Iron	0.45
Calcium	0.16

Figure 28. SEM image and EDS microanalysis of membrane surface from the lead RO element membrane samples of the MBR-RO system.



Elements (wt. %)	SN#10464235
Carbon	66.90
Silicon	0.65
Sulfur	6.81
Oxygen	23.05
Aluminum	0.41
Phosphorous	0.16
Calcium	0.71
Iron	1.19
Iodine	0.12

Figure 29. SEM image and EDS microanalysis of membrane surface from the tail RO element membrane samples of the MBR-RO system.

2.1.10. CEI analysis

Chromatic Elemental Imaging (CEI) was employed to resolve the spatial distribution of inorganic elements on fouled areas of the membrane samples. The color and color intensity in a CEI image can reveal the location and concentration levels of various elements on the fouled areas of the membrane surface. For membrane samples taken from the UF-RO system, CEI indicated that the foulant materials on the lead and tail RO elements were primarily composed of metal silicates and iron-bearing material. The patches of foulant material found on the lead element (**Fig. 26**) were likely to be clay (calcium aluminum silicates), along with traces of organic material (phosphorous and carbon) (**Fig. 30**). The granular foulant material on the tail element (**Fig. 27**) was composed mainly of calcium silicates and iron-bearing material (**Fig. 31**). For the MBR-RO system, CEI of the surface foulant material on the lead element sample revealed a heterogeneous mixture of calcium, aluminum and iron, with traces of organic material (carbon) (**Fig. 32**). The tail element sample appeared to be covered by a clay (calcium aluminum silicate) and iron foulant layers, as well as organic material (carbon and phosphorus) (**Fig. 33**).

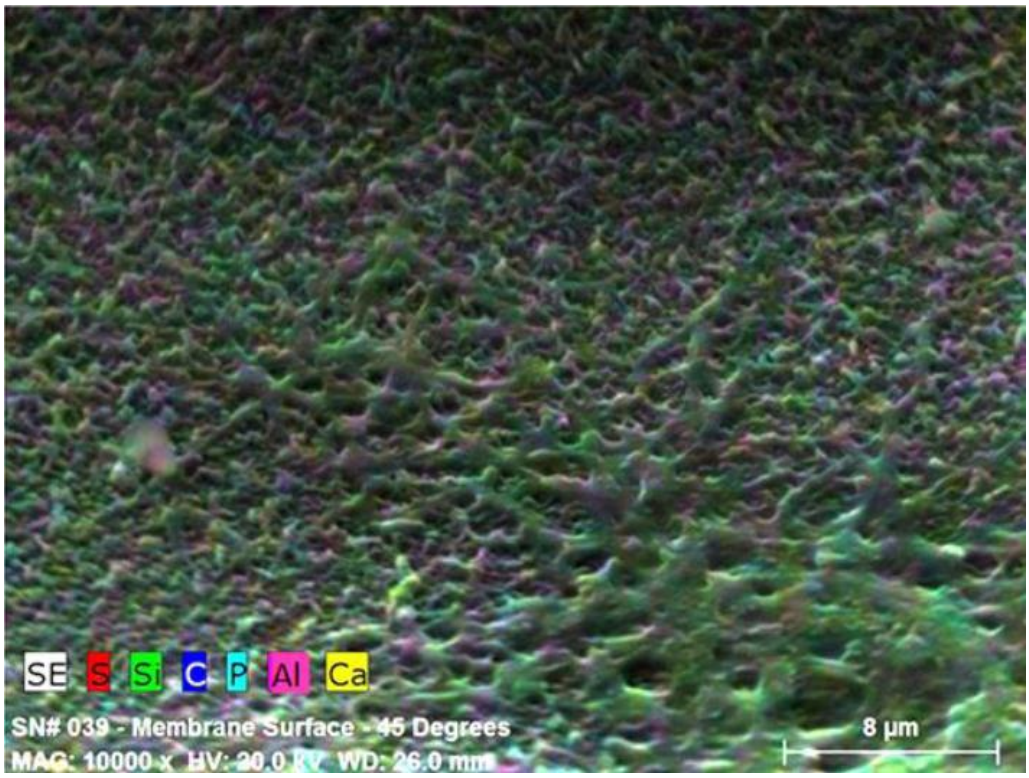


Figure 30. CEI image of membrane surface from the lead RO element membrane samples of the UF-RO system.

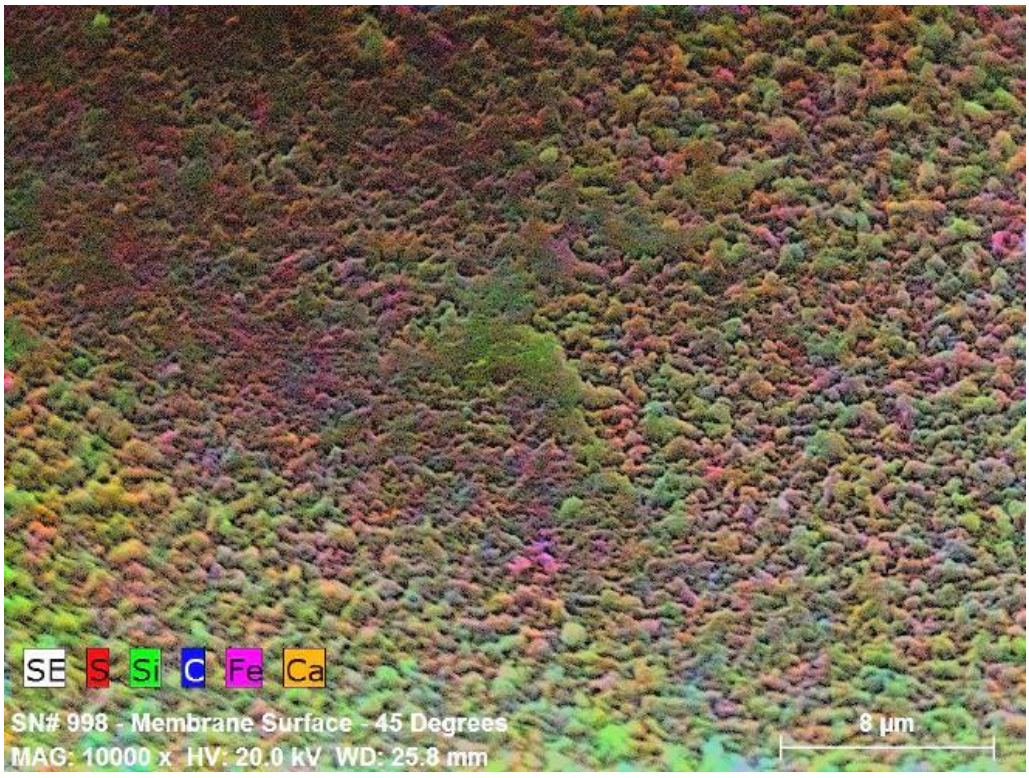


Figure 31. CEI image of membrane surface from the tail RO element membrane samples of the UF-RO system.

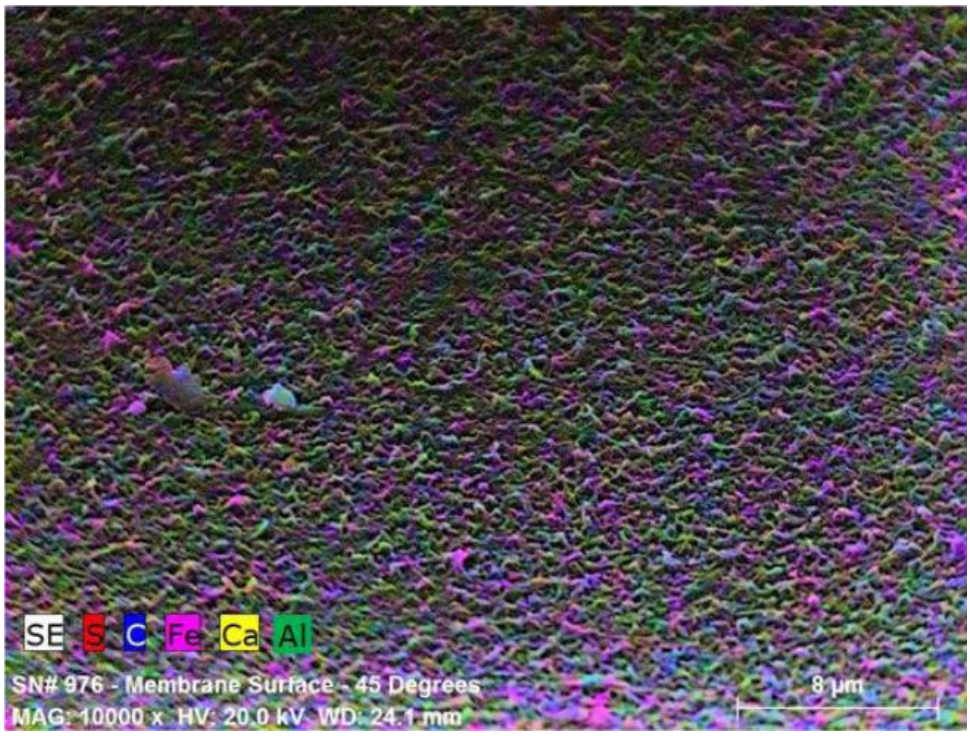


Figure 32. CEI image of membrane surface from the lead RO element membrane samples of the MBR-RO system.

Figure 33. CEI image of membrane surface from the tail RO element membrane samples of the MBR-RO system.

2.1.11. Membrane sample coupons performance

Membrane performance (water permeability and salt transport coefficient), based on membrane sample coupons from the RO elements, was evaluated using dechlorinated tap water (~1000 μS), before and after membrane cleaning. Cleaning of membrane sample coupons were conducted for initial assessments of membrane cleaning feasibility. Membrane cleaning was done using a low pH membrane cleaner (pH 2.5-3.5) containing EDTA at elevated temperature (35-40 ^{o}C) for ~2 hours. The results of membrane sample performance testing are listed in **Table 2**.

Water permeability for the lead element membrane samples from both the UF-RO and MBR-RO systems were within manufacturer's specifications. The salt transport coefficient (i.e., salt passage) was normal for the lead element membrane sample of the UF-RO system, but was slightly below normal (by 17%) for the lead element sample of the MBR-RO system. The lower-than-normal salt transport coefficient indicated that the membrane salt rejection was higher than specified by the manufacturer. Given that membrane performance (permeability and salt transport) was still satisfactory, cleaning was not necessary for the lead element membrane samples.

Water permeability for the tail element membrane samples from both the UF-RO and MBR-RO systems were lower than normal by 24% and 12%, respectively. Salt transport coefficient for the MBR-RO tail element was normal, while the salt transport coefficient of the UF-RO tail element sample was 29% below normal. Upon membrane cleaning, water permeability values of the tail element membrane samples from both systems were recovered to within normal range. It is noted that foulant removal due to cleaning was visually observable for both samples (**Fig. 34-35**). Post-cleaning salt transport coefficient of the UF-RO tail element sample was above the pre-cleaning values, but within manufacturer specification for the MBR-RO tail element sample and somewhat below (by 13%) the lower expected value for the UF-RO tail element sample (**Table 4**).

Table 4. Performance of membrane sample coupons before and after membrane cleaning.

Source of Membrane Sample		**Water Permeability (10^{-8} m/s/kPa)**	**Salt Transport Coeff. (10^{-8} m/s)**
UF-RO System: Lead RO Element	Pre-Clean	1.17	6.83
SN 6008011642	Post-Clean	-	-
UF-RO System: Tail RO Element	Pre-Clean	0.77	3.86
SN 6008011004	Post-Clean	1.10	4.74
MBR-RO System: Lead RO Element	Pre-Clean	1.07	4.54
SN 6008011637	Post-Clean	-	-
MBR-RO System: Tail RO Element	Pre-Clean	0.89	5.58
SN 6008011167	Post-Clean	1.47	7.30
Manufacturer's specifications		**1.02-1.50**	**5.46-7.39**

In comparing the results of membrane sample coupon testing with membrane element testing (**Section 2.1.2**), one should note that membrane sample coupon testing is a more sensitive test for quantifying membrane sheet performance. The results of membrane sample coupon testing only represents membrane performance in specific sections of the membrane element. However, membrane sample coupon testing excludes the impact of flow channel integrity of the membrane element, as well as the effect of flow channel spacers. Therefore, testing of small membrane area (from membrane sample coupons) should not be taken as representative of the whole membrane element test. Tests with small sections of the membrane serve as indicators of potential performance problems that may develop over time and thus are useful for evaluation and optimization of process conditions.

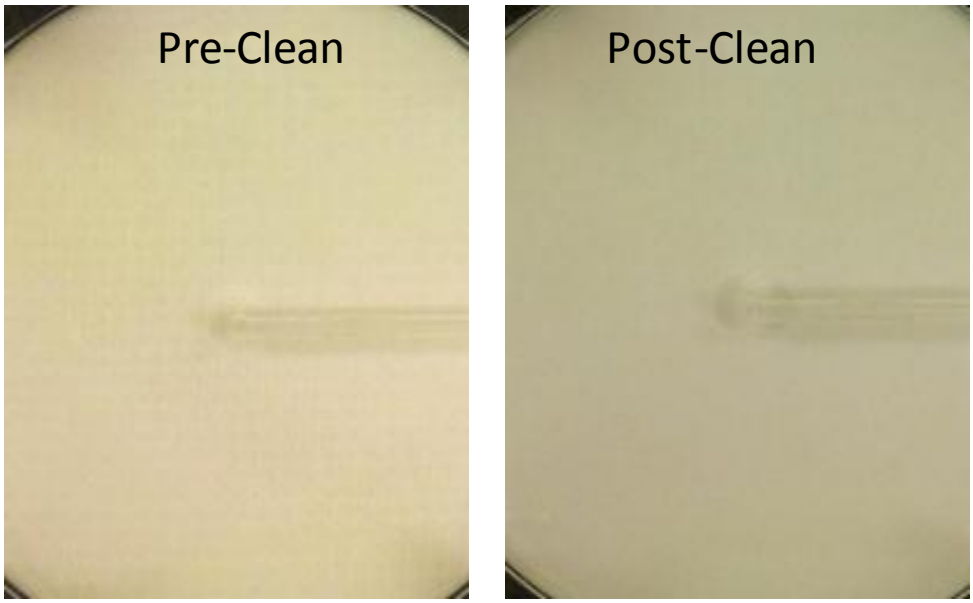


Fig 34. Images of membrane surface before and after chemical cleaning. Membrane samples were taken from the tail RO element of the UF-RO system.

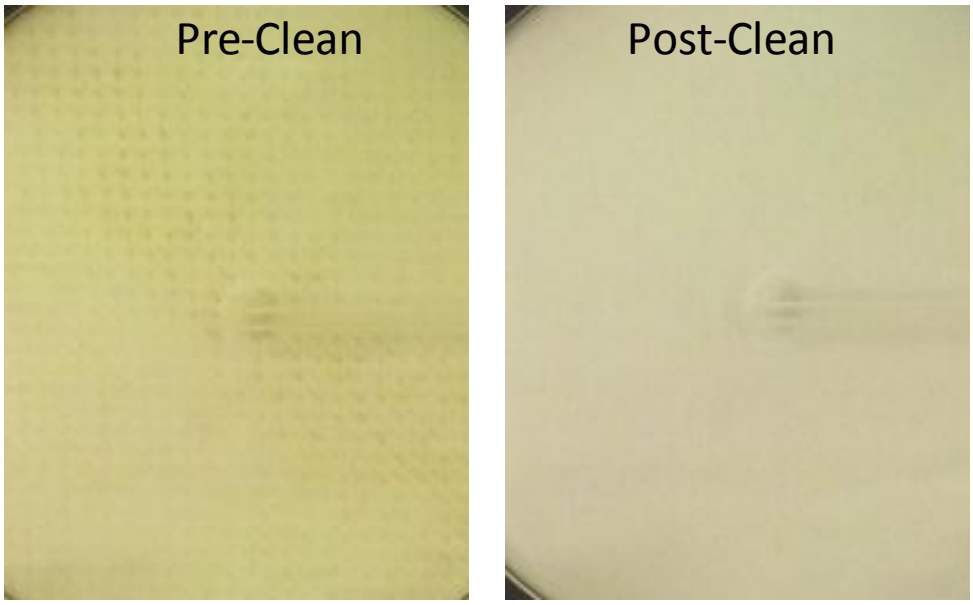


Fig 35. Images of membrane surface before and after chemical cleaning. Membrane samples were taken from the tail RO element of the MBR-RO system.

2.1.12. Other tests

The following tests could not be conducted due to insufficient foulant material on the surfaces of the membrane samples: a) Loss on ignition, and b) ion analysis on digested sample coupons.

3. Conclusions

a) Examinations of the submitted RO membrane elements revealed no visually-observable evidence of physical damage. Fiberglass wraps, end caps, brine seals, and permeate tubes appeared to be in good condition. Feed and permeate spacers and glue lines were also in satisfactory mechanical condition.

b) Lower than normal membrane productivities were evident based on both RO element and membrane sample coupon tests. Productivities of the lead RO elements from the UF-RO and MBR-RO systems were slightly lower than normal (by 8% and 15%, respectively). However, performance testing of membrane sample coupons revealed normal water productivity level, suggesting that fouling in the lead elements were localized and in the early stages. The tail element productivities were significantly below normal for both the UF-RO (by 41%) and MBR-RO (by 25%) systems. The lower-than-normal performance levels of the tail elements were consistent with the results of membrane sample coupon performance testing, with the UF-RO tail element having the lowest level of productivity.

c) Results of performance testing of membrane elements and membrane sample coupons revealed normal or near normal levels of salt rejection (i.e., within 0.1% below normal). Fujiwara test was positive for membrane halogenation only for membranes samples from the RO membrane elements of the MBR-RO system.

d) Internal visual examinations, optical imaging, light microscope analysis, FTIR analysis, and SEM-EDS, CEI analysis of the membrane surfaces indicated the presence of brownish foulant materials on the membrane surfaces of all membrane elements, with the tail RO element from the UF-RO system appearing to be most fouled. The foulant layers appeared to be composed primarily of metal silicates (calcium silicates), clay, and iron-bearing material, as well as gram negative bacteria and amorphous organic material.

e) Preliminary assessments of membrane cleaning suggest that foulant materials can be removed to recover RO membrane permeability to within manufacturer's specifications. Cleaning resulted in slight elevation of the salt passage (i.e., salt transport coefficient), but the salt passage coefficients remained within the expected range of (or slightly below) manufacturer specifications.

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APPENDIX E

ADDITIONAL DATA FOR
GENERAL WATER QUALITY PARAMETERS

This appendix provides additional data for the general water quality parameters discussed in Chapter 5. The effects of temperature on RO removals are discussed in Section E.1, Results from the AOP experiments are discussed in Section E.2, and Section E.3 provides tables of statistics for each analyte.

E.1 TEMPERATURE EFFECTS ON RO REMOVAL

For most of the general water quality parameters that were detected in the UF filtrate or MBR permeate, the observed removals by RO followed a seasonal trend, with removals increasing during the colder winter months and decreasing during the warmer winter months. This phenomenon has been documented previously (Kim et *al*., 2009), and was attributed to an increase in the diffusivity of compounds through the RO membranes. Because compounds diffused faster through the membranes at higher temperatures, the resulting permeate concentrations were higher.

The effect of temperature on boron, nitrate, and silica was discussed in Chapter 5. The other parameters are presented in this section. Most analytes followed a general trend of decreasing removal with increasing temperature, except fluoride, which showed no trend with temperature. As discussed in Chapter 5, the removals of silica (and to a lesser degree, nitrate) in Phase 2 were lower than expected for the temperatures; this change was attributed to chlorine degradation of the RO membranes, which was exposed by the deep cleaning conducted between Phases 1 and 2 (Section 4.3). A similar but small effect was observed for chloride, calcium, and strontium. However, the effects of temperature and membrane condition did not impact the ability of the RO units to meet the water quality targets.

Figure E-1. Alkalinity (Total) Removals by RO Alone as a Function of (a) Time and (b) Temperature

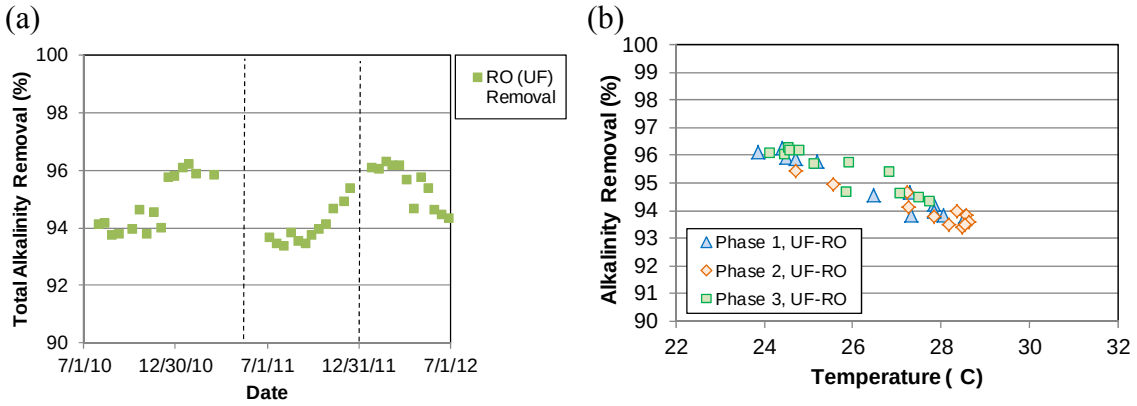


Figure E-2. Ammonia Removals by RO Alone as a Function of (a) Time and (b) Temperature

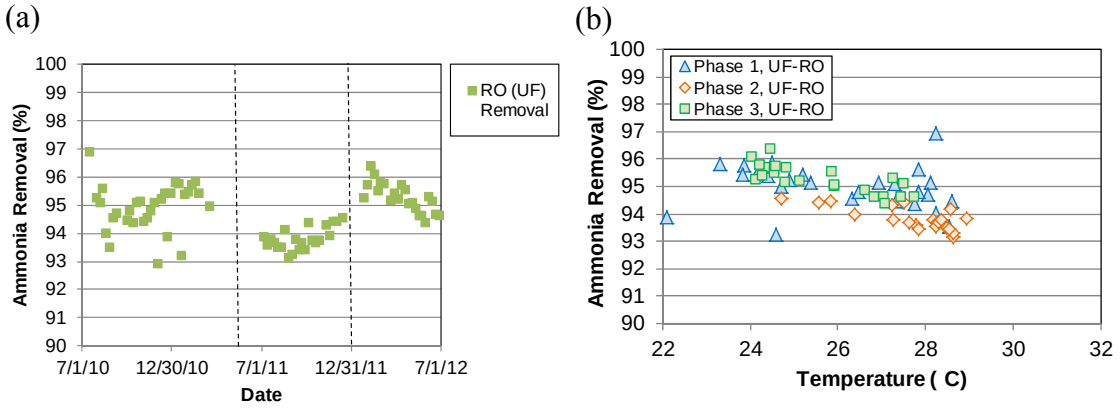


Figure E-3. Calcium Removals by RO Alone as a Function of (a) Time and (b) Temperature

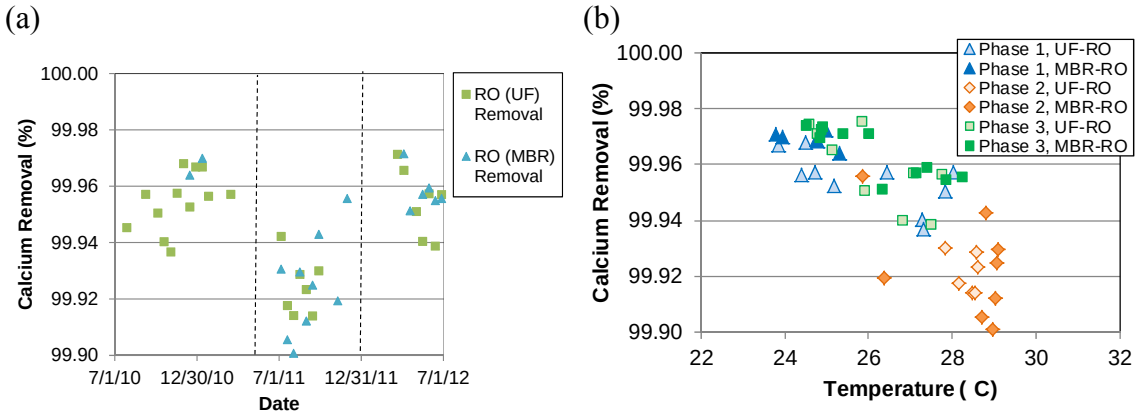


Figure E-4. Chloride Removals by RO Alone as a Function of (a) Time and (b) Temperature

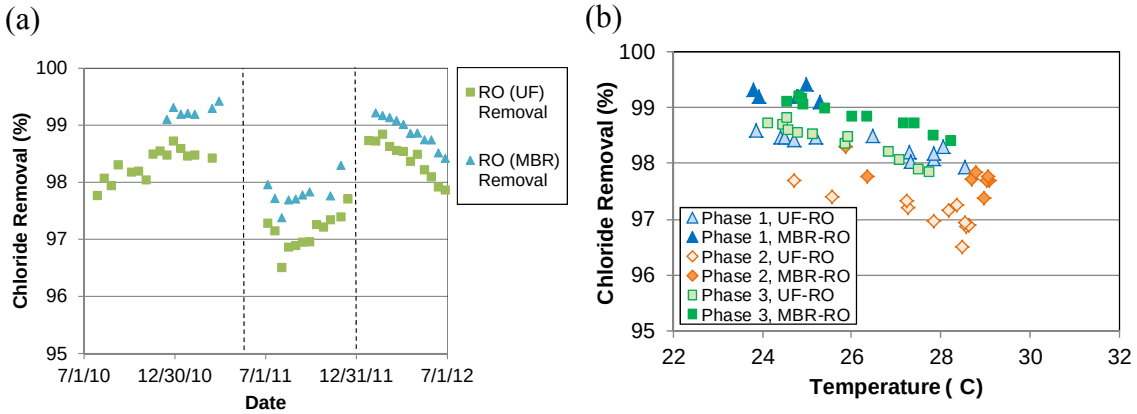


Figure E-5. Fluoride Removals by RO Alone as a Function of (a) Time and (b) Temperature

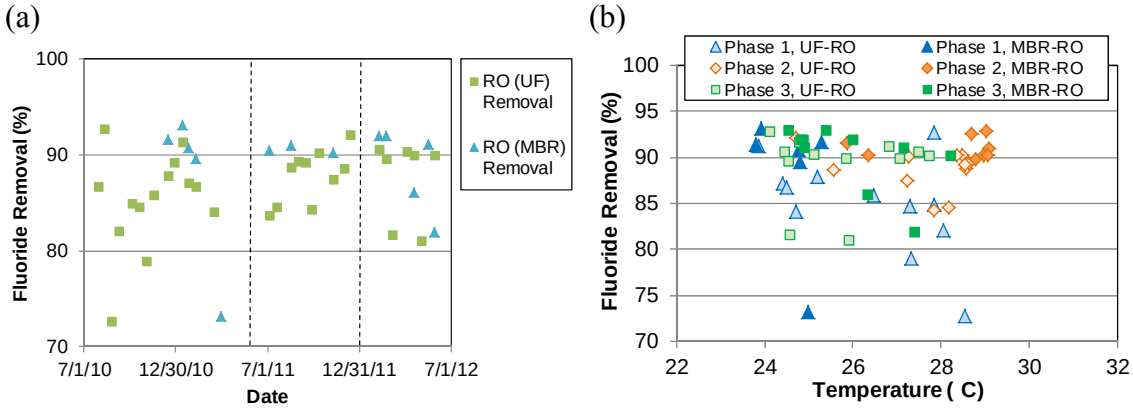


Figure E-6. Potassium Removals by RO Alone as a Function of (a) Time and (b) Temperature

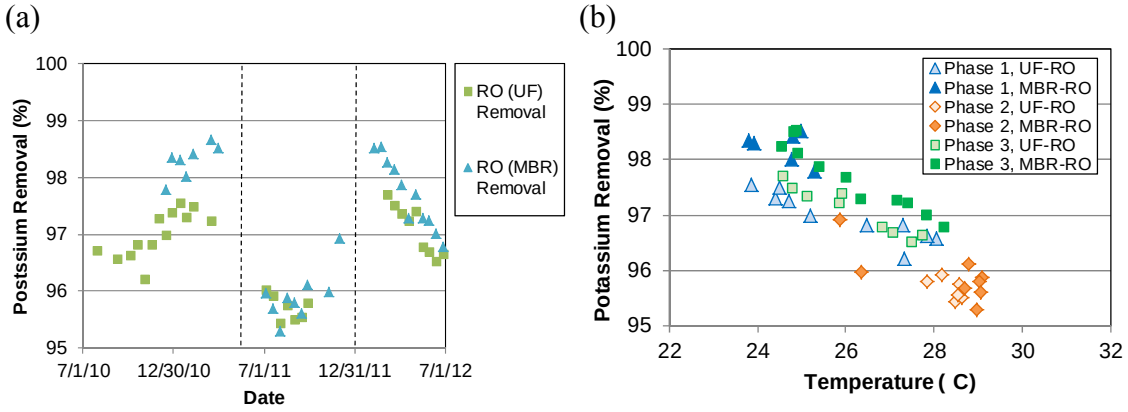


Figure E-7. Sodium Removals by RO Alone as a Function of (a) Time and (b) Temperature

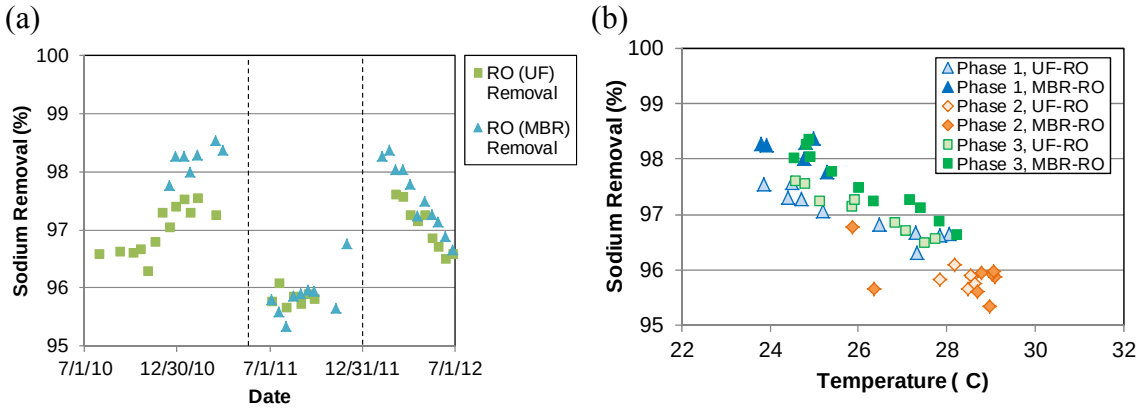


Figure E-8. Strontium Removals by RO Alone as a Function of (a) Time and (b) Temperature

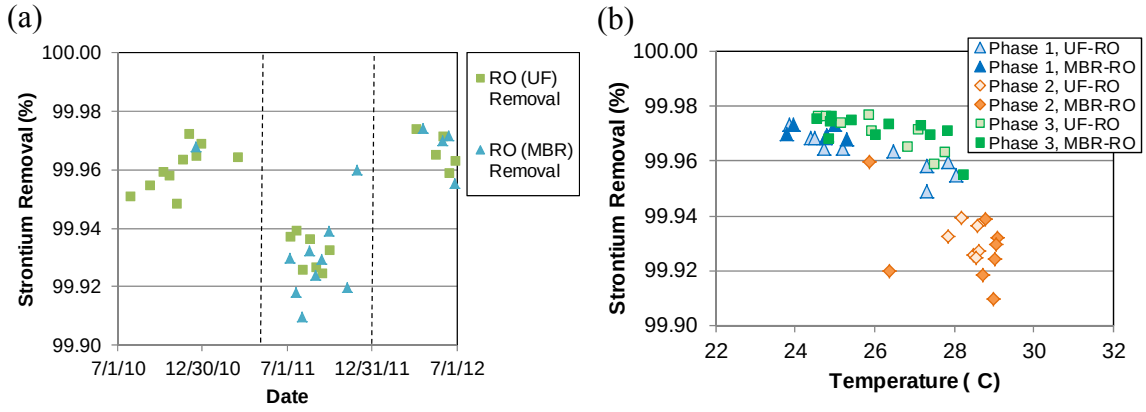


Figure E-9. TDS Removals by RO Alone as a Function of (a) Time and (b) Temperature

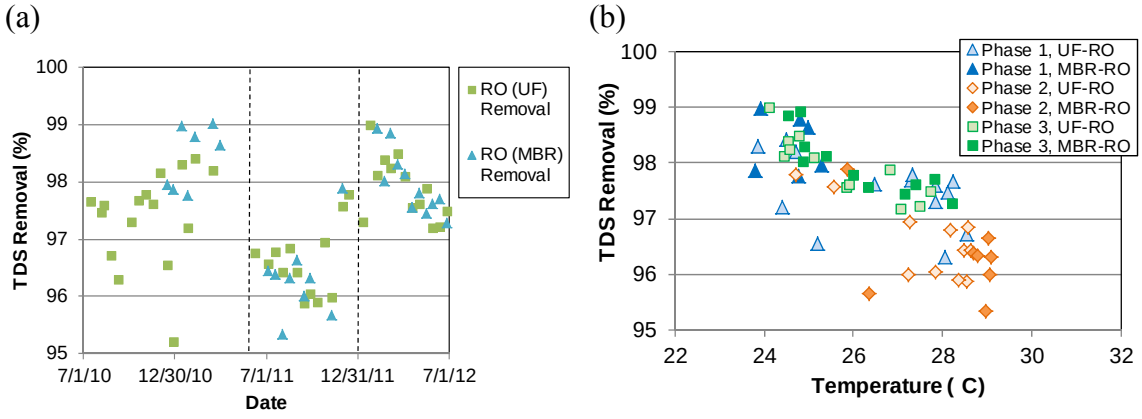
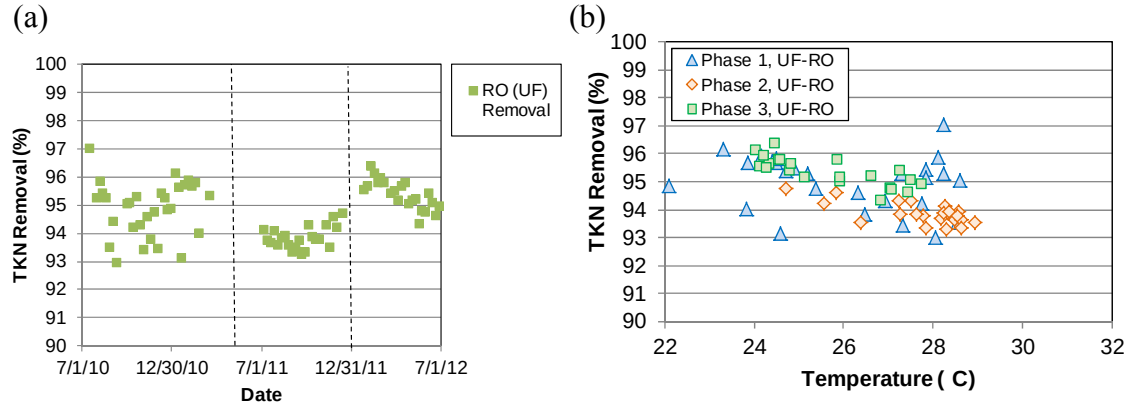


Figure E-10. TKN Removals by RO Alone as a Function of (a) Time and (b) Temperature



E.2 AOP RESULTS

The following sections cover ammonia and TKN (Section E.2.1), nitrate (Section E.2.2), nitrite (Section E.2.3), UVT (Section E.2.4), and the PPCPs, EDCs, and other wastewater indicators (Section E.2.5). TOC and COD were also measured during the AOP experiments, but are not discussed because their concentrations were generally below the reporting limits before and after AOP.

E.2.1 Ammonia and TKN

Figures E-14 and E-15 present the effects of AOP on ammonia and TKN. Neither compound was affected by hydrogen peroxide, regardless of the UV EED. Concentrations of both ammonia and TKN decreased with increasing UV EED, which was likely caused by oxidation of the reduced nitrogen; see the nitrate and nitrite results in Sections E.2.2 and E.2.3 for more information.

Figure E-14. Ammonia Results, UF-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.

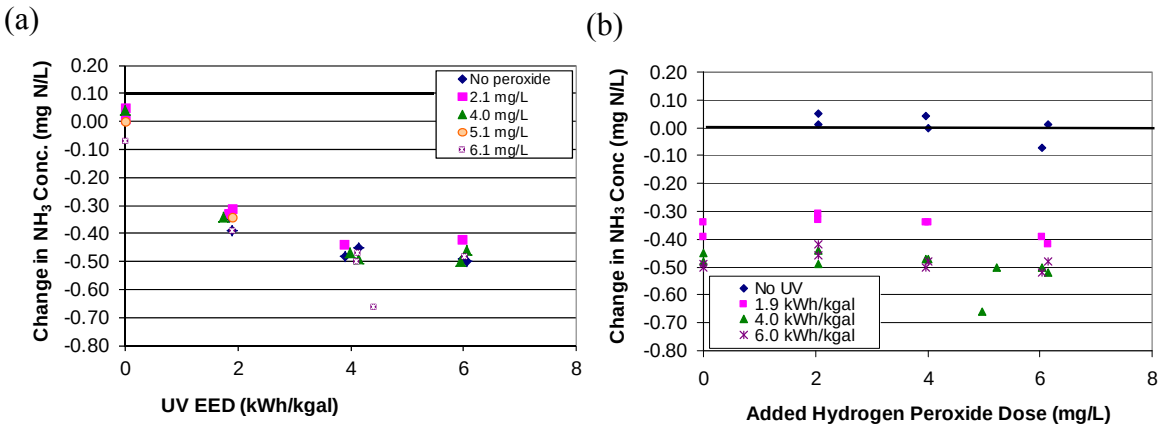
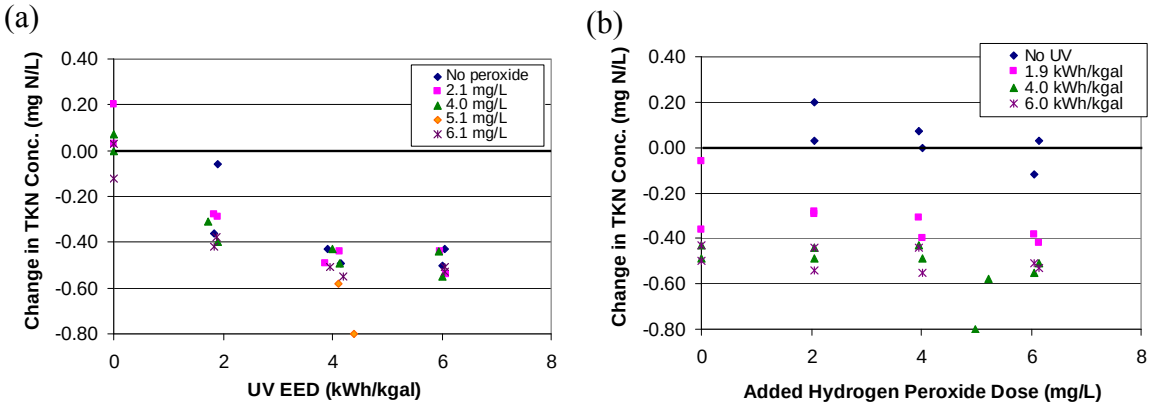


Figure E-15. TKN Results, UF-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.



E.2.2 Nitrate

Figure E-16 and E-17 show the effects of AOP on nitrate for the UF and MBR trains, respectively. Although the nitrate concentrations in the UF-RO permeate were below reporting limits, the AOP increased nitrate concentrations to levels above the reporting limit. It is difficult to identify any trends in nitrate formation with UV EED or hydrogen peroxide dose, but statistical t-test analysis indicated that nitrate formation was statistically significant for both treatment trains when UV was applied. No differences were observed between the UF-RO and MBR-RO effluents.

Figure F-16. Nitrate Results, UF-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.

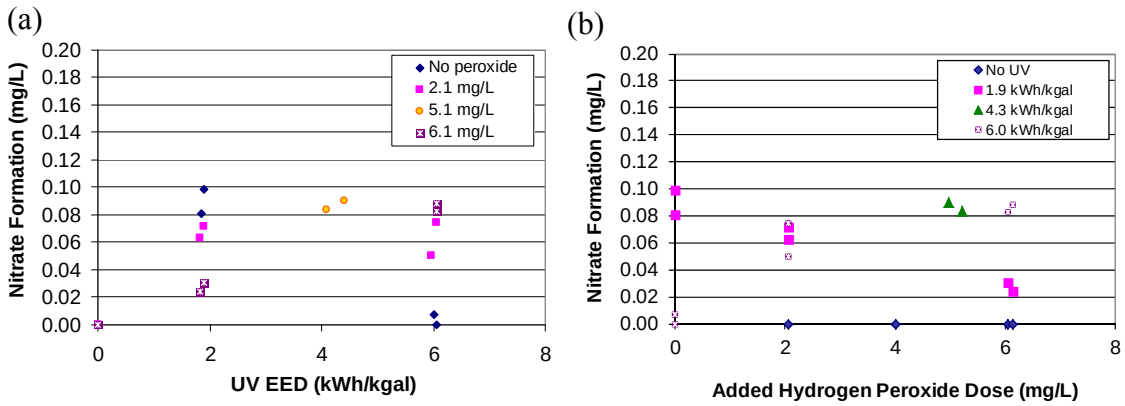
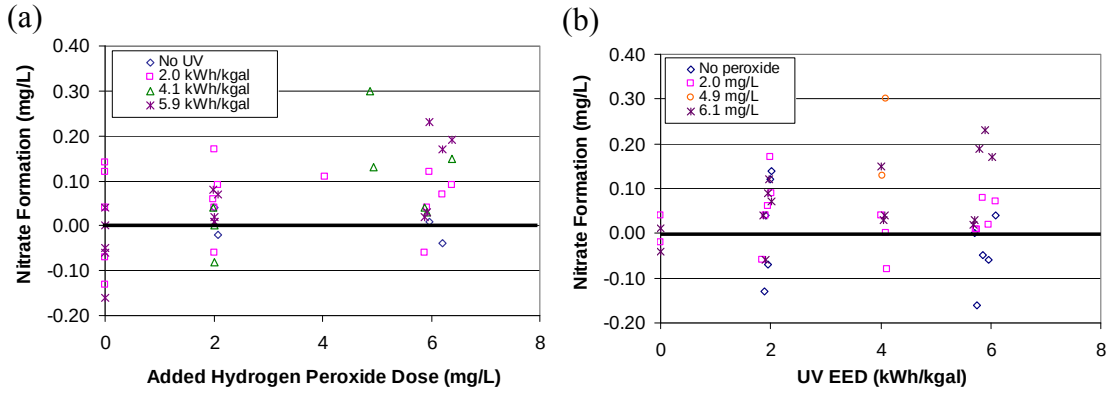


Figure F-17. Nitrate Results, MBR-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.



E.2.3 Nitrite

Figures E-18 and E-19 show AOP results for nitrite in UF-RO and MBR-RO effluents, respectively. Nitrite formation clearly increased as the UV EED increased, and decreased as the hydrogen peroxide dose increased. Nitrite could be formed from the oxidation of reduced nitrogen species, such as ammonia (Zhu et al., 2005) or from the photolysis of chloramine residuals present in the effluent (Li and Blatchley, 2009); higher UV EEDs would cause more oxidation and photolysis. The decrease in nitrite formation with increasing peroxide dose may be caused by subsequent oxidation of nitrite to nitrate (Zhu et al., 2005), or could be due to the fact

that peroxide also absorbs UV radiation, potentially decreasing the amount of UV available to react with the ammonia or chloramines.

Overall, the AOP results for the nitrogen species are consistent with the oxidation of reduced nitrogen species (ammonia, TKN) to more oxidized forms. Although the observed nitrate and nitrite concentrations cannot account for all of the ammonia that is lost, Li and Blatchley (2009) suggest that other oxidized forms, such as nitrous oxide, may also be formed.

Figure E-18. Nitrite Results, UF-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.

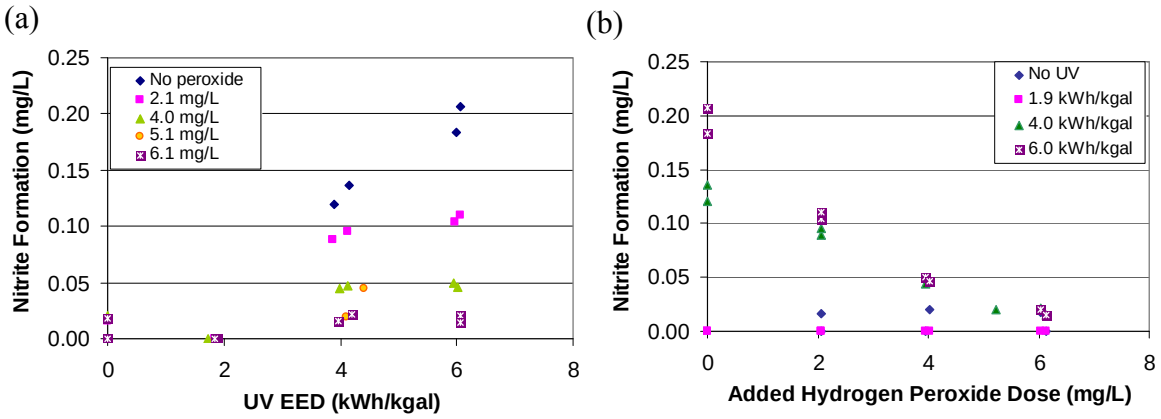
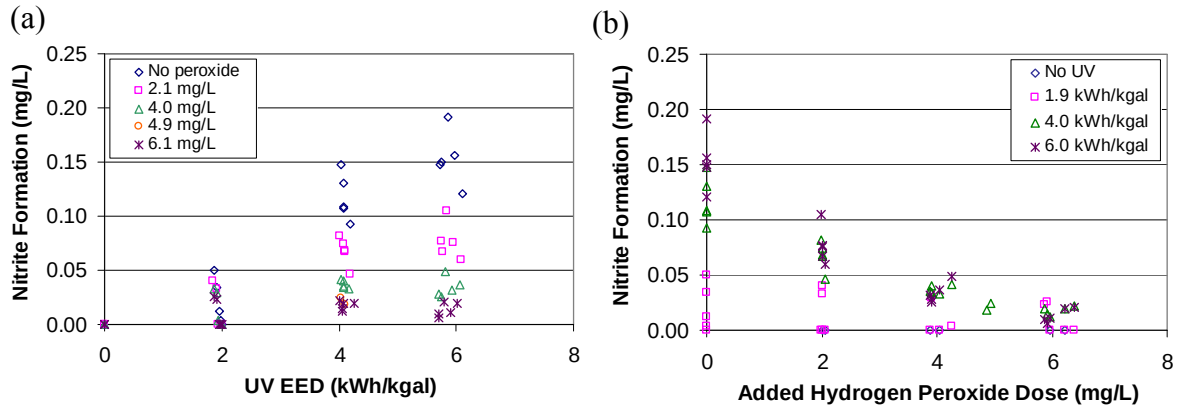


Figure E-19. Nitrite Results, MBR-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.



E.2.4 UVT

Figures E-20 and E-21 plot the UVT for the AOP on the two trains. UVT increased with increasing UV EED; these results may suggest that UV-absorbing bonds are photolyzed by the radiation, thereby increasing the UVT. Hydrogen peroxide had no effect on UVT, and no differences were observed between the UF-RO and MBR-RO effluents.

Figure E-20. UVT Results, UF-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.

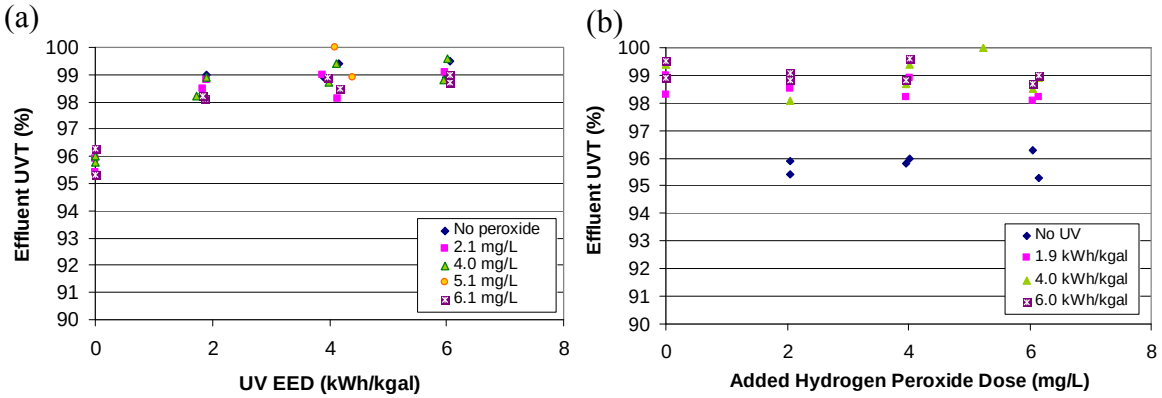
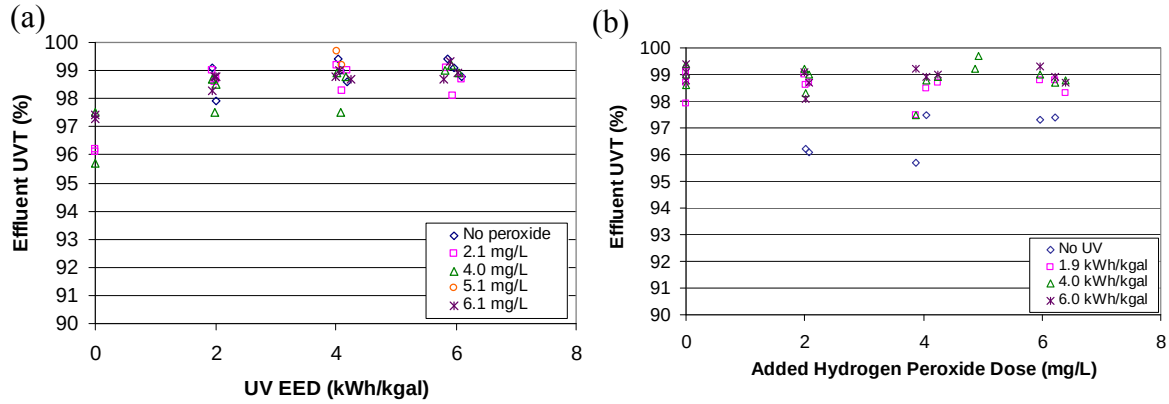


Figure E-21. UVT Results, MBR-RO-AOP Train.
(a) Effect of UV EED, (b) Effect of Hydrogen Peroxide Dose.



E.2.5 PPCPs, EDCs, and Other Wastewater Indicators

During the Phase 1 AOP experiments, 24 PPCPs, EDCs, and other wastewater indicators were measured under selected conditions. These compounds included 17α-ethinylestradiol, 17β-estradiol, acetaminophen, azithromycin, bisphenol A, caffeine, DEET, Dilantin, estrone, gemfibrozil, ibuprofen, iopromide, meprobamate, progesterone, sucralose, sulfamethoxazole, TCEP, triclosan, and six alkylphenolic compounds (octylphenol, nonylphenol, and their mono- and di- ethoxylates). A total of 25 RO permeate samples were taken on six days, three each from the UF-RO and MBR-RO.

In general, these compounds were not detected in the RO permeate, with three exceptions. Caffeine was detected once in UF-RO permeate at a concentration of 58 ng/L on December 7, 2010. Nonylphenol was detected twice: once at a concentration of 27 ng/L in UF-RO permeate on January 19, 2011, and once in MBR-RO permeate at a concentration of 33 ng/L on June 21, 2011. In all three cases, UV alone at a reactor-specific EED of 4 kWh/kgal in the Trojan UV Max G reactor reduced the levels to below the reporting limits of 10 ng/L for caffeine and 25 ng/L for nonylphenol; lower EED values were not tested.

The low detection rate and easy removal by UV indicate that these compounds should not pose an issue in the final product water.

E.3 STATISTICS FOR WATER QUALITY DATA

The following tables provide water quality statistics for each of the general water quality parameters. Concentrations below the reporting limit were conservatively assigned a value of the reporting limit in calculating the averages, standard deviations, and p-values. The tables are organized alphabetically, by the parameter name.

Table E-1. Statistics for Alkalinity, Total

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L $CaCO_3$)	UF	Secondary Effluent	16	365	11	366	337	379	[a]
			UF Filtrate	16	363	12	364	334	380	[a]
			RO Permeate	15	19	4	20	14	23	[a]
			RO Concentrate	2	1,190	85	1,190	1,130	1,250	[a]
		MBR	Secondary Effluent	8	363	13	367	337	379	[a]
			MBR Permeate	7	95	6	97	84	103	[a]
			RO Permeate	7	5	0	5	<5	6	[a]
			RO Concentrate	1	335	[b]	335	335	335	[a]
	Removal (%)	UF	UF	16	0	1	0	-1	4	2.2E-01
			RO	15	95	1	95	94	96	1.9E-29
			UF + RO	15	95	1	95	94	96	1.7E-29
		MBR	MBR	7	74	1	74	73	75	1.3E-12
			RO	5	94	0	94	94	95	9.0E-11
			MBR + RO	5	99	0	99	98	99	7.6E-13
Phase 2	Concentration (mg/L $CaCO_3$)	UF	Secondary Effluent	12	368	12	370	347	383	[a]
			UF Filtrate	12	364	11	366	348	382	[a]
			RO Permeate	13	22	3	23	16	25	[a]
			RO Concentrate	2	1,620	85	1620	1,560	1,680	[a]
		MBR	Secondary Effluent	11	368	12	372	347	383	[a]
			MBR Permeate	10	111	13	119	84	123	[a]
			RO Permeate	9	6	1	6	<5	6	[a]
			RO Concentrate	2	500	31	500	478	522	[a]
	Removal (%)	UF	UF	12	1	1	1	-1	3	1.8E-02
			RO	12	94	1	94	93	95	2.3E-25
			UF + RO	12	94	1	94	93	96	3.1E-25
		MBR	MBR	10	70	3	69	67	76	3.9E-14
			RO	9	95	0	95	94	95	1.2E-20
			MBR + RO	8	98	0	98	98	99	3.4E-22
Phase 3	Concentration (mg/L $CaCO_3$)	UF	Secondary Effluent	12	383	9	380	372	401	[a]
			UF Filtrate	12	381	8	380	371	395	[a]
			RO Permeate	12	17	3	16	14	21	[a]
			RO Concentrate	2	1,570	57	1,570	1,530	1,610	[a]
		MBR	Secondary Effluent	12	383	9	380	372	401	[a]
			MBR Permeate	12	99	19	101	47	125	[a]
			RO Permeate	10	5	0	5	<5	5	[a]
			RO Concentrate	2	484	57	484	444	524	[a]
	Removal (%)	UF	UF	12	0	1	1	-1	2	7.7E-02
			RO	12	96	1	96	94	96	9.7E-25
			UF + RO	12	96	1	96	94	96	1.2E-24
		MBR	MBR	12	74	5	74	67	88	1.7E-14
			RO	1	95	[b]	95	95	95	[b]
			MBR + RO	1	99	[b]	99	99	99	[b]

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-2. Statistics for Aluminum

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (µg/L)	UF	Secondary Effluent	18	25	4	25	20	35	[a]
			UF Filtrate	14	10	1	<10	<10	12	[a]
			RO Permeate	15	<10	0	<10	<10	<10	[a]
			RO Concentrate	2	60	11	60	52	68	[a]
		MBR	Secondary Effluent	8	25	5	24	20	33	[a]
			MBR Permeate	7	<10	0	<10	<10	<10	[a]
			RO Permeate	7	<10	0	<10	<10	<10	[a]
			RO Concentrate	1	51	[b]	51	51	52	[a]
	Removal (%)	UF	UF	6	55	7	55	49	68	5.9E-06
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	1	61	[b]	61	61	61	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (µg/L)	UF	Secondary Effluent	12	22	4	21	18	30	[a]
			UF Filtrate	7	<10	0	<10	<10	<10	[a]
			RO Permeate	12	10	0	<10	<10	11	[a]
			RO Concentrate	2	43	1	43	43	44	[a]
		MBR	Secondary Effluent	11	22	4	20	18	30	[a]
			MBR Permeate	10	11	2	<10	<10	17	[a]
			RO Permeate	9	<10	0	<10	<10	<10	[a]
			RO Concentrate	2	29	0	29	29	30	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	1	36	[b]	36	36	36	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (µg/L)	UF	Secondary Effluent	12	26	3	25	21	32	[a]
			UF Filtrate	9	11	3	<10	<10	18	[a]
			RO Permeate	12	<10	0	<10	<10	<10	[a]
			RO Concentrate	2	50	4	50	47	53	[a]
		MBR	Secondary Effluent	12	26	3	25	21	32	[a]
			MBR Permeate	12	10	1	<10	<10	13	[a]
			RO Permeate	11	<10	0	<10	<10	<10	[a]
			RO Concentrate	2	30	1	30	29	30	[a]
	Removal (%)	UF	UF	3	40	14	48	24	49	3.8E-02
			RO	1	44	[b]	44	44	44	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	1	43	[b]	43	43	43	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-3. Statistics for Ammonia as Nitrogen

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg N/L)	UF	Secondary Effluent	168	36	2	36	22	42	[a]
			UF Filtrate	33	35	3	35	25	38	[a]
			RO Permeate	31	1.8	0.3	1.8	1.0	2.6	[a]
			RO Concentrate	2	215	8	215	209	221	[a]
		MBR	Secondary Effluent	80	36	3	37	22	42	[a]
			MBR Permeate	72	<1.0	0	<1.0	<1.0	<1.0	[a]
			RO Permeate	16	<1.0	0	<1.0	<1.0	<1.0	[a]
			RO Concentrate	1	11	[b]	11	11	11	[a]
	Removal (%)	UF	UF	33	0	2	1	-8	3	5.3E-01
			RO	31	95	1	95	93	97	1.9E-63
			UF + RO	31	95	1	95	93	97	1.8E-63
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg N/L)	UF	Secondary Effluent	106	36	2	35	30	46	[a]
			UF Filtrate	23	35	2	35	32	41	[a]
			RO Permeate	23	2.2	0.1	2.2	1.9	2.5	[a]
			RO Concentrate	2	214	0	214	214	214	[a]
		MBR	Secondary Effluent	104	36	2	35	30	46	[a]
			MBR Permeate	99	<1.0	0	<1.0	<1.0	<1.0	[a]
			RO Permeate	18	<1.0	0	<1.0	<1.0	<1.0	[a]
			RO Concentrate	2	2.2	0.6	2.2	1.8	2.7	[a]
	Removal (%)	UF	UF	23	0	5	1	-19	5	8.1E-01
			RO	22	94	0	94	93	95	1.6E-51
			UF + RO	23	94	0	94	93	95	1.1E-54
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg N/L)	UF	Secondary Effluent	112	40	3	40	33	49	[a]
			UF Filtrate	22	40	3	39	34	49	[a]
			RO Permeate	22	1.9	0.2	1.9	1.5	2.4	[a]
			RO Concentrate	2	242	31	242	220	264	[a]
		MBR	Secondary Effluent	112	40	3	40	33	49	[a]
			MBR Permeate	109	1	0	<1.0	<1.0	2	[a]
			RO Permeate	23	<1.0	0	<1.0	<1.0	<1.0	[a]
			RO Concentrate	2	2.3	0.0	2.3	2.3	2.4	[a]
	Removal (%)	UF	UF	22	1	1	1	-1	3	2.3E-04
			RO	22	95	1	95	94	96	2.9E-49
			UF + RO	22	95	1	95	94	97	4.1E-49
		MBR	MBR	1	96	[b]	96	96	96	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-4. Statistics for Barium

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (µg/L)	UF	Secondary Effluent	18	106	13	109	87	131	[a]
			UF Filtrate	14	100	12	100	77	123	[a]
			RO Permeate	15	<0.5	0.0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	623	124	623	535	710	[a]
		MBR	Secondary Effluent	8	123	17	118	107	159	[a]
			MBR Permeate	7	116	21	111	97	158	[a]
			RO Permeate	7	<0.5	0.0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	1	724	[b]	724	724	724	[a]
	Removal (%)	UF	UF	14	9	2	10	6	13	1.9E-10
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	7	8	4	8	1	14	2.9E-03
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (µg/L)	UF	Secondary Effluent	12	137	13	139	110	158	[a]
			UF Filtrate	7	122	13	122	103	145	[a]
			RO Permeate	12	0.7	0.7	<0.5	<0.5	2.8	[a]
			RO Concentrate	2	772	16	772	760	783	[a]
		MBR	Secondary Effluent	11	138	13	141	110	158	[a]
			MBR Permeate	10	117	12	117	97	143	[a]
			RO Permeate	9	<0.5	0.0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	755	32	755	732	777	[a]
	Removal (%)	UF	UF	7	13	3	14	8	18	2.5E-05
			RO	1	98	[b]	98	98	98	[b]
			UF + RO	1	98	[b]	98	98	98	[b]
		MBR	MBR	10	14	3	15	9	19	3.5E-07
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (µg/L)	UF	Secondary Effluent	12	150	27	146	116	199	[a]
			UF Filtrate	9	134	24	127	106	172	[a]
			RO Permeate	12	<0.5	0.0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	718	11	718	710	726	[a]
		MBR	Secondary Effluent	12	150	27	146	116	199	[a]
			MBR Permeate	12	129	26	127	98	182	[a]
			RO Permeate	11	0.6	0.3	<0.5	<0.5	1.7	[a]
			RO Concentrate	2	639	76	639	585	692	[a]
	Removal (%)	UF	UF	9	14	1	14	12	15	5.5E-10
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	12	14	3	14	9	20	8.6E-09
			RO	1	99	[b]	99	99	99	[b]
			MBR + RO	1	99	[b]	99	99	99	[b]

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-5. Statistics for Boron

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	18	0.82	0.05	0.81	0.74	0.90	[a]
			UF Filtrate	14	0.84	0.04	0.84	0.75	0.89	[a]
			RO Permeate	15	0.58	0.03	0.58	0.50	0.64	[a]
			RO Concentrate	2	2.25	0.35	2.25	2.00	2.50	[a]
		MBR	Secondary Effluent	8	0.82	0.05	0.81	0.74	0.90	[a]
			MBR Permeate	7	0.84	0.07	0.83	0.72	0.94	[a]
			RO Permeate	7	0.46	0.05	0.47	0.39	0.52	[a]
			RO Concentrate	1	3.10	[b]	3.10	3.10	3.10	[a]
	Removal (%)	UF	UF	14	-2	2	-1	-8	2	2.8E-02
			RO	13	31	3	32	25	35	6.0E-14
			UF + RO	15	29	3	30	24	34	6.7E-15
		MBR	MBR	7	-2	4	-1	-9	3	1.4E-01
			RO	7	45	4	44	40	51	1.1E-07
			MBR + RO	7	44	4	44	38	51	1.1E-07
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	0.88	0.05	0.89	0.78	0.95	[a]
			UF Filtrate	7	0.88	0.05	0.87	0.82	0.95	[a]
			RO Permeate	12	0.70	0.04	0.71	0.64	0.76	[a]
			RO Concentrate	2	1.80	0.14	1.80	1.70	1.90	[a]
		MBR	Secondary Effluent	11	0.89	0.05	0.90	0.78	0.95	[a]
			MBR Permeate	10	0.87	0.03	0.88	0.80	0.91	[a]
			RO Permeate	9	0.70	0.03	0.71	0.64	0.75	[a]
			RO Concentrate	2	1.90	0.21	1.85	1.70	2.00	[a]
	Removal (%)	UF	UF	7	2	2	2	0	6	3.3E-02
			RO	7	18	3	17	15	23	5.9E-06
			UF + RO	12	20	2	21	16	24	5.3E-12
		MBR	MBR	10	1	3	1	-3	8	3.4E-01
			RO	9	20	4	19	15	28	2.9E-07
			MBR + RO	8	21	4	21	15	26	2.4E-06
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	0.92	0.09	0.92	0.80	1.10	[a]
			UF Filtrate	9	0.92	0.09	0.90	0.82	1.10	[a]
			RO Permeate	11	0.66	0.06	0.64	0.58	0.77	[a]
			RO Concentrate	2	2.30	0.28	2.30	2.10	2.50	[a]
		MBR	Secondary Effluent	12	0.92	0.09	0.92	0.80	1.10	[a]
			MBR Permeate	12	0.92	0.08	0.92	0.81	1.10	[a]
			RO Permeate	11	0.62	0.07	0.60	0.52	0.77	[a]
			RO Concentrate	2	2.60	0.21	2.60	2.40	2.70	[a]
	Removal (%)	UF	UF	9	1	2	1	-2	4	3.6E-01
			RO	8	27	5	29	20	34	1.3E-06
			UF + RO	11	28	5	30	21	36	2.7E-09
		MBR	MBR	12	0	1	0	-2	2	9.4E-01
			RO	11	32	5	30	25	39	2.1E-09
			MBR + RO	11	32	6	30	25	40	3.0E-09

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-6. Statistics for Calcium

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	18	70	4	70	63	77	[a]
			UF Filtrate	14	70	4	71	63	77	[a]
			RO Permeate	15	0.03	0	0.03	<0.02	0.05	[a]
			RO Concentrate	2	424	28	424	404	443	[a]
		MBR	Secondary Effluent	8	69	4	71	63	74	[a]
			MBR Permeate	7	68	4	68	63	73	[a]
			RO Permeate	7	0.02	0	<0.02	<0.02	0.03	[a]
			RO Concentrate	1	419	[b]	419	419	419	[a]
	Removal (%)	UF	UF	14	0	2	0	-2	3	3.9E-01
			RO	12	100	0	100	100	100	1.7E-45
			UF + RO	14	100	0	100	100	100	6.7E-54
		MBR	MBR	7	1	2	0	-1	5	2.4E-01
			RO	2	100	0	100	100	100	1.9E-05
			MBR + RO	2	100	0	100	100	100	1.5E-05
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	72	4	73	67	78	[a]
			UF Filtrate	7	70	2	71	67	73	[a]
			RO Permeate	12	0.04	0	0.05	0.04	0.07	[a]
			RO Concentrate	2	486	5	486	482	489	[a]
		MBR	Secondary Effluent	11	73	4	73	67	78	[a]
			MBR Permeate	10	71	3	71	66	75	[a]
			RO Permeate	9	0.05	0	0.05	0.03	0.07	[a]
			RO Concentrate	2	449	30	449	428	470	[a]
	Removal (%)	UF	UF	7	1	3	1	-2	6	2.2E-01
			RO	7	100	0	100	100	100	2.2E-25
			UF + RO	12	100	0	100	100	100	8.8E-44
		MBR	MBR	10	2	2	2	-2	5	1.5E-02
			RO	9	100	0	100	100	100	1.6E-31
			MBR + RO	9	100	0	100	100	100	1.6E-31
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	75	5	76	66	82	[a]
			UF Filtrate	9	76	4	77	70	82	[a]
			RO Permeate	12	0.02	0	0.03	<0.02	0.04	[a]
			RO Concentrate	2	462	7	462	457	467	[a]
		MBR	Secondary Effluent	12	75	5	76	66	82	[a]
			MBR Permeate	12	74	5	73	66	84	[a]
			RO Permeate	11	0.02	0	<0.02	<0.02	0.04	[a]
			RO Concentrate	2	417	57	417	377	457	[a]
	Removal (%)	UF	UF	9	1	3	0	-4	6	5.5E-01
			RO	7	100	0	100	100	100	6.2E-25
			UF + RO	9	100	0	100	100	100	8.4E-33
		MBR	MBR	12	2	2	2	-3	4	3.1E-02
			RO	6	100	0	100	100	100	3.7E-22
			MBR + RO	6	100	0	100	100	100	5.5E-22

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-7. Statistics for Chloride

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	16	445	26	445	398	492	[a]
			UF Filtrate	16	459	21	460	414	487	[a]
			RO Permeate	15	8	1	7	5	10	[a]
			RO Concentrate	2	2,855	205	2,860	2,710	3,000	[a]
		MBR	Secondary Effluent	8	450	33	458	398	492	[a]
			MBR Permeate	7	461	29	472	405	495	[a]
			RO Permeate	7	3	1	4	3	4	[a]
			RO Concentrate	1	2,810	[b]	2,810	2,810	2,810	[a]
	Removal (%)	UF	UF	16	-3	4	-2	-16	2	4.0E-03
			RO	15	98	0	98	98	99	1.7E-37
			UF + RO	15	98	0	98	98	99	2.4E-37
		MBR	MBR	7	-1	1	-1	-2	0	5.8E-02
			RO	7	99	0	99	99	99	2.7E-19
			MBR + RO	7	99	0	99	99	99	3.4E-19
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	476	20	479	440	506	[a]
			UF Filtrate	12	486	16	487	456	509	[a]
			RO Permeate	12	14	2	14	11	17	[a]
			RO Concentrate	2	2,855	21	2,860	2,840	2,870	[a]
		MBR	Secondary Effluent	11	475	21	478	440	506	[a]
			MBR Permeate	10	489	19	492	458	519	[a]
			RO Permeate	9	11	1	11	9	14	[a]
			RO Concentrate	2	2,940	170	2,940	2,820	3,060	[a]
	Removal (%)	UF	UF	12	-2	4	-2	-10	6	6.7E-02
			RO	12	97	0	97	97	98	5.5E-29
			UF + RO	12	97	0	97	97	98	2.5E-29
		MBR	MBR	10	-2	3	-2	-9	0	2.5E-02
			RO	9	98	0	98	97	98	2.6E-22
			MBR + RO	8	98	0	98	97	98	2.6E-19
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	487	28	482	460	554	[a]
			UF Filtrate	12	502	28	498	471	564	[a]
			RO Permeate	12	8	2	8	6	11	[a]
			RO Concentrate	2	3,105	35	3,110	3,080	3,130	[a]
		MBR	Secondary Effluent	12	487	28	482	460	554	[a]
			MBR Permeate	12	496	29	492	460	559	[a]
			RO Permeate	11	6	1	5	4	8	[a]
			RO Concentrate	2	2,855	177	2,860	2,730	2,980	[a]
	Removal (%)	UF	UF	12	-3	1	-3	-6	-1	3.5E-06
			RO	12	98	0	99	98	99	7.4E-29
			UF + RO	12	98	0	98	98	99	1.1E-28
		MBR	MBR	12	-2	2	-2	-5	1	3.4E-03
			RO	11	99	0	99	98	99	2.9E-27
			MBR + RO	11	99	0	99	98	99	3.0E-27

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-8. Statistics for COD, Soluble

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	159	43	7	42	20	67	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	Secondary Effluent	73	46	8	44	29	67	[a]
			MBR Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	105	45	6	45	20	73	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	Secondary Effluent	103	45	6	45	20	73	[a]
			MBR Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	109	50	5	50	29	66	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	Secondary Effluent	109	50	5	50	29	66	[a]
			MBR Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-9. Statistics for COD, Total

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	164	50	7	50	29	82	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	2	219	1	219	218	219	[a]
		MBR	Secondary Effluent	69	52	8	52	34	82	[a]
			MBR Permeate	70	32	7	32	21	64	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	1	163	[b]	163	163	163	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	62	38	12	40	-14	59	3.8E-33
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	106	52	6	53	36	67	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	2	194	107	194	118	270	[a]
		MBR	Secondary Effluent	104	52	6	52	36	67	[a]
			MBR Permeate	99	30	6	30	16	56	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	2	152	103	152	79	225	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	99	42	10	42	-4	64	8.9E-66
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	112	60	6	61	45	75	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	2	288	54	288	250	326	[a]
		MBR	Secondary Effluent	112	60	6	61	45	75	[a]
			MBR Permeate	109	35	5	35	20	66	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	2	222	0	222	222	222	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	109	42	10	44	-20	69	4.9E-72
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-10. Statistics for Fluoride

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	16	1.4	0.7	1.1	0.9	3.0	[a]
			UF Filtrate	16	1.4	0.7	1.2	0.9	3.1	[a]
			RO Permeate	15	0.2	0.1	0.2	<0.1	0.3	[a]
			RO Concentrate	2	12	8.8	12	5.3	18	[a]
		MBR	Secondary Effluent	8	1.6	0.7	1.2	0.9	3.0	[a]
			MBR Permeate	7	1.8	0.9	1.2	1.0	3.5	[a]
			RO Permeate	7	0.2	0.1	0.2	<0.1	0.3	[a]
			RO Concentrate	1	20	[b]	20	20	20	[a]
	Removal (%)	UF	UF	16	-1	4	0	-15	4	4.0E-01
			RO	14	85	5	86	73	93	1.4E-17
			UF + RO	14	85	5	86	72	93	3.6E-17
		MBR	MBR	7	-4	8	-4	-16	11	2.7E-01
			RO	5	88	8	91	73	93	1.8E-05
			MBR + RO	5	87	8	91	72	92	1.9E-05
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	1.2	0.4	1.1	0.9	2.3	[a]
			UF Filtrate	12	1.2	0.3	1.1	1.0	2.2	[a]
			RO Permeate	12	0.1	0.0	<0.1	<0.1	0.2	[a]
			RO Concentrate	2	3.2	4.3	3.2	<0.1	6.2	[a]
		MBR	Secondary Effluent	11	1.1	0.1	1.1	0.9	1.4	[a]
			MBR Permeate	10	1.1	0.1	1.1	1.0	1.4	[a]
			RO Permeate	9	<0.1	0.0	<0.1	<0.1	<0.1	[a]
			RO Concentrate	2	6.4	0.2	6.4	6.3	6.5	[a]
	Removal (%)	UF	UF	12	1	4	0	-2	9	2.8E-01
			RO	10	88	3	89	84	92	5.3E-15
			UF + RO	10	88	3	89	84	93	1.2E-14
		MBR	MBR	10	-2	6	-3	-11	10	2.5E-01
			RO	3	91	0	90	90	91	6.1E-06
			MBR + RO	2	91	1	91	90	92	6.5E-03
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	1.2	0.1	1.2	1.0	1.4	[a]
			UF Filtrate	12	1.2	0.2	1.2	1.0	1.5	[a]
			RO Permeate	12	0.1	0.1	<0.1	<0.1	0.3	[a]
			RO Concentrate	2	7.4	0.8	7.4	6.8	7.9	[a]
		MBR	Secondary Effluent	12	1.2	0.1	1.2	1.0	1.4	[a]
			MBR Permeate	12	1.2	0.1	1.2	1.0	1.4	[a]
			RO Permeate	11	0.2	0.3	<0.1	<0.1	1.1	[a]
			RO Concentrate	2	7.1	0.0	7.1	7.1	7.1	[a]
	Removal (%)	UF	UF	12	0	5	0	-9	11	7.8E-01
			RO	7	88	4	90	81	91	2.7E-09
			UF + RO	7	88	4	90	82	91	1.1E-09
		MBR	MBR	12	1	4	0	-4	7	6.1E-01
			RO	6	74	36	89	1	92	4.0E-03
			MBR + RO	5	89	4	91	82	92	1.5E-06

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-11. Statistics for Iron

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	29	1.3	0.4	1.2	0.9	2.6	[a]
			UF Filtrate	29	0.1	0.0	0.1	0.1	0.2	[a]
			RO Permeate	15	<0.02	0.0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	0.7	0.1	0.7	0.6	0.7	[a]
		MBR	Secondary Effluent	14	1.50	0.40	1.40	1.10	2.60	[a]
			MBR Permeate	13	0.10	0.02	0.10	0.07	0.14	[a]
			RO Permeate	7	<0.02	0.00	<0.02	<0.02	<0.02	[a]
			RO Concentrate	1	0.55	[b]	0.55	0.55	0.55	[a]
	Removal (%)	UF	UF	29	90	2	90	86	96	3.8E-46
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	13	93	2	92	90	97	3.3E-21
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	23	1.3	0.4	1.2	0.1	2.1	[a]
			UF Filtrate	23	0.1	0.0	0.1	0.1	0.2	[a]
			RO Permeate	12	<0.02	0.0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	0.7	0.0	0.7	0.7	0.7	[a]
		MBR	Secondary Effluent	22	1.26	0.43	1.20	0.12	2.10	[a]
			MBR Permeate	21	0.11	0.01	0.11	0.09	0.15	[a]
			RO Permeate	9	<0.02	0.00	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	0.55	0.04	0.55	0.52	0.58	[a]
	Removal (%)	UF	UF	22	86	21	90	-8	94	9.7E-15
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	21	88	16	91	17	94	2.1E-16
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	23	1.5	0.2	1.5	1.1	1.9	[a]
			UF Filtrate	22	0.1	0.1	0.1	0.1	0.4	[a]
			RO Permeate	12	<0.02	0.00	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	0.9	0.3	0.9	0.7	1.1	[a]
		MBR	Secondary Effluent	23	1.5	0.2	1.5	1.1	1.9	[a]
			MBR Permeate	23	0.1	0.0	0.1	0.1	0.2	[a]
			RO Permeate	11	<0.02	0.00	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	0.7	0.2	0.7	0.6	0.8	[a]
	Removal (%)	UF	UF	22	90	3	91	78	94	4.5E-32
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	23	92	2	93	89	95	6.7E-41
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-12. Statistics for Magnesium

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	18	22	1	23	20	24	[a]
			UF Filtrate	14	23	2	23	20	26	[a]
			RO Permeate	15	<0.02	0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	149	1	149	148	150	[a]
		MBR	Secondary Effluent	8	22	2	23	20	24	[a]
			MBR Permeate	7	22	1	23	20	24	[a]
			RO Permeate	7	<0.02	0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	1	143	[b]	143	143	143	[a]
	Removal (%)	UF	UF	14	0	3	0	-8	5	7.9E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	7	-2	3	0	-8	2	2.7E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	24	2	24	20	28	[a]
			UF Filtrate	7	23	1	23	22	26	[a]
			RO Permeate	12	<0.02	0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	154	18	154	141	167	[a]
		MBR	Secondary Effluent	11	24	2	24	20	28	[a]
			MBR Permeate	10	23	2	24	21	26	[a]
			RO Permeate	9	0.02	0	<0.02	<0.02	0.03	[a]
			RO Concentrate	2	147	11	147	139	154	[a]
	Removal (%)	UF	UF	7	1	2	0	-2	4	5.3E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	10	0	2	-1	-2	3	7.7E-01
			RO	3	100	0	100	100	100	1.5E-09
			MBR + RO	3	100	0	100	100	100	1.5E-09
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	25	2	24	22	29	[a]
			UF Filtrate	9	25	2	25	23	28	[a]
			RO Permeate	12	<0.02	0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	163	6	163	158	167	[a]
		MBR	Secondary Effluent	12	25	2	24	22	29	[a]
			MBR Permeate	12	25	2	24	23	28	[a]
			RO Permeate	11	<0.02	0	<0.02	<0.02	<0.02	[a]
			RO Concentrate	2	145	26	145	126	163	[a]
	Removal (%)	UF	UF	9	0	1	0	-3	2	7.4E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	12	0	2	-1	-2	3	8.3E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-13. Statistics for Nitrate as Nitrogen

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg N/L)	UF	Secondary Effluent	31	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			UF Filtrate	31	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			RO Permeate	29	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			RO Concentrate	2	0.13	0.0	0.13	0.12	0.14	[a]
		MBR	Secondary Effluent	14	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			MBR Permeate	70	38	3.9	38	23	45	[a]
			RO Permeate	14	1.5	0.4	1.5	0.93	2.2	[a]
			RO Concentrate	1	224	[b]	224	224	224	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	13	-36,669	418	-36,600	-41,400	-25,400	6.3E-13
			RO	14	96	1	96	95	97	1.3E-28
			MBR + RO	13	-1,401	361	-1,350	-2,100	-830	8.7E-09
Phase 2	Concentration (mg N/L)	UF	Secondary Effluent	23	<0.10	0.0	<0.10	0.0	<0.10	[a]
			UF Filtrate	23	<0.10	0.0	<0.10	0.0	<0.10	[a]
			RO Permeate	23	<0.10	0.0	<0.10	0.0	<0.10	[a]
			RO Concentrate	2	0.2	0.1	0.2	0.1	0.3	[a]
		MBR	Secondary Effluent	22	<0.10	0.0	<0.10	0.0	<0.10	[a]
			MBR Permeate	99	37	2.6	37	30	46	[a]
			RO Permeate	18	4.6	0.4	4.5	3.9	5.2	[a]
			RO Concentrate	2	200	0.7	200	199	200	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	21	-50,751	609	-38,000	-316,567	-32,500	1.1E-03
			RO	18	88	1	87	85	90	2.3E-34
			MBR + RO	18	-6,717	921	-4,515	-43,625	-3,800	6.6E-03
Phase 3	Concentration (mg N/L)	UF	Secondary Effluent	23	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			UF Filtrate	22	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			RO Permeate	22	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			RO Concentrate	2	<0.10	0.0	<0.10	<0.10	<0.10	[a]
		MBR	Secondary Effluent	23	<0.10	0.0	<0.10	<0.10	<0.10	[a]
			MBR Permeate	109	41	2.7	41	34	55	[a]
			RO Permeate	22	2.6	0.9	2.6	<0.10	4.1	[a]
			RO Concentrate	2	225	9	225	218	231	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	23	-41,417	265	-41,500	-46,100	-35,500	5.6E-28
			RO	22	94	2	94	90	100	4.7E-36
			MBR + RO	21	-2,509	918	-2,510	-3,970	161	6.3E-11

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-14. Statistics for Nitrite as Nitrogen

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg N/L)	UF	Secondary Effluent	31	0.04	0.01	0.04	<0.01	0.07	[a]
			UF Filtrate	31	0.04	0.01	0.04	<0.01	0.07	[a]
			RO Permeate	29	<0.01	0.00	<0.01	<0.01	<0.01	[a]
			RO Concentrate	2	0.29	0.11	0.29	0.21	0.37	[a]
		MBR	Secondary Effluent	14	0.03	0.01	0.03	<0.01	0.05	[a]
			MBR Permeate	70	0.03	0.01	0.03	<0.01	0.07	[a]
			RO Permeate	14	<0.01	0.00	<0.01	<0.01	<0.01	[a]
			RO Concentrate	1	0.17	[b]	0.17	0.17	0.17	[a]
	Removal (%)	UF	UF	30	-4	14	-2	-41	18	1.2E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	12	-16	44	-8	-111	32	2.4E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg N/L)	UF	Secondary Effluent	23	0.04	0.01	0.04	0.02	0.06	[a]
			UF Filtrate	23	0.04	0.01	0.04	0.03	0.07	[a]
			RO Permeate	23	0.01	0.00	0.01	0.01	0.01	[a]
			RO Concentrate	2	0.27	0.00	0.27	0.27	0.27	[a]
		MBR	Secondary Effluent	22	0.04	0.01	0.04	0.02	0.06	[a]
			MBR Permeate	99	0.02	0.01	<0.01	<0.01	0.05	[a]
			RO Permeate	18	<0.01	0.00	<0.01	<0.01	<0.01	[a]
			RO Concentrate	2	0.09	0.08	0.09	0.03	0.15	[a]
	Removal (%)	UF	UF	22	-30	18	-30	-62	-1	1.2E-07
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	13	55	25	65	-7	76	3.7E-06
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg N/L)	UF	Secondary Effluent	23	0.02	0.01	0.02	0.01	0.04	[a]
			UF Filtrate	22	0.03	0.01	0.03	0.02	0.05	[a]
			RO Permeate	22	<0.01	0.00	<0.01	<0.01	<0.01	[a]
			RO Concentrate	2	0.13	0.01	0.13	0.13	0.14	[a]
		MBR	Secondary Effluent	23	0.02	0.01	0.02	<0.01	0.04	[a]
			MBR Permeate	109	0.03	0.01	0.02	0.02	0.08	[a]
			RO Permeate	21	<0.01	0.00	<0.01	<0.01	<0.01	[a]
			RO Concentrate	2	0.08	0.05	0.08	0.05	0.12	[a]
	Removal (%)	UF	UF	22	-54	32	-46	-142	-2	9.5E-08
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	23	-56	76	-39	-255	36	1.8E-03
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-15. Statistics for pH

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration	UF	Secondary Effluent	159	7.2	0.1	7.2	7.0	7.2	[a]
			UF Filtrate	29	7.3	0.1	7.3	7.2	7.4	[a]
			RO Permeate	27	5.6	0.1	5.6	5.5	5.7	[a]
			RO Concentrate	2	7.1	0.0	7.1	7.1	7.1	[a]
		MBR	Secondary Effluent	76	7.2	0.1	7.2	6.9	7.4	[a]
			MBR Permeate	70	7.0	0.1	7.0	6.6	7.2	[a]
			RO Permeate	12	5.7	0.2	5.6	5.5	6.0	[a]
			RO Concentrate	1	7.4	0.3	7.4	7.2	7.6	[a]
	Removal (%)	UF	UF	29	-2	1	-2	-3	4	1.3E-07
			RO	26	26	2	26	16	28	6.4E-28
			UF + RO	27	25	2	25	14	27	2.1E-28
		MBR	MBR	69	2	2	3	-1	6	2.7E-17
			RO	12	21	3	22	13	24	1.7E-11
			MBR + RO	12	23	2	23	18	25	6.6E-14
Phase 2	Concentration	UF	Secondary Effluent	106	7.1	0.1	7.1	7.0	7.3	[a]
			UF Filtrate	23	7.3	0.0	7.3	7.2	7.3	[a]
			RO Permeate	23	5.6	0.1	5.7	5.3	5.9	[a]
			RO Concentrate	2	7.3	0.1	7.3	7.2	7.3	[a]
		MBR	Secondary Effluent	104	7.1	0.1	7.1	7.0	7.3	[a]
			MBR Permeate	98	7.1	0.1	7.2	6.8	7.5	[a]
			RO Permeate	18	5.9	0.3	5.9	5.5	6.6	[a]
			RO Concentrate	2	7.4	0.3	7.4	7.2	7.6	[a]
	Removal (%)	UF	UF	23	-2	1	-1	-3	0	1.4E-09
			RO	22	22	2	22	19	27	9.1E-24
			UF + RO	23	21	2	21	18	25	8.7E-25
		MBR	MBR	98	0	2	0	-6	4	6.8E-01
			RO	18	17	4	17	7	21	5.2E-13
			MBR + RO	18	17	4	17	7	23	4.2E-12
Phase 3	Concentration	UF	Secondary Effluent	105	7.2	0.1	7.2	7.0	7.2	[a]
			UF Filtrate	20	7.3	0.1	7.3	7.2	7.4	[a]
			RO Permeate	21	5.6	0.1	5.6	5.5	5.7	[a]
			RO Concentrate	2	7.1	0.0	7.1	7.1	7.1	[a]
		MBR	Secondary Effluent	105	7.2	0.1	7.2	7.0	7.2	[a]
			MBR Permeate	99	7.0	0.1	7.0	6.6	7.2	[a]
			RO Permeate	21	5.7	0.2	5.6	5.5	6.0	[a]
			RO Concentrate	2	7.4	0.3	7.4	7.2	7.6	[a]
	Removal (%)	UF	UF	20	-2	1	-3	-4	-1	1.4E-09
			RO	20	24	1	24	22	26	1.2E-26
			UF + RO	20	22	1	22	20	24	5.8E-26
		MBR	MBR	98	2	1	1	-1	7	8.7E-27
			RO	20	18	2	19	13	23	2.7E-18
			MBR + RO	20	20	2	21	15	23	1.5E-19

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-16. Statistics for Phosphate as Phosphorus

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg P/L)	UF	Secondary Effluent	16	0.36	0.06	0.37	0.26	0.45	[a]
			UF Filtrate	16	0.18	0.05	0.18	<0.13	0.27	[a]
			RO Permeate	15	<0.13	0.00	<0.13	<0.13	<0.13	[a]
			RO Concentrate	2	0.86	0.71	0.86	0.36	1.36	[a]
		MBR	Secondary Effluent	8	0.36	0.09	0.35	0.26	0.52	[a]
			MBR Permeate	7	0.15	0.04	<0.13	<0.13	0.22	[a]
			RO Permeate	7	<0.13	0.00	<0.13	<0.13	<0.13	[a]
			RO Concentrate	1	0.24	[b]	0.24	0.24	0.24	[a]
	Removal (%)	UF	UF	13	48	8	49	37	65	1.0E-10
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	2	56	7	56	51	61	5.4E-02
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg P/L)	UF	Secondary Effluent	12	0.62	0.15	0.57	0.46	0.84	[a]
			UF Filtrate	12	0.39	0.11	0.42	0.25	0.56	[a]
			RO Permeate	12	<0.13	0.00	<0.13	<0.13	<0.13	[a]
			RO Concentrate	2	2.22	0.76	2.22	1.68	2.76	[a]
		MBR	Secondary Effluent	11	0.63	0.15	0.60	0.46	0.84	[a]
			MBR Permeate	10	0.41	0.12	0.43	0.23	0.57	[a]
			RO Permeate	9	<0.13	0.00	<0.13	<0.13	<0.13	[a]
			RO Concentrate	2	1.60	0.15	1.60	1.49	1.70	[a]
	Removal (%)	UF	UF	12	36	12	36	7	54	4.2E-07
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	10	34	17	38	1	49	1.3E-04
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg P/L)	UF	Secondary Effluent	12	0.61	0.15	0.56	0.44	0.85	[a]
			UF Filtrate	12	0.31	0.11	0.31	0.14	0.49	[a]
			RO Permeate	12	<0.13	0.00	<0.13	<0.13	<0.13	[a]
			RO Concentrate	12	0.35	0.15	0.32	0.18	0.73	[a]
		MBR	Secondary Effluent	12	0.61	0.15	0.56	0.44	0.85	[a]
			MBR Permeate	12	0.35	0.15	0.32	0.18	0.73	[a]
			RO Permeate	10	<0.13	0.00	<0.13	<0.13	<0.13	[a]
			RO Concentrate	2	1.84	0.76	1.84	1.30	2.38	[a]
	Removal (%)	UF	UF	12	51	12	53	27	69	1.1E-08
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	12	44	17	47	7	66	2.3E-06
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-17. Statistics for Potassium

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	18	21	1	21	19	23	[a]
			UF Filtrate	14	21	1	21	19	22	[a]
			RO Permeate	15	0.6	0.1	0.6	0.5	0.8	[a]
			RO Concentrate	2	128	5	128	124	131	[a]
		MBR	Secondary Effluent	8	21	1	21	19	23	[a]
			MBR Permeate	7	21	1	21	19	23	[a]
			RO Permeate	7	0.36	0.07	0.35	0.27	0.49	[a]
			RO Concentrate	1	127	[b]	127	127	127	[a]
	Removal (%)	UF	UF	14	-1	3	0	-9	2	3.5E-01
			RO	13	97	0	97	96	98	4.2E-30
			UF + RO	15	97	0	97	96	98	8.7E-35
		MBR	MBR	7	-1	1	0	-3	0	2.0E-01
			RO	7	98	0	98	98	99	1.5E-16
			MBR + RO	7	98	0	98	98	99	1.3E-16
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	20	1	20	19	21	[a]
			UF Filtrate	7	20	0	20	19	20	[a]
			RO Permeate	12	0.8	0.1	0.8	0.7	0.9	[a]
			RO Concentrate	2	124	5	124	120	127	[a]
		MBR	Secondary Effluent	11	20	1	20	19	21	[a]
			MBR Permeate	10	20	1	20	19	21	[a]
			RO Permeate	9	0.82	0.09	0.83	0.64	0.96	[a]
			RO Concentrate	2	123	7	123	118	128	[a]
	Removal (%)	UF	UF	7	1	2	1	-1	4	2.5E-01
			RO	7	96	0	96	95	96	3.1E-17
			UF + RO	12	96	0	96	95	97	2.2E-28
		MBR	MBR	10	1	1	0	-2	2	2.4E-01
			RO	9	96	0	96	95	97	3.9E-20
			MBR + RO	8	96	0	96	95	97	1.2E-17
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	22	1	22	20	24	[a]
			UF Filtrate	9	22	1	22	21	24	[a]
			RO Permeate	12	0.59	0.11	0.58	0.44	0.74	[a]
			RO Concentrate	2	123	5	123	120	127	[a]
		MBR	Secondary Effluent	12	22	1	22	20	24	[a]
			MBR Permeate	12	22	1	21	20	23	[a]
			RO Permeate	11	0.50	0.13	0.50	0.31	0.70	[a]
			RO Concentrate	2	132	11.3	132	124	140	[a]
	Removal (%)	UF	UF	9	0	2	0	-2	3	4.8E-01
			RO	9	97	0	97	97	98	2.6E-20
			UF + RO	12	97	1	97	97	98	1.1E-26
		MBR	MBR	12	1	2	1	-3	4	4.3E-02
			RO	11	98	1	98	97	99	1.5E-23
			MBR + RO	11	98	1	98	97	99	1.7E-23

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-18. Statistics for Silica as SiO_2

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	16	25	2	26	22	28	[a]
			UF Filtrate	16	25	1	25	22	28	[a]
			RO Permeate	15	0.47	0.09	0.48	0.33	0.65	[a]
			RO Concentrate	4	138	8	138	132	144	[a]
		MBR	Secondary Effluent	8	25	2	24	22	28	[a]
			MBR Permeate	5	24	1	24	22	26	[a]
			RO Permeate	7	0.18	0.03	0.17	0.13	0.24	[a]
			RO Concentrate	1	143	[b]	143	143	143	[a]
	Removal (%)	UF	UF	16	2	6	0	-6	17	2.9E-01
			RO	15	98	0	98	98	99	9.1E-37
			UF + RO	15	98	0	98	98	99	6.2E-36
		MBR	MBR	5	1	5	0	-2	9	5.5E-01
			RO	5	99	0	99	99	99	1.8E-13
			MBR + RO	7	99	0	99	99	99	2.4E-19
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	25	2	25	22	28	[a]
			UF Filtrate	12	24	1	24	22	25	[a]
			RO Permeate	12	0.99	0.12	1.1	0.75	1.1	[a]
			RO Concentrate	2	157	4	157	154	160	[a]
		MBR	Secondary Effluent	11	25	2	25	22	28	[a]
			MBR Permeate	10	25	1	25	23	27	[a]
			RO Permeate	9	1.1	0.16	1.1	0.79	1.4	[a]
			RO Concentrate	2	148	1	148	147	148	[a]
	Removal (%)	UF	UF	12	3	3	2	0	12	7.4E-03
			RO	12	96	0	96	95	97	1.3E-27
			UF + RO	12	96	0	96	96	97	3.4E-28
		MBR	MBR	10	0	6	1	-13	12	8.1E-01
			RO	9	96	1	96	95	97	9.7E-19
			MBR + RO	8	96	1	96	95	97	1.3E-16
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	24	1	24	23	25	[a]
			UF Filtrate	12	25	2	24	22	30	[a]
			RO Permeate	11	0.39	0.12	0.35	0.25	0.62	[a]
			RO Concentrate	2	163	1	163	162	163	[a]
		MBR	Secondary Effluent	12	24	1	24	23	25	[a]
			MBR Permeate	12	24	1	24	23	26	[a]
			RO Permeate	11	0.34	0.13	0.33	0.20	0.58	[a]
			RO Concentrate	2	145	10	145	138	152	[a]
	Removal (%)	UF	UF	12	-2	8	-1	-23	8	4.4E-01
			RO	11	98	0	99	98	99	8.5E-25
			UF + RO	11	98	0	98	98	99	8.9E-25
		MBR	MBR	12	0	4	0	-8	6	8.0E-01
			RO	11	99	1	99	98	99	2.5E-24
			MBR + RO	11	99	1	99	98	99	2.3E-24

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-19. Statistics for Sodium

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	18	394	22	397	340	423	[a]
			UF Filtrate	14	400	29	403	345	447	[a]
			RO Permeate	15	12	2	12	9	15	[a]
			RO Concentrate	2	2,500	113	2,500	-6	2,580	[a]
		MBR	Secondary Effluent	8	397	28	396	340	423	[a]
			MBR Permeate	7	397	34	395	335	432	[a]
			RO Permeate	7	7	1	7	6	9	[a]
			RO Concentrate	1	2,430	[b]	2,430	2,430	2,430	[a]
	Removal (%)	UF	UF	14	-2	2	-2	-6	1	4.2E-03
			RO	13	97	0	97	96	98	6.2E-30
			UF + RO	15	97	0	97	96	97	7.0E-35
		MBR	MBR	7	0	2	1	-2	3	7.6E-01
			RO	7	98	0	98	98	99	5.6E-17
			MBR + RO	7	98	0	98	98	99	6.4E-17
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	410	19	410	386	449	[a]
			UF Filtrate	7	421	24	413	387	459	[a]
			RO Permeate	12	16	2	17	13	20	[a]
			RO Concentrate	2	2,630	226	2,630	2,470	2,790	[a]
		MBR	Secondary Effluent	11	412	19	410	386	449	[a]
			MBR Permeate	10	409	20	407	371	444	[a]
			RO Permeate	9	17	2	17	13	21	[a]
			RO Concentrate	2	2,375	205	2,380	2,230	2,520	[a]
	Removal (%)	UF	UF	7	0	4	1	-6	6	9.5E-01
			RO	7	96	0	96	96	96	1.7E-18
			UF + RO	12	96	0	96	96	97	1.8E-29
		MBR	MBR	10	1	2	1	-2	4	1.9E-01
			RO	9	96	0	96	95	97	1.3E-20
			MBR + RO	8	96	0	96	95	97	3.8E-18
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	430	23	433	386	457	[a]
			UF Filtrate	9	442	22	450	408	471	[a]
			RO Permeate	12	12	2	12	9	15	[a]
			RO Concentrate	2	2,580	255	2,580	2,400	2,760	[a]
		MBR	Secondary Effluent	12	430	23	433	386	457	[a]
			MBR Permeate	12	433	22	437	394	476	[a]
			RO Permeate	11	11	3	11	7	15	[a]
			RO Concentrate	2	2,390	57	2,390	2,350	2,430	[a]
	Removal (%)	UF	UF	9	-3	3	-3	-7	2	1.6E-02
			RO	9	97	0	97	97	98	1.8E-20
			UF + RO	12	97	0	97	96	98	7.6E-27
		MBR	MBR	12	-1	3	-1	-5	4	2.8E-01
			RO	11	98	1	97	97	98	7.7E-24
			MBR + RO	11	98	1	97	97	98	1.4E-23

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-20. Statistics for Strontium

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (µg/L)	UF	Secondary Effluent	18	706	45	710	628	770	[a]
			UF Filtrate	14	707	49	719	620	762	[a]
			RO Permeate	15	0.27	0.06	0.26	<0.20	0.39	[a]
			RO Concentrate	6	4,445	629	4,445	4,000	4,890	[a]
		MBR	Secondary Effluent	8	703	58	723	628	760	[a]
			MBR Permeate	7	686	60	666	608	751	[a]
			RO Permeate	7	0.21	0.02	<0.20	<0.20	0.24	[a]
			RO Concentrate	1	4,540	[b]	4,540	4,540	4,540	[a]
	Removal (%)	UF	UF	14	0	2	1	-3	3	4.0E-01
			RO	10	100	0	100	100	100	1.4E-38
			UF + RO	12	100	0	100	100	100	3.8E-47
		MBR	MBR	7	1	2	0	0	5	1.5E-01
			RO	1	100	[b]	100	100	100	[b]
			MBR + RO	1	100	[b]	100	100	100	[b]
Phase 2	Concentration (µg/L)	UF	Secondary Effluent	12	759	43	758	704	848	[a]
			UF Filtrate	7	736	17	739	711	756	[a]
			RO Permeate	12	0.47	0.09	0.47	0.33	0.66	[a]
			RO Concentrate	2	5,020	170	5,020	4,900	5,140	[a]
		MBR	Secondary Effluent	11	763	42	762	704	848	[a]
			MBR Permeate	10	745	35	750	697	812	[a]
			RO Permeate	9	0.53	0.11	0.51	0.30	0.68	[a]
			RO Concentrate	2	4,850	735	4,850	4,330	5,370	[a]
	Removal (%)	UF	UF	7	1	2	2	-1	5	1.3E-01
			RO	7	100	0	100	100	100	9.2E-27
			UF + RO	12	100	0	100	100	100	3.3E-45
		MBR	MBR	10	2	2	2	-3	5	6.2E-02
			RO	9	100	0	100	100	100	3.2E-32
			MBR + RO	9	100	0	100	100	100	2.6E-32
Phase 3	Concentration (µg/L)	UF	Secondary Effluent	12	792	83	826	652	895	[a]
			UF Filtrate	9	806	61	818	694	881	[a]
			RO Permeate	12	0.23	0.04	<0.20	<0.20	0.32	[a]
			RO Concentrate	2	4,675	106	4,680	4,600	4,750	[a]
		MBR	Secondary Effluent	12	792	83	826	652	895	[a]
			MBR Permeate	12	776	84	796	632	924	[a]
			RO Permeate	11	0.22	0.05	<0.20	<0.20	0.36	[a]
			RO Concentrate	2	4,305	785	4,305	3,750	4,860	[a]
	Removal (%)	UF	UF	9	2	2	2	-2	7	8.9E-02
			RO	5	100	0	100	100	100	3.6E-18
			UF + RO	5	100	0	100	100	100	2.5E-18
		MBR	MBR	12	2	3	3	-3	4	3.0E-02
			RO	4	100	0	100	100	100	1.6E-13
			MBR + RO	4	100	0	100	100	100	1.3E-13

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-21. Statistics for Sulfate

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	16	215	19	213	180	248	[a]
			UF Filtrate	16	218	16	219	182	247	[a]
			RO Permeate	15	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	2,225	262	2,225	2,040	2,410	[a]
		MBR	Secondary Effluent	8	224	24	233	180	248	[a]
			MBR Permeate	7	230	23	238	180	247	[a]
			RO Permeate	7	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	1	1,610	[b]	1,610	1,610	1,610	[a]
	Removal (%)	UF	UF	16	-2	4	-1	-13	2	8.0E-02
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	7	-1	1	0	-2	0	1.3E-01
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	12	238	24	239	197	276	[a]
			UF Filtrate	12	235	25	235	196	272	[a]
			RO Permeate	12	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	2,075	417	2,075	1,780	2,370	[a]
		MBR	Secondary Effluent	11	241	23	240	197	276	[a]
			MBR Permeate	10	238	23	238	197	275	[a]
			RO Permeate	9	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	1,480	368	1,480	1,220	1,740	[a]
	Removal (%)	UF	UF	12	1	3	1	-1	9	9.3E-02
			RO	2	100	0	100	100	100	3.4E-05
			UF + RO	2	100	0	100	100	100	4.8E-05
		MBR	MBR	10	0	1	0	-3	2	5.4E-01
			RO	2	100	0	100	100	100	1.2E-04
			MBR + RO	2	100	0	100	100	100	1.2E-04
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	243	18	248	204	273	[a]
			UF Filtrate	12	244	20	246	201	284	[a]
			RO Permeate	12	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	2,355	276	2,355	2,160	2,550	[a]
		MBR	Secondary Effluent	12	243	18	248	204	273	[a]
			MBR Permeate	12	244	19	246	203	281	[a]
			RO Permeate	10	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	1,480	113	1,480	1,400	1,560	[a]
	Removal (%)	UF	UF	12	0	1	0	-4	1	4.6E-01
			RO	1	100	0	100	100	100	[b]
			UF + RO	1	100	0	100	100	100	[b]
		MBR	MBR	12	0	2	0	-3	2	4.2E-01
			RO	1	100	0	100	100	100	[b]
			MBR + RO	1	100	0	100	100	100	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-22. Statistics for Total Dissolved Solids

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	18	1,340	64	1,340	1,170	1,450	[a]
			UF Filtrate	18	1,350	53	1,350	1,210	1,420	[a]
			RO Permeate	17	36	10	33	22	58	[a]
			RO Concentrate	2	8,730	42	8,730	8,700	8,760	[a]
		MBR	Secondary Effluent	7	1,356	86	1,400	1,170	1,410	[a]
			MBR Permeate	6	1,360	79	1,390	1,210	1,420	[a]
			RO Permeate	6	36	15	31	22	58	[a]
			RO Concentrate	1	8,720	[b]	8,720	8,720	8,720	[a]
	Removal (%)	UF	UF	17	-1	2	-1	-3	2	5.8E-02
			RO	17	98	1	98	95	100	3.1E-33
			UF + RO	17	98	1	98	95	100	4.8E-33
		MBR	MBR	7	-8	2	-8	-12	-6	4.3E-05
			RO	7	98	1	99	98	99	6.0E-15
			MBR + RO	7	98	1	99	98	99	6.0E-15
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	11	1,366	92	1,410	1,220	1,500	[a]
			UF Filtrate	11	1,382	98	1,420	1,240	1,570	[a]
			RO Permeate	11	47	11	51	28	59	[a]
			RO Concentrate	1	8,960	[b]	8,960	8,960	8,960	[a]
		MBR	Secondary Effluent	10	1,376	90	1,420	1,220	1,500	[a]
			MBR Permeate	10	1,396	90	1,430	1,280	1,570	[a]
			RO Permeate	10	49	9	51	31	59	[a]
			RO Concentrate	1	7,250	[b]	7,250	7,250	7,250	[a]
	Removal (%)	UF	UF	11	-1	6	-1	-13	8	5.1E-01
			RO	11	97	1	96	96	98	3.3E-23
			UF + RO	11	97	1	96	95	98	1.3E-22
		MBR	MBR	9	-8	8	-6	-19	5	1.7E-02
			RO	8	96	1	96	95	98	3.5E-16
			MBR + RO	8	96	1	96	95	98	3.5E-16
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	12	1,446	71	1,430	1,320	1,570	[a]
			UF Filtrate	12	1,465	68	1,460	1,350	1,570	[a]
			RO Permeate	12	30	8	28	15	40	[a]
			RO Concentrate	2	9,190	679	9,190	8,710	9,670	[a]
		MBR	Secondary Effluent	12	1,446	71	1,430	1,320	1,570	[a]
			MBR Permeate	12	1,542	69	1,530	1,410	1,680	[a]
			RO Permeate	11	31	8	33	16	41	[a]
			RO Concentrate	2	8,905	431	8,910	8,600	9,210	[a]
	Removal (%)	UF	UF	12	-1	3	-1	-6	3	9.2E-02
			RO	12	98	1	98	97	99	2.4E-26
			UF + RO	12	98	1	98	97	99	1.8E-26
		MBR	MBR	12	-7	2	-7	-9	-2	5.5E-08
			RO	11	98	1	98	97	99	4.5E-24
			MBR + RO	11	98	1	98	97	99	4.5E-24

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-23. Statistics for Total Kjeldahl Nitrogen

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg N/L)	UF	Secondary Effluent	168	38	3	38	23	46	a
			UF Filtrate	33	37	3	37	26	40	a
			RO Permeate	31	2	0	2	1	3	a
			RO Concentrate	13	225	11	225	217	232	a
		MBR	Secondary Effluent	80	38	4	39	23	46	a
			MBR Permeate	15	<1.0	0	<1.0	<1.0	<1.0	a
			RO Permeate	16	<1.0	0	<1.0	<1.0	<1.0	a
			RO Concentrate	1	<1.0	[b]	<1.0	<1.0	<1.0	a
	Removal (%)	UF	UF	33	2	3	2	-8	7	2.8E-03
			RO	31	95	1	95	93	97	1.5E-61
			UF + RO	31	95	1	95	93	97	2.1E-61
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg N/L)	UF	Secondary Effluent	106	38	2	37	31	49	a
			UF Filtrate	23	37	2	37	33	43	a
			RO Permeate	23	2	0	2	2	3	a
			RO Concentrate	2	222	3	222	220	224	a
		MBR	Secondary Effluent	104	38	2	37	31	49	a
			MBR Permeate	21	<1.0	0	<1.0	<1.0	<1.0	a
			RO Permeate	18	<1.0	0	<1.0	<1.0	<1.0	a
			RO Concentrate	2	<1.0	0	<1.0	<1.0	<1.0	a
	Removal (%)	UF	UF	23	3	3	3	-6	5	3.2E-04
			RO	22	94	0	94	93	95	1.4E-51
			UF + RO	23	94	0	94	93	95	1.7E-53
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg N/L)	UF	Secondary Effluent	112	42	3	42	35	51	a
			UF Filtrate	22	42	3	41	36	50	a
			RO Permeate	22	2	0	2	2	2	a
			RO Concentrate	2	254	24	254	237	271	a
		MBR	Secondary Effluent	112	42	3	42	35	51	a
			MBR Permeate	25	<1.0	0	<1.0	<1.0	<1.0	a
			RO Permeate	23	<1.0	0	<1.0	<1.0	<1.0	a
			RO Concentrate	2	<1.0	0	<1.0	<1.0	<1.0	a
	Removal (%)	UF	UF	22	3	2	3	0	8	9.0E-09
			RO	22	95	1	95	94	96	3.3E-49
			UF + RO	22	96	1	96	95	96	1.9E-49
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-24. Statistics for Total Organic Carbon

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	35	15	1	15	14	17	[a]
			UF Filtrate	33	12	1	12	11	14	[a]
			RO Permeate	31	0.5	0	<0.5	<0.5	0.9	[a]
			RO Concentrate	2	77	5	77	74	81	[a]
		MBR	Secondary Effluent	18	15	1	15	14	17	[a]
			MBR Permeate	15	9	1	9	8	10	[a]
			RO Permeate	15	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	1	56	[b]	56	56	56	[a]
	Removal (%)	UF	UF	33	19	2	19	15	25	6.2E-33
			RO	10	95	1	95	93	96	1.4E-19
			UF + RO	10	96	1	96	94	97	2.8E-20
		MBR	MBR	15	40	3	39	36	46	2.0E-18
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	23	16	1	16	13	18	[a]
			UF Filtrate	23	13	0	13	12	14	[a]
			RO Permeate	23	0.6	0	<0.5	<0.5	0.8	[a]
			RO Concentrate	2	81	1	81	81	81	[a]
		MBR	Secondary Effluent	22	16	1	16	13	18	[a]
			MBR Permeate	21	9	0	9	8	9	[a]
			RO Permeate	18	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	57	2	57	55	59	[a]
	Removal (%)	UF	UF	22	19	4	19	1	23	3.1E-15
			RO	9	95	1	95	94	96	3.0E-18
			UF + RO	10	96	1	96	95	97	5.4E-21
		MBR	MBR	21	44	3	45	33	49	7.1E-24
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	25	18	1	18	16	20	[a]
			UF Filtrate	22	14	1	14	12	15	[a]
			RO Permeate	22	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	87	7	87	82	92	[a]
		MBR	Secondary Effluent	25	18	1	18	16	20	[a]
			MBR Permeate	25	10	1	10	9	12	[a]
			RO Permeate	23	<0.5	0	<0.5	<0.5	<0.5	[a]
			RO Concentrate	2	61	4	61	58	63	[a]
	Removal (%)	UF	UF	22	22	2	22	17	26	7.0E-23
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	25	44	5	45	35	52	3.9E-25
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-25. Statistics for Total Suspended Solids

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (mg/L)	UF	Secondary Effluent	164	10	2	10	5	17	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	Secondary Effluent	76	11	2	11	6	17	[a]
			MBR Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (mg/L)	UF	Secondary Effluent	106	10	2	10	4	16	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	Secondary Effluent	104	10	2	10	4	16	[a]
			MBR Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (mg/L)	UF	Secondary Effluent	111	13	2	13	9	23	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	Secondary Effluent	111	13	2	13	9	23	[a]
			MBR Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[b]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table E-26. Statistics for Turbidity

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (NTU)	UF	Secondary Effluent	156	3	1	3	2	6	[a]
			UF Filtrate	142	0.1	0.1	0.1	0.1	1.4	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[a]
		MBR	Secondary Effluent	69	3	1	3	2	6	[a]
			MBR Permeate	70	0.1	0.0	0.1	0.1	0.1	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[a]
	Removal (%)	UF	UF	24	93	7	95	63	96	9.0E-28
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	4	95	1	96	94	96	1.1E-07
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 2	Concentration (NTU)	UF	Secondary Effluent	105	3	1	3	2	6	[a]
			UF Filtrate	102	0.1	0.1	0.1	<0.1	0.9	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[a]
		MBR	Secondary Effluent	103	3	1	3	2	6	[a]
			MBR Permeate	97	0.1	0.1	0.1	<0.1	0.8	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[a]
	Removal (%)	UF	UF	27	95	5	96	72	98	1.1E-35
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	37	95	4	96	75	98	2.0E-52
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (NTU)	UF	Secondary Effluent	111	4	1	4	2	5	[a]
			UF Filtrate	102	0.1	0.0	0.1	<0.1	0.3	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[a]
		MBR	Secondary Effluent	111	4	1	4	2	5	[a]
			MBR Permeate	108	0.1	0.0	0.1	<0.1	0.2	[a]
			RO Permeate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Concentrate	0	[b]	[b]	[b]	[b]	[b]	[a]
	Removal (%)	UF	UF	34	96	1	97	92	98	3.9E-62
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	34	96	1	96	93	98	3.6E-65
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

APPENDIX F

STATISTICS FOR NITROSAMINES AND 1,4-DIOXANE

The following tables provide water quality statistics for each of the general water quality parameters. Concentrations below the reporting limit were conservatively assigned a value of the reporting limit in calculating the averages, standard deviations, and p-values.

Table F-1. Statistics for NDMA

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	34	393	186	340	190	1,100	[a]
			UF Filtrate	13	357	88	350	200	510	[a]
			RO Permeate	45	310	152	270	130	830	[a]
		MBR	Secondary Effluent	19	413	180	340	190	860	[a]
			MBR Permeate	12	390	245	305	170	970	[a]
			RO Permeate	33	219	172	150	85	700	[a]
	Removal (%)	UF	UF	13	5	12	3	-15	29	1.8E-01
			RO	11	28	16	33	-10	46	1.7E-04
			UF + RO	26	29	11	31	-2	55	7.5E-13
		MBR	MBR	12	9	17	9	-18	41	8.6E-02
			RO	12	47	10	51	18	54	6.3E-09
			MBR + RO	14	52	9	56	29	65	9.7E-12
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	351	91	320	240	590	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[a]
			RO Permeate	11	275	70	260	180	450	[a]
		MBR	Secondary Effluent	10	356	94	330	240	590	[a]
			MBR Permeate	9	260	71	290	110	360	[a]
			RO Permeate	8	213	40	200	170	290	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	21	5	23	13	29	7.8E-08
		MBR	MBR	9	27	15	29	3	54	8.2E-04
			RO	8	24	6	22	17	33	7.2E-06
			MBR + RO	8	42	10	44	22	51	5.0E-06
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	21	542	355	400	240	1,400	[a]
			UF Filtrate	15	504	317	390	240	1,300	[a]
			RO Permeate	12	295	166	245	170	780	[a]
		MBR	Secondary Effluent	21	542	355	400	240	1,400	[a]
			MBR Permeate	21	451	321	330	170	1,100	[a]
			RO Permeate	12	262	204	180	120	790	[a]
	Removal (%)	UF	UF	15	-6	6	-6	-19	3	2.6E-03
			RO	9	31	5	32	23	37	9.1E-08
			UF + RO	12	31	6	29	23	44	1.7E-09
		MBR	MBR	21	18	10	16	6	41	6.1E-08
			RO	12	36	10	34	24	53	5.0E-08
			MBR + RO	12	49	6	49	38	59	8.6E-12

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-2. Statistics for NDEA

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	153	91	145	35	440	[a]
			UF Filtrate	7	327	96	370	170	420	[a]
			RO Permeate	31	61	62	38	8	210	[a]
		MBR	Secondary Effluent	19	147	93	120	35	440	[a]
			MBR Permeate	12	398	200	395	150	790	[a]
			RO Permeate	37	41	20	39	2	94	[a]
	Removal (%)	UF	UF	7	-152	64	-147	-240	-50	7.2E-04
			RO	5	91	3	91	86	95	5.2E-07
			UF + RO	13	75	13	75	56	95	1.4E-10
		MBR	MBR	12	-218	143	-238	-491	5	2.5E-04
			RO	12	89	2	89	86	93	2.5E-19
			MBR + RO	14	65	18	66	26	93	5.7E-09
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	175	64	170	86	320	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	11	127	50	120	53	240	[a]
		MBR	Secondary Effluent	10	161	45	165	86	240	[a]
			MBR Permeate	9	739	295	660	340	1,300	[a]
			RO Permeate	8	238	100	225	110	450	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	25	20	33	0	53	1.8E-03
		MBR	MBR	9	-378	171	-412	-710	-113	1.6E-04
			RO	8	69	5	68	64	79	1.2E-09
			MBR + RO	8	-44	56	-23	-150	31	6.3E-02
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	21	271	123	220	130	540	[a]
			UF Filtrate	15	908	355	770	490	1,600	[a]
			RO Permeate	12	103	49	97	55	200	[a]
		MBR	Secondary Effluent	21	271	123	220	130	540	[a]
			MBR Permeate	21	1,176	634	960	220	2,700	[a]
			RO Permeate	13	181	92	160	68	410	[a]
	Removal (%)	UF	UF	15	-255	123	-260	-525	-53	1.4E-06
			RO	8	88	3	88	83	91	7.9E-12
			UF + RO	12	58	18	65	29	77	2.5E-07
		MBR	MBR	21	-367	194	-355	-838	51	3.3E-08
			RO	13	86	5	85	79	94	1.0E-16
			MBR + RO	13	22	37	24	-46	70	4.8E-02

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-3. Statistics for NDPA

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	1,389	817	1,250	410	3,200	[a]
			UF Filtrate	7	1,986	505	2,000	1,500	2,700	[a]
			RO Permeate	31	11	5	11	4	24	[a]
		MBR	Secondary Effluent	19	1,447	798	1,600	490	3,200	[a]
			MBR Permeate	12	86	47	82	33	200	[a]
			RO Permeate	37	3	2	<2	<2	10	[a]
	Removal (%)	UF	UF	7	8	13	8	-17	22	1.6E-01
			RO	5	99	0	99	99	100	3.4E-11
			UF + RO	13	99	0	99	98	100	1.3E-29
		MBR	MBR	12	91	4	92	81	95	3.3E-16
			RO	12	97	2	98	94	99	4.3E-21
			MBR + RO	14	100	0	100	100	100	1.4E-40
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	1,348	734	1,400	290	2,500	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	11	36	16	44	16	60	[a]
		MBR	Secondary Effluent	10	1,454	680	1,400	550	2,500	[a]
			MBR Permeate	9	110	98	71	16	320	[a]
			RO Permeate	8	5	5	3	<2	16	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	97	2	97	92	99	8.4E-19
		MBR	MBR	8	92	4	93	85	98	9.7E-11
			RO	7	95	2	95	93	99	1.5E-11
			MBR + RO	7	100	0	100	99	100	1.7E-17
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	21	<2	0	<2	<2	<2	[a]
			UF Filtrate	15	<2	0	<2	<2	<2	[a]
			RO Permeate	12	<2	0	<2	<2	<2	[a]
		MBR	Secondary Effluent	21	<2	0	<2	<2	<2	[a]
			MBR Permeate	21	<2	0	<2	<2	<2	[a]
			RO Permeate	13	<2	0	<2	<2	<2	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-4. Statistics for NDBA

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	162	89	145	30	310	[a]
			UF Filtrate	7	173	64	180	42	250	[a]
			RO Permeate	31	5	5	2	<2	28	[a]
		MBR	Secondary Effluent	19	178	95	150	46	350	[a]
			MBR Permeate	12	90	75	60	27	290	[a]
			RO Permeate	37	4	3	2	<2	20	[a]
	Removal (%)	UF	UF	7	5	20	9	-29	33	5.4E-01
			RO	5	97	3	99	92	99	3.0E-07
			UF + RO	13	96	4	98	88	99	2.1E-18
		MBR	MBR	12	44	29	51	-4	79	2.2E-04
			RO	12	95	2	95	93	98	3.4E-20
			MBR + RO	14	97	2	98	93	99	1.4E-23
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	127	57	120	65	220	[a]
			UF Filtrate	0	0	0	0	0	0	[b]
			RO Permeate	11	3	3	<2	<2	12	[a]
		MBR	Secondary Effluent	10	128	60	120	65	220	[a]
			MBR Permeate	9	40	22	39	18	75	[a]
			RO Permeate	8	2	0	<2	<2	2	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	97	1	97	95	99	4.4E-20
		MBR	MBR	8	63	17	63	38	87	1.5E-05
			RO	7	94	3	95	89	97	2.3E-10
			MBR + RO	7	98	1	98	97	99	4.9E-14
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	21	225	225	140	<2	740	[a]
			UF Filtrate	15	288	274	160	<2	740	[a]
			RO Permeate	12	2	1	2	<2	6	[a]
		MBR	Secondary Effluent	21	225	225	140	<2	740	[a]
			MBR Permeate	21	149	163	83	<2	570	[a]
			RO Permeate	13	<2	0	<2	<2	2	[a]
	Removal (%)	UF	UF	13	-8	38	0	-123	36	4.4E-01
			RO	7	99	1	99	97	100	1.3E-12
			UF + RO	11	98	3	99	92	100	4.1E-17
		MBR	MBR	19	-21	183	25	-733	99	6.3E-01
			RO	12	97	2	98	93	100	3.4E-20
			MBR + RO	12	97	5	99	83	100	5.7E-16

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-5. Statistics for NMEA

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	30	30	24	<2	110	[a]
			UF Filtrate	7	55	36	70	<2	94	[a]
			RO Permeate	31	3	2	<2	<2	10	[a]
		MBR	Secondary Effluent	19	30	32	25	<2	110	[a]
			MBR Permeate	12	17	29	2	<2	95	[a]
			RO Permeate	37	3	1	<2	<2	6	[a]
	Removal (%)	UF	UF	5	-26	11	-25	-39	-13	6.7E-03
			RO	4	87	19	97	58	98	2.9E-03
			UF + RO	9	94	2	94	91	97	1.7E-14
		MBR	MBR	5	31	54	14	-19	95	2.8E-01
			RO	4	85	19	94	57	96	3.0E-03
			MBR + RO	7	94	2	94	92	96	5.6E-12
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	<2	0	<2	<2	2	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	11	<2	0	<2	<2	2	[a]
		MBR	Secondary Effluent	10	<2	0	<2	<2	2	[a]
			MBR Permeate	9	<2	0	<2	<2	2	[a]
			RO Permeate	8	<2	0	<2	<2	2	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	21	5	7	2	<2	25	[a]
			UF Filtrate	15	8	11	2	<2	33	[a]
			RO Permeate	12	3	2	2	<2	8	[a]
		MBR	Secondary Effluent	21	5	7	2	<2	25	[a]
			MBR Permeate	21	4	4	2	<2	17	[a]
			RO Permeate	13	2	0	2	<2	3	[a]
	Removal (%)	UF	UF	4	-23	15	-22	-40	-10	5.6E-02
			RO	2	75	21	75	60	90	1.3E-01
			UF + RO	2	71	22	71	56	86	1.3E-01
		MBR	MBR	4	69	7	70	60	77	2.7E-04
			RO	2	51	2	51	50	52	1.4E-02
			MBR + RO	2	87	2	87	86	88	8.5E-03

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-6. Statistics for NPIP

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	465	271	400	98	1300	[a]
			UF Filtrate	7	566	347	490	260	1300	[a]
			RO Permeate	31	4	2	3	<2	9	[a]
		MBR	Secondary Effluent	19	486	263	420	220	1300	[a]
			MBR Permeate	12	60	24	56	26	110	[a]
			RO Permeate	37	3	1	2	<2	9	[a]
	Removal (%)	UF	UF	7	10	13	7	-2	38	9.4E-02
			RO	5	99	0	99	99	100	1.1E-12
			UF + RO	13	99	1	99	98	100	1.8E-28
		MBR	MBR	12	85	4	86	77	90	1.0E-15
			RO	12	96	2	96	92	98	1.5E-20
			MBR + RO	14	99	0	99	99	100	6.4E-36
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	246	164	230	110	670	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	11	5	4	<2	<2	12	[a]
		MBR	Secondary Effluent	10	204	90	185	110	370	[a]
			MBR Permeate	9	88	63	80	22	190	[a]
			RO Permeate	8	<2	0	<2	<2	2	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	98	1	98	96	99	3.3E-20
		MBR	MBR	9	57	21	53	30	83	4.2E-05
			RO	8	96	3	97	91	99	6.2E-12
			MBR + RO	8	99	0	99	98	99	1.4E-17
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	21	501	343	490	<2	1300	[a]
			UF Filtrate	15	561	338	580	<2	1100	[a]
			RO Permeate	12	2	0	<2	<2	2	[a]
		MBR	Secondary Effluent	21	501	343	490	<2	1300	[a]
			MBR Permeate	21	109	96	75	<2	340	[a]
			RO Permeate	13	2	0	<2	<2	2	[a]
	Removal (%)	UF	UF	13	-21	38	-13	-133	15	6.4E-02
			RO	7	100	0	100	99	100	1.2E-18
			UF + RO	11	100	0	100	99	100	1.7E-27
		MBR	MBR	19	77	16	83	42	99	3.9E-14
			RO	10	98	2	98	95	99	8.2E-18
			MBR + RO	11	99	0	100	98	100	2.2E-25

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-7. Statistics for NPYR

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	22	18	18	3	74	[a]
			UF Filtrate	7	37	26	28	13	83	[a]
			RO Permeate	31	3	1	<2	<2	4	[a]
		MBR	Secondary Effluent	19	21	19	17	<2	74	[a]
			MBR Permeate	12	5	5	3	<2	15	[a]
			RO Permeate	37	3	1	<2	<2	8	[a]
	Removal (%)	UF	UF	7	-39	59	-12	-158	4	1.3E-01
			RO	5	92	6	96	85	97	4.9E-06
			UF + RO	13	86	8	86	72	97	5.9E-14
		MBR	MBR	11	60	32	67	0	90	9.8E-05
			RO	9	49	27	43	19	87	7.0E-04
			MBR + RO	13	81	17	88	30	92	7.8E-10
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	<2	0	<2	<2	<2	[a]
			UF Filtrate	0	0	0	0	0	0	[b]
			RO Permeate	11	<2	0	<2	<2	<2	[a]
		MBR	Secondary Effluent	10	<2	0	<2	<2	<2	[a]
			MBR Permeate	9	<2	0	<2	<2	<2	[a]
			RO Permeate	8	<2	0	<2	<2	<2	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	19	<2	0	<2	<2	<2	[a]
			UF Filtrate	13	<2	0	<2	<2	<2	[a]
			RO Permeate	12	<2	0	<2	<2	<2	[a]
		MBR	Secondary Effluent	19	<2	0	<2	<2	<2	[a]
			MBR Permeate	19	<2	0	<2	<2	<2	[a]
			RO Permeate	13	<2	0	<2	<2	<2	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	0	[b]	[b]	[b]	[b]	[b]	[b]
		MBR	MBR	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			MBR + RO	0	[b]	[b]	[b]	[b]	[b]	[b]

[a] T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b] Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-8. Statistics for 1,4 Dioxane

				No. of Values	Avg	Std Dev	Median	Min	Max	p-value[a]
Phase 1	Concentration (ng/L)	UF	Secondary Effluent	20	8.7	2.1	8.4	4.0	13.1	[a]
			UF Filtrate	2	8.1	0.3	8.1	7.9	8.3	[a]
			RO Permeate	17	0.5	0.2	0.5	<0.4	1.1	[a]
		MBR	Secondary Effluent	11	8.8	2.0	8.2	6.7	13.1	[a]
			MBR Permeate	9	8.9	2.5	8.1	6.7	14.2	[a]
			RO Permeate	9	0.4	0.0	<0.4	<0.4	0.4	[a]
	Removal (%)	UF	UF	2	3	7	3	-1	8	7.4E-01
			RO	2	95	0	95	95	95	2.1E-03
			UF + RO	17	94	2	94	90	96	6.2E-30
		MBR	MBR	9	-1	15	-6	-11	38	9.0E-01
			RO	9	95	1	95	94	97	4.0E-17
			MBR + RO	9	95	1	95	94	97	3.0E-17
Phase 2	Concentration (ng/L)	UF	Secondary Effluent	11	10.2	1.6	9.7	8.3	13.6	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	11	1.1	0.2	1.2	0.8	1.4	[a]
		MBR	Secondary Effluent	10	10.4	1.6	9.8	8.8	13.6	[a]
			MBR Permeate	9	10.4	1.0	9.9	9.0	11.7	[a]
			RO Permeate	8	1.3	0.2	1.4	1.1	1.6	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	89	1	89	87	91	1.9E-19
		MBR	MBR	9	-4	6	-5	-12	8	6.4E-02
			RO	8	87	1	87	86	90	3.7E-14
			MBR + RO	8	87	1	86	86	89	5.5E-14
Phase 3	Concentration (ng/L)	UF	Secondary Effluent	13	9.2	1.7	8.9	6.6	12.4	[a]
			UF Filtrate	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO Permeate	11	0.5	0.2	0.4	<0.4	0.9	[a]
		MBR	Secondary Effluent	13	9.2	1.7	8.9	6.6	12.4	[a]
			MBR Permeate	13	9.3	1.9	9.0	5.8	12.4	[a]
			RO Permeate	12	0.5	0.1	<0.4	<0.4	0.8	[a]
	Removal (%)	UF	UF	0	[b]	[b]	[b]	[b]	[b]	[b]
			RO	0	[b]	[b]	[b]	[b]	[b]	[b]
			UF + RO	11	94	1	95	93	97	5.8E-20
		MBR	MBR	13	-1	5	-1	-9	12	6.7E-01
			RO	12	95	1	95	93	96	7.8E-23
			MBR + RO	12	94	1	94	93	96	2.4E-23

[a]T-tests were conducted only for removals, not concentrations. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-9. Statistics for Removal Between Phases

			P-VALUES[a]							
			NDMA	**NDEA**	**NDPA**	**NDBA**	**NMEA**	**NPIP**	**NPYR**	**1,4 Dioxane**
Phase 1 vs 2	**Removal (%)**									
	UF	UF	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]
		RO	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]
		UF + RO	5.1E-03	2.4E-06	2.2E-03	1.2E-01	[b]	2.1E-02	[b]	1.3E-08
	MBR	MBR	2.3E-02	3.7E-02	5.8E-01	8.7E-02	[b]	4.5E-03	[b]	5.1E-01
		RO	4.1E-06	1.3E-06	4.6E-01	4.6E-01	[b]	8.1E-01	[b]	5.0E-09
		MBR + RO	2.5E-02	7.3E-04	1.6E-01	3.5E-01	[b]	5.1E-03	[b]	4.5E-09
Phase 2 vs 3	**Removal (%)**									
	UF	UF	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]
		RO	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]
		UF + RO	4.0E-04	6.0E-04	[b]	7.7E-01	[b]	2.9E-03	[b]	9.4E-09
	MBR	MBR	1.6E-01	8.7E-01	[b]	6.4E-02	[b]	2.9E-02	[b]	1.6E-01
		RO	1.9E-03	1.4E-06	2.7E-02	2.7E-02	[b]	1.4E-01	[b]	1.2E-08
		MBR + RO	9.5E-02	1.3E-02	[b]	3.4E-01	[b]	5.6E-03	[b]	2.2E-08
Phase 1 vs 3	**Removal (%)**									
	UF	UF	1.1E-02	1.8E-02	[b]	3.1E-01	7.5E-01	1.5E-02	[b]	[b]
		RO	5.4E-01	1.5E-01	[b]	5.0E-01	5.6E-01	1.3E-02	[b]	[b]
		UF + RO	5.5E-01	1.6E-02	[b]	1.2E-01	3.7E-01	2.4E-02	[b]	2.8E-01
	MBR	MBR	1.4E-01	1.8E-02	[b]	1.4E-01	1.9E-01	5.0E-02	[b]	9.9E-01
		RO	2.2E-02	1.5E-02	2.7E-02	2.7E-02	[b]	1.4E-01	[b]	1.5E-01
		MBR + RO	3.1E-01	1.3E-03	[b]	5.9E-01	5.4E-02	8.9E-01	[b]	1.0E-01

[a]T-tests were conducted only for removals. The null hypothesis was that the removal was zero; p-values < 1.0E-01 indicate statistically significant removal.

[b]Removals were calculated only for paired samples taken on the same day; in some cases, there were no paired samples (or only one pair) and statistics could not be calculated.

Table F-10. Statistical Analysis of the Effect of Effluent Source on AOP

UV EED (kWh/kgal)	1,4-Dioxane		NDMA		NDEA	
	Effect[1]	P-value[2]	Effect[1]	P-value[2]	Effect[1]	P-value[2]
0	0.03	6.4E-02	-0.02	4.9E-02	-0.01	4.2E-01
2	0.12	9.5E-04	0.15	4.6E-03	0.06	4.3E-02
4	0.11	5.8E-05	-0.10	2.6E-01[3]	0.14	3.5E-03
6	0.13	1.6E-04	0.09	5.2E-01[3]	0.06	2.1E-01[3]

[1]Effect on log removal of treating MBR-RO effluent, relative to UF-RO effluent. For example, an effect of 0.1 indicates that the log removal effluent was 0.1-log higher in MBR-RO effluent than in UF-RO effluent.

[2]The effect of the effluent source was considered significant for p-values ≤ 0.01. P-values > 0.01 indicate that no significant difference could be observed; a difference may still exist but be too small to be observed with the data available.

[3]Limited data points for the MBR-RO and/or UF-RO effluents, because concentrations were frequently below reporting limits. The low number of data points made it difficult to identify differences between the UF-RO and MBR-RO data.

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APPENDIX G

TITLE 22+ DATA

Table G-1. Title 22+ Analytes in UF Filtrate or MBR Permeate: General Parameters[1]

Category	Analyte	Units	RL	UF 2/16/11	UF 2/23/11	MBR 3/2/11	MBR 3/9/11	MBR 5/15/12	MBR 5/22/12
General	Apparent Color	ACU	3	50	40	50	30	30	30
Physical	Odor at 60 C (TON)	TON	1	200	200	200	200	200	200
Parameters	Turbidity	NTU	0.05	0.12	0.13	0.15	0.12	0.14	0.17
	Alkalinity , Total	mg $CaCO_3$/L	2	370	350	110	110	86	120
	Ammonia	mg N/L	0.05	39	37	0.06	ND	ND	0.08
	Nitrate	mg N/L	0.05	ND	ND	39	37	43	43
	Total Nitrate, Nitrite	mg N/L	0.1	ND	ND	39	37	43	43
	Organic Nitrogen	mg N/L	1.0	1.5	1	ND	ND	ND	ND
	pH	-	0.1	7.4	7.5	7.1	7.4	7.9	7.5
	Surfactants	mg/L	0.05	0.22	0.23	0.17	0.15	0.18	0.15
	Specific Conductance, 25ºC	µmho/cm	2	2,700	2,700	2,500	2,500	2,200	2,500
	Total Chlorine Residual	mg/L	0.05	3.9	4.8	ND	0.07	ND	0.05
	Total Dissolved Solids	mg/L	10	1,400	1,400	1,500	1,500	1,400	1,500
	Total Hardness	mg $CaCO_3$/L	3	240	250	270	240	270	260
	Total Organic Carbon	mg/L	0.5	12	12	9.7	9.4	8.6	9.4
	UV Transmittance (254 nm)	%	0.0	56.7	58.1	56.8	58.2	61.2	58.4

[1] Note: In all tables, ND = not detected (below reporting limit), NS = not sampled, RL = reporting limit. In addition, for all averages, standard deviations, and p-values, concentrations below the reporting limit were conservatively assigned a value of the reporting limit.

Table G-2. Title 22+ Analytes in UF Filtrate or MBR Permeate: Minerals and Trace Metals

Category	Analyte	Units	RL	UF 2/16/11	UF 2/23/11	MBR 3/2/11	MBR 3/9/11	MBR 5/15/12	MBR 5/22/12
General	Boron, Total	mg/L	0.05	0.84	0.93	1.1	0.89	0.88	0.94
Mineral	Bromide	µg/L	5	1,500	1,600	1,700	1,700	1,600	1,600
Parameters	Calcium, Total	mg/L	1	63	67	68	61	67	66
	Chloride	mg/L	1	490	490	460	460	460	500
	Fluoride	mg/L	0.05	1.2	1.0	2.6	1.1	1.1	2.3
	Magnesium, Total	mg/L	0.1	21	21	24	21	24	24
	Phosphorus, Total	mg/L	0.02	0.15	0.15	0.1	0.12	0.26	0.38
	Potassium, Total	mg/L	1	20	20	24	20	19	21
	Sodium, Total	mg/L	1	380	370	390	390	340	420
	Sulfate	mg/L	0.5	220	240	230	210	180	250
Trace Metals	Antimony, Total	µg/L	1	2.8	2.0	7.5	3.0	3.6	1.9
	Arsenic, Total	µg/L	1	3.6	2.2	1.5	ND	2.5	3.4
	Barium, Total	µg/L	2	120	100	120	110	100	120
	Chromium, Total	µg/L	1	1.4	1.1	ND	ND	17	4.7
	Hexavalent Chromium	µg/L	0.02-0.05	ND	0.05	ND	ND	0.62	0.10
	Iron, Total	mg/L	0.02	0.1	0.12	0.11	0.12	0.10	0.14
	Copper	µg/L	2	2.4	ND	ND	ND	ND	ND
	Manganese	µg/L	2	90	87	43	59	7.8	6.6
	Nickel, Total	µg/L	5	11	11	9.4	10	7.5	8.8
	Selenium, Total	µg/L	5	12	8.9	7.4	9.8	7.0	10
	Vanadium, Total	µg/L	3	ND	ND	ND	ND	ND	3

Table G-3. Title 22+ Analytes in UF Filtrate or MBR Permeate: Trace Constituents and Microbes

Category	Analyte	Units	RL	UF 2/16/11	UF 2/23/11	MBR 3/2/11	MBR 3/9/11	MBR 5/15/12	MBR 5/22/12
Hormones	Estrone	ng/L	10	16	11	ND	ND	ND	ND
	17-Beta Estradiol	ng/L	2	4.3	ND	ND	ND	ND	ND
Industrial	Bisphenol A	ng/L	25	40	29	34	ND	22	ND
EDCs	4-Nonylphenol (Tech Mix)	ng/L	25	380	570	170	ND	231	31
	Nonylphenol Diethoxylate	ng/L	125	8,000	7,200	985	765	628	540
	Nonylphenol Monoethoxylate	ng/L	125	1,930	1,780	438	399	292	258
	4-tert Octylphenol	ng/L	25	360	250	85	40	34	59
	Octylphenol Diethoxylate	ng/L	125	5,300	3,650	191	ND	ND	ND
	Octylphenol Monoethoxylate	ng/L	125	1,340	805	ND	ND	ND	ND
Pharmaceuticals	Acetaminophen	ng/L	20	21	25	20	24	23	59
	Azithromycin	ng/L	10	937	937	853	908	388	274
	Dilantin	ng/L	25	335	294	300	326	418	296
	Gemfibrozil	ng/L	20	1,020	1,220	351	354	134	121
	Ibuprofen	ng/L	10	ND	14	ND	ND	ND	ND
	Meprobamate	ng/L	10	392	378	430	446	468	428
	Sulfamethoxazole	ng/L	10	681	742	1,780	1,640	1,300	1,390
Personal Care	DEET	ng/L	10	487	465	297	290	256	212
Products	Triclosan	ng/L	25	355	341	94	78	57	65
Other	Caffeine	ng/L	10	355	434	253	209	326	238
Wastewater	Iopromide	ng/L	30	920	844	678	727	1,370	1,130
Indicators	Sucralose	ng/L	40	20,400	19,300	20,200	20,100	31,200	34,400
	TCEP	ng/L	10	373	388	354	419	478	458
Microbes	Giardia	Cysts/10L	1	0	1	0	0	NS	NS
	Heterotrophic Plate Count	cfu/mL	1	130	1	4,300	2,400	3,200	ND
	Total Coliform	MPN/100 mL	1.1	ND	ND	12	1.1	ND	5.1
	Fecal Coliform	MPN/100 mL	1.1	ND	ND	ND	1.1	ND	ND

Table G-4. Other Title 22+ Analytes in UF Filtrate or MBR Permeate

Category	Analyte	Units	RL	UF 2/16/11	UF 2/23/11	MBR 3/2/11	MBR 3/9/11	MBR 5/15/12	MBR 5/22/12
Radiological	Gross Beta	pCi/L	1.7-3.4	6.5	8.7	11	14	9.3	12
	Tritium	pCi/L	202	240	ND	ND	ND	ND	ND
	Uranium	pCi/L	0.7	1.4	1.2	2.3	2.3	1.1	2.4
Volatile	Bromochloromethane	µg/L	0.5	0.67	0.57	ND	ND	ND	ND
Organic	Bromodichloromethane	µg/L	0.5	ND	0.62	ND	ND	ND	ND
Compounds	Chloroform	µg/L	0.5	11	9.8	1.6	1.4	1.3	1.0
	Dibromomethane	µg/L	0.5	0.73	0.56	ND	ND	ND	ND
	Dichloromethane	µg/L	0.5	2.0	3.3	0.6	ND	ND	ND
	Methyl Tert-butyl Ether (MTBE)	µg/L	0.5	18	2.8	ND	ND	ND	ND
	Total THM	µg/L	0.5	11	10	1.6	1.4	1.3	1.0
Pesticides	Aldicarb Sulfone	µg/L	0.5	2.3	2.0	1.9	1.9	1.6	1.5
	Bromacil	µg/L	0.2	ND	ND	0.9	0.3	ND	ND
	3-Hydroxycarbofuran	µg/L	0.5	1.9	1.6	2.1	2.2	1.8	1.6
	Diuron	µg/L	1	ND	ND	1	ND	ND	ND
	Methomyl	µg/L	0.5	0.96	ND	ND	ND	ND	ND
	Oxamyl (Vydate)	µg/L	1	ND	ND	ND	ND	1.1	1.2
SWRCB Surrogates	Dissolved Organic Carbon	mg/L	0.5	12	12	9.4	9.4	8.5	9.1
Other	2,4-Dimethyphenol	µg/L	0.2	0.24	ND	ND	ND	ND	ND
Chemicals	Formaldehyde	µg/L	5	44	36	12	17	16	14
	Phenol	µg/L	0.2	0.23	ND	ND	ND	0.46	0.46
	t-Butyl Alcohol	µg/L	2	11	7.4	ND	ND	ND	ND
	Captan	µg/L	0.05	ND	0.07	ND	ND	ND	ND
	Chlorate	µg/L	10	590	640	ND	ND	ND	ND

Table G-5. Title 22+ Analytes in RO Permeate: General Parameters

Category	Analyte	Units	RL	2/16/11	2/23/11	3/2/11	3/9/11	5/15/12	5/22/12
General	Odor at 60 C (TON)	TON	1	ND	ND	1	ND	ND	1
Physical	Turbidity	NTU	0.05	ND	ND	0.07	0.05	0.10	0.10
Parameters	Alkalinity , Total	mg $CaCO_3$/L	2	22	16	6.1	6.9	4.6	4.5
	Ammonia	mg N/L	0.05	1.3	1.3	0.59	0.37	0.23	0.27
	Nitrate	mg N/L	0.05	ND	ND	0.83	1.3	3.2	3.6
	Total Nitrate, Nitrite	mg N/L	0.1	ND	ND	0.83	1.3	3.2	3.6
	pH	-	0.1	5.5	5.9	5.6	5.8	6.5	6.2
	Specific Conductance, 25ºC	µmho/cm	2	74	68	39	34	57	66
	Total Chlorine Residual	mg/L	0.05	3.7	4.5	5.2	2.8	2.0	2.3
	Total Dissolved Solids	mg/L	10	26	25	13	15	33	40
	UV Transmittance (254 nm)	%	0.0	97.0	96.1	93.8	97.0	99.0	97.0
General	Boron, Total	mg/L	0.05	0.57	0.61	0.44	0.48	0.59	0.65
Mineral	Bromide	µg/L	5	31	32	140	62	75	83
Parameters	Chloride	mg/L	1	6.8	6.8	2.4	2.7	5.2	6.3
	Fluoride	mg/L	0.05	0.09	0.09	0.11	0.07	0.06	0.09
	Sodium, Total	mg/L	1	10	10	5.2	7.2	11	13

Table G-6. Other Title 22+ Analytes in RO Permeate

Category	Analyte	Units	RL	2/16/11	2/23/11	3/2/11	3/9/11	5/15/12	5/22/12
Volatile Organic Compounds	Bromochloromethane	µg/L	0.5	0.66	0.62	ND	ND	ND	ND
	Bromodichloromethane	µg/L	0.5	ND	ND	1.2	1.7	1.4	2.0
	Bromoform	µg/L	0.5	ND	ND	2.4	ND	ND	ND
	Chlorodibromomethane	µg/L	0.5	ND	ND	1.5	1.4	0.72	1.2
	Chloroform	µg/L	0.5	5.9	5.4	1.0	1.6	1.5	1.5
	Dibromomethane	µg/L	0.5	0.67	0.50	ND	ND	ND	ND
	Dichloromethane	µg/L	0.5	1.8	3.1	ND	ND	1.4	2.0
	Total THM	µg/L	0.5	5.9	5.4	6.2	4.7	3.7	4.7
Other Wastewater Indicators	Iopromide	ng/L	30	ND	ND	ND	ND	72	ND
Microbes	Heterotrophic Plate Count	cfu/mL	1	ND	ND	ND	ND	2	ND
SWRCB Surrogates	Dissolved Organic Carbon	mg/L	0.5	ND	0.50	ND	ND	ND	0.75
Other Chemicals	Formaldehyde	µg/L	5	7.3	6.3	6.6	11	12	8.9
	Chloropicrin	µg/L	0.5	ND	0.63	ND	ND	ND	ND
	Chlorate	µg/L	10	11	14	ND	ND	ND	ND

Table G-7. Title 22+ Analytes in AOP Effluent: General Parameters

Category	Analyte	Units	RL	2/16/11	2/23/11	3/2/11	3/9/11	LP 5/15/12	MP 5/15/12	LP 5/22/12	MP 5/22/12
General	Odor at 60 C (TON)	TON	1	ND	NS	1	NS	1	ND	1	2
Physical	Turbidity	NTU	0.05	ND	NS	0.06	NS	0.06	0.15	0.15	0.08
Parameters	Alkalinity , Total	mg $CaCO_3$/L	2	14	NS	3.9	NS	3.6	4.0	3.9	3.9
	Ammonia	mg N/L	0.05	1.3	NS	0.28	NS	0.19	0.24	0.22	0.25
	Nitrate	mg N/L	0.05	0.16	NS	1	NS	3.2	3.3	3.7	3.7
	Total Nitrate, Nitrite	mg N/L	0.1	0.16	NS	1	NS	3.2	3.3	3.7	3.7
	pH	-	0.1	5.6	NS	5.2	NS	6.3	6.5	6.2	6.1
	Specific Conductance, 25ºC	µmho/cm	2	72	NS	36	NS	58	60	66	68
	Total Dissolved Solids	mg/L	10	30	NS	19	NS	38	40	37	36
	Total Chlorine Residual	mg/L	0.05	0.4	0.6	0.6	0.4	0.2	0.7	0.5	0.6
	UV Transmittance (254 nm)	%	0.0	99.0	NS	100	NS	100	100	98.0	98.8
General	Boron, Total	mg/L	0.05	0.60	NS	0.48	NS	0.59	0.60	0.65	ND
Mineral	Bromide	µg/L	5	48	NS	140	NS	71	85	86	83
Parameters	Chloride	mg/L	1	9.1	NS	3.8	NS	6.0	6.1	7.5	7.6
	Fluoride	mg/L	0.05	0.11	NS	0.11	NS	0.06	0.06	0.09	0.09
	Sodium, Total	mg/L	1	11	NS	5.6	NS	11	11	12	13

Table G-8. Other Title 22+ Analytes in AOP Effluent

Category	Analyte	Units	RL	2/16/11	2/23/11	3/2/11	3/9/11	LP 5/15/12	MP 5/15/12	LP 5/22/12	MP 5/22/12
Trace Metals	Hexavalent Chromium	µg/L	0.05	0.13	NS	0.09	NS	0.13	0.11	0.14	0.12
	Copper, Total	µg/L	2	27	NS	21	NS	3.5	3.5	2.9	3.1
	Lead, Total	µg/L	0.5	0.68	NS	0.68	NS	ND	ND	ND	ND
Volatile	Bromochloromethane	µg/L	0.5	0.57	NS	ND	NS	ND	ND	ND	ND
Organic	Bromodichloromethane	µg/L	0.5	ND	NS	0.82	NS	1.0	1.2	1.5	1.6
Compounds	Chlordibromomethane	µg/L	0.5	ND	NS	ND	NS	ND	ND	ND	0.56
	Chloroform	µg/L	0.5	5.2	NS	1.0	NS	1.4	1.4	1.3	1.3
	Dichloromethane	µg/L	0.5	1.6	NS	ND	NS	1.0	1.2	1.5	1.6
	Total THM	µg/L	0.5	5.2	NS	1.9	NS	2.4	2.5	2.8	3.5
Industrial EDCs	Bisphenol A	ng/L	25	ND	ND	ND	ND	26	ND	ND	ND
Pharmaceuticals	Azithromycin	ng/L	10	ND	ND	ND	ND	ND	19	ND	ND
Microbes	Heterotrophic Plate Count	cfu/mL	1	ND	NS	ND	NS	>5,700*	28	2,500*	ND
Carbamate	Aldicarb Sulfone	µg/L	0.5	ND	NS	ND	NS	ND	ND	ND	ND
Pesticides	3-Hydroxycarbofuran	µg/L	0.5	ND	NS	ND	NS	ND	ND	ND	ND
SWRCB Surrogates	Dissolved Organic Carbon	mg/L	0.5	0.7	ND	ND	ND	ND	ND	0.60	0.6
Other	Formaldehyde	µg/L	5	27	NS	23	NS	70	42	56	39
Chemicals	Chlorate	µg/L	10	ND	NS	ND	NS	19	ND	ND	ND

*Value is likely an error resulting from samples being switched. The secondary effluent sample on May 15, 2012 was expected to be >5,700 cfu/mL, but was < 1 cfu/mL. Similarly, the MBR sample on May 22, 2012 was expected to be ~3,000 cfu/mL, but was < 1 cfu/mL.