THE QUEST TO COST EFFECTIVELY MEET RECYCLED WATER STANDARDS WITH PREOZONATION AND BIOLOGICALLY ACTIVE FILTRATION

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ABSTRACT
The latest NPDES permit adopted for the Sacramento Regional Wastewater Treatment Plant included a requirement for tertiary treatment, equivalent to the water quality requirements of Title 22, unrestricted use recycled water. Initial cost projections for the required plant upgrades exceeded $2 billion to upgrade the 691 ML/day (181 mgd) facility. To help in the selection process for tertiary treatment alternatives, a demonstration scale study was undertaken. A 0.95 ML/Day (0.25 mgd) BNR process was constructed to feed three filtration and three disinfection processes operated in parallel. Filtration alternatives tested were granular media, conventional and biologically active, and membrane. Disinfection alternatives were chlorine, ozone, and UV. Objectives of the demonstration scale study were determination of performance of and life cycle costs for each process alternative. The performance and costs for each process alternative will be reported in the presentation, along with trace organic compound removal performance for 12 tested compounds.

KEYWORDS Filtration, Disinfection, Title 22, Trace Organic Compounds, Tertiary Treatment, Cost, Ozone, UV, Chlorine, Membrane

INTRODUCTION

The Sacramento Regional County Sanitation District (District) owns and operates the Sacramento Regional Wastewater Treatment Plant (SRWTP), a high purity oxygen activated sludge (HPOAS) system with chlorine disinfection and sulfur dioxide dechlorination, with permitted discharge to the Sacramento River. Recent discharge permit revisions specify stricter discharge requirements than the existing HPOAS process is capable of meeting. New permit requirements include ammonia and nitrate limits and tertiary treatment to produce the equivalent of California Title 22, unlimited use reclaimed water quality effluent. To identify the most cost-effective treatment technologies to implement, the District embarked on the Advanced Treatment Technology Pilot (ATTP) Project to demonstrate that the new treatment technologies selected by the District will meet the new permit requirements, possible future permit limits, and to refine criteria for detailed design.

Through a series of technology selection workshops that culminated in the plan to conduct the ATTP project, the District selected three filtration alternatives and three disinfection alternatives to test. Filtration alternatives consisted of membrane filtration (MF), conventional granular media filtration (CGMF), and biologically active granular media filtration preceded by ozonation

(OGMF). Disinfection alternatives included ultraviolet (UV) irradiation, chlorination, and ozonation. The ATTP project was designed to test all permutations of filtration and disinfection alternatives to identify the alternatives that most cost effectively produced recycled water quality equivalent effluent.

The technology selection team also selected a Modified Ludzack-Ettinger (MLE), air activated sludge process to achieve the required ammonia and nitrate removals. Although the MLE process is a mature technology that the team decided did not require pilot testing, the difference in water quality produced by the HPOAS process and the MLE process necessitated constructing and operating a MLE process as part of the ATTP project to produce secondary effluent to supply the filtration and disinfection processes being studied.

The ATTP project was designed to measure the treatment performance and to determine the life cycle cost of each tested process. Treatment performance included the ability to reliably meet water quality requirements of the new permit and the ability to remove, or be readily adaptable to remove, constituents that the team identified as future potential regulated compounds. These potential future regulated compounds included total nitrogen, phosphorus, and trace organic compounds (TOrCs). The pre-ozonated, biologically active filtration alternative was selected for testing specifically because it has been shown to be effective at reducing TOrCs (Gerrity et al., 2011).

As part of the planning process for the demonstration-scale pilot study to inform design and construction of advanced treatment facilities at the SRWTP, a study of TOrC treatability was included in the evaluation of tested treatment processes. Although regulation of TOrCs is not part of current NPDES permit requirements, regulation of TOrCs may occur in the future. The demonstration study provided the opportunity to evaluate the effectiveness of the treatment process alternatives for reducing TOrCs so the study scope was expanded to include TOrC treatability.

METHODOLOGY

Pilot Plant Overview

Figures 1 and 2 provide a process flow diagram of the pilot facilities constructed at the SRWTP. The pilot facilities included biological nutrient removal (BNR), filtration (MF, CGMF, and OGMF), and disinfection (chlorination, ultraviolet irradiation (UV), and ozonation). The pilot plant design included a high level of automation so that operators could focus on process control, sampling, equipment maintenance, and troubleshooting.

Figure 1. SRWTP Advanced Treatment Technology Pilot Project Secondary Treatment TOrC Sample Locations

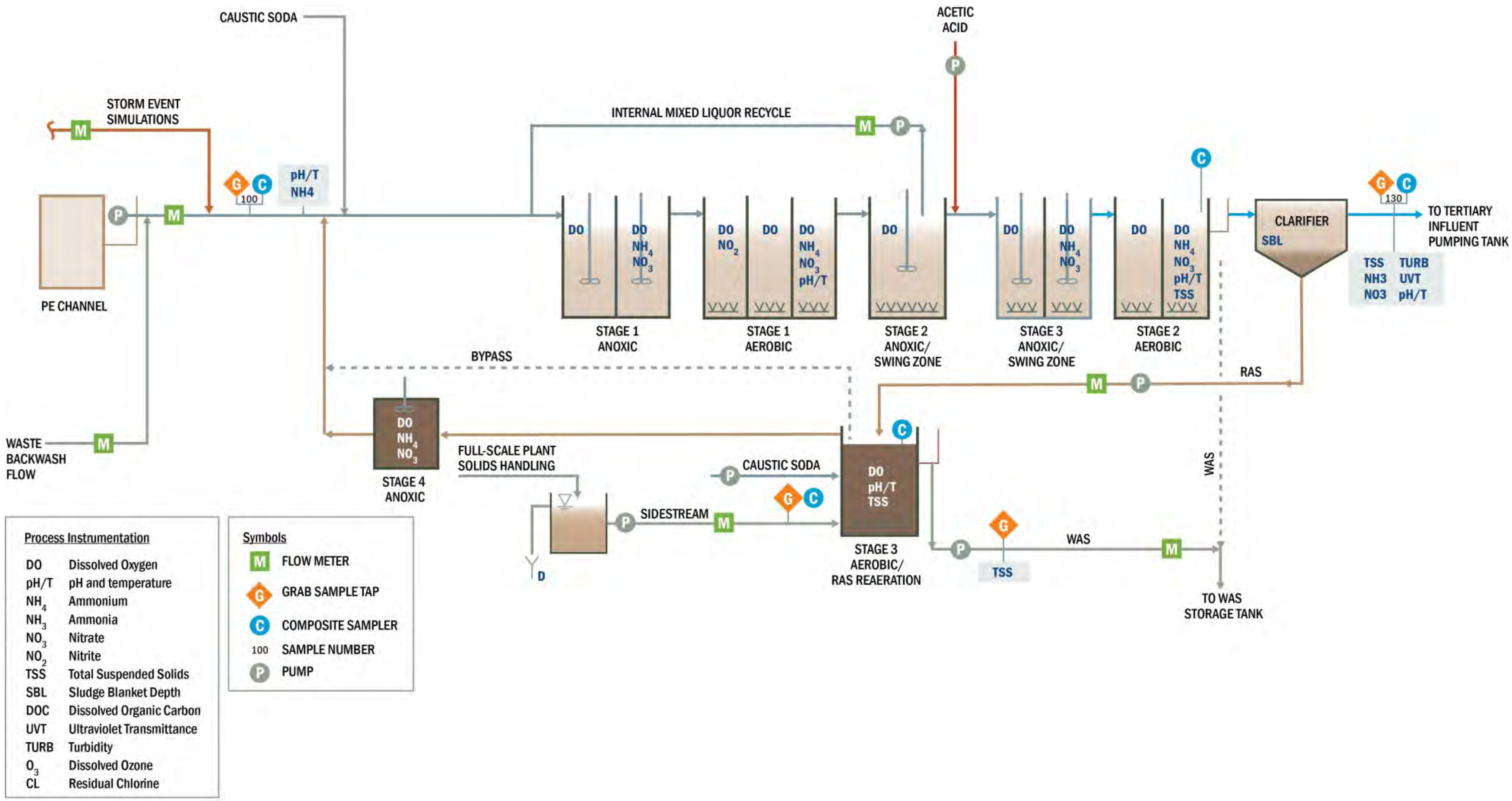
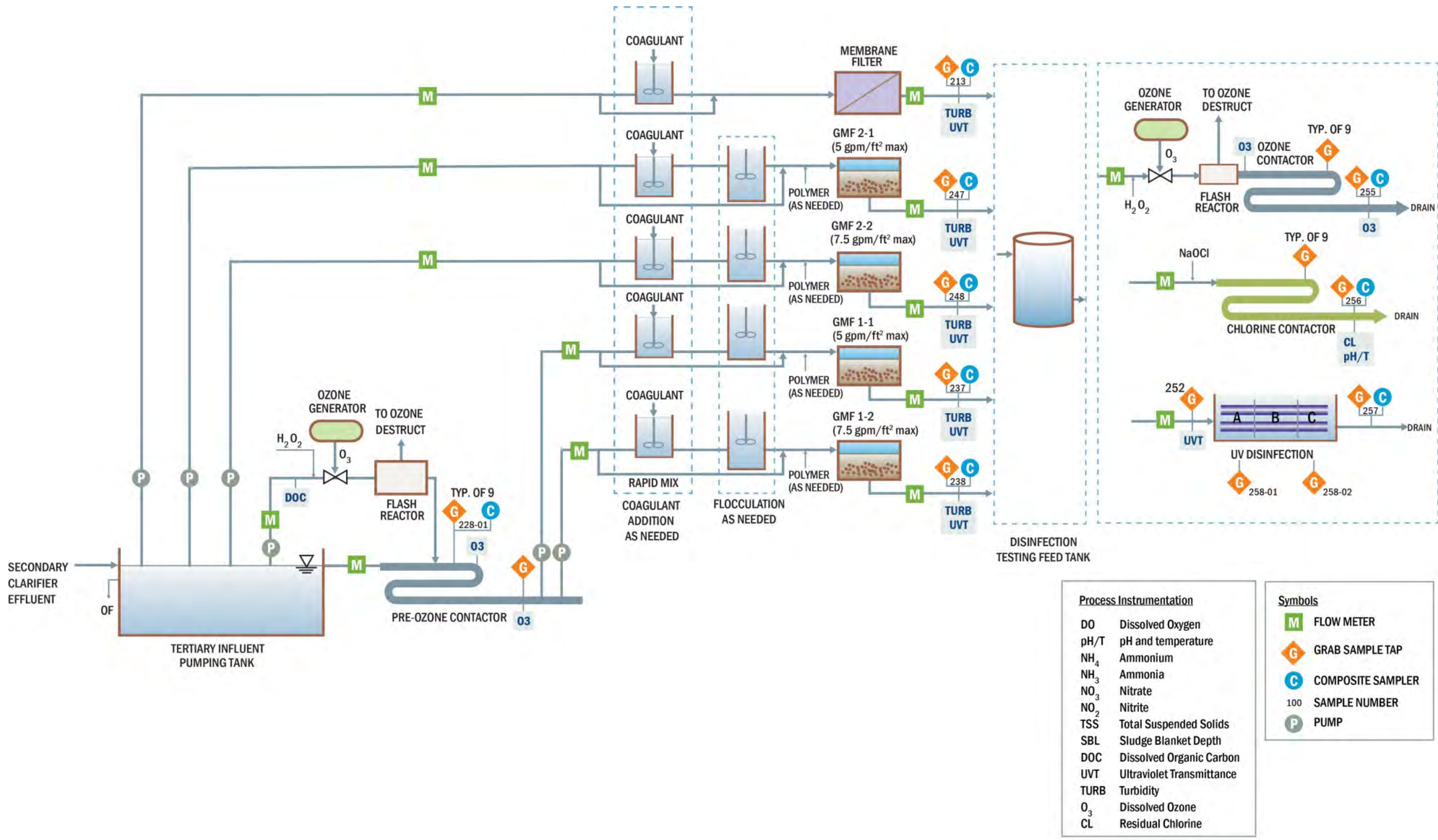


Figure 1. SRWTP Advanced Treatment Technology Pilot Project Tertiary Treatment TOrC Sample Locations



Pilot Feed Water

The pilot plant received primary effluent from the full-scale SRWTP. The pilot influent flow was proportioned to full-scale plant flow. A scale factor was used in the supervisory control and data acquisition (SCADA) system to allow pilot diurnal flows to mimic full-scale diurnal flows. The scaling factor was increased during two periods to simulate a maximum month flow and loading conditions for summer and winter, respectively.

In addition to primary effluent, sidestream flow from the solids processing facilities was routed to Stage 3 Aerobic of the BNR process. To mimic the full-scale plant, sidestream from the full-scale plant was set at a constant flow to target an ammonia loading of 7.3 kilograms (16.5 pounds) of nitrogen per day (kg-N/d).

Sidestream liquid was continuously delivered to the pilot through a supply tank from which it was pumped to the pilot plant at a controlled rate. Excess flow from this tank overflowed and went to the drain. This kept a fresh supply of sidestream water for the sidestream metering pump to pump to Stage 3 Aerobic.

Secondary Treatment

Table 1 provides an overview of each compartment of the BNR process. Table 2 presents a summary of BNR design and operating parameters. The aeration basin had the capability to provide internal mixed liquor return (IMLR) to promote denitrification. The IMLR pump was set at 200% of the pilot influent flow rate.

Table 1. Overview of BNR Pilot Plant Tankage

BNR Stage	Number of Zones	Operation	Process Objective	Tank Liquid Vol., L (gal)
Stage 1 Anoxic	2	Divided into two zones; each zone was mixed with mechanical mixers. DO should be <0.1 mg/L.	Using two zones mitigates short circuiting and promotes denitrification of nitrate present in the IMLR stream.	150,300 (39,700)
Stage 1A Aerobic Stage 1B Aerobic Stage 1C Aerobic	3	Zones 1 and 2 DO concentration was set at 3 mg/L. Zone 3 DO concentration was set at 2 mg/L using fine-bubble aeration.	Three zones mitigate short circuiting and promote nitrification. Elevated DO concentration in Zone 1 and 2 will increase nitrifier kinetics (Bratby and Parker, 2009). Reduced Zone 3 DO concentration of 2 mg/L is to prevent DO carryover into anoxic zones.	226,700 (59,900)
Stage 2 Anoxic/ Swing Zone	1	Zones are mixed with mechanical mixers. DO should be <0.1 mg/L. Alternatively, aeration can be used to maintain a DO of 2 mg/L.	During normal operation, this zone serves to "deoxygenate" mixed liquor before it flows to Stage 1 Anoxic via IMLR and Stage 3 Anoxic. If additional nitrification is necessary, the tank can be aerated.	30,700 (8,100)
Stage 3 A Anoxic/ Swing Zone Stage 3B Anoxic/ Swing Zone	1	Zones are mixed with mechanical mixers. DO should be <0.1 mg/L. Alternatively, aeration can be used during times when additional nitrification is required.	During normal operation, this zone serves to remove nitrate. Supplemental carbon can be added to this tank if necessary. If additional nitrification is necessary, the tank can be aerated.	61,300 (16,200)
Stage 2A Aerobic Stage 2B Aerobic	2	Divided into two zones; both zones should be operated at DO concentration of 2 mg/L using fine-bubble aeration.	In addition to providing additional nitrification, both zones act to strip out nitrogen gas formed in Stage 3 anoxic before secondary clarification.	40,900 (10,800)
Stage 3 Aerobic/ RAS Reaeration	1	DO concentration was set at 2 mg/L using fine-bubble aeration.	Nitrogen-laden solids processing return streams should be directed to this tank so that nitrification can be performed separately from BNR influent flow.	25,400 (6,700)
Stage 4 Anoxic	1	Zone was mixed with mechanical mixers. DO should be <0.1 mg/L.	This zone serves to "deoxygenate" return activated sludge before it flows to Stage 1 Anoxic.	5,300 (1,400)
WAS Storage Tank	---	WAS was collected for daily quantification. Tank was pump mixed to keep solids in suspension. The tank contents were emptied once per day to prevent septicity after volume has been recorded and a representative sample has been collected.	Provides an accurate account of mass of solids that are wasted, which is necessary to calculate SRT and make accurate mass balances within the pilot plant.	38,400 (10,150)

Table 2. Overview of Select BNR Design Criteria and Operating Procedures

Parameter	Value	Control Strategy
Aerobic SRT	7.5 days	SCADA is equipped with SRT controller that sets WAS pump flow. SRT is calculated using on-line TSS probes in Stage 2B Aerobic and Stage 3 Aerobic.
Average hydraulic retention time (HRT)	12.9 hr	---
Internal Mixed Liquor Recycle (IMLR) Flow	200% of Influent (flow paced)	Internal mixed liquor recycle pumps are equipped with VFDs that receive a flow signal from SCADA. Flow proportioning is based on the sum of the influent flow meter and storm event simulation flow meter.
RAS Flow	50% of Influent (flow paced)	RAS pumps are equipped with VFDs that receive a flow signal from SCADA. Flow proportioning is based on the sum of the influent flow meter and storm event simulation flow meter.
Sludge Blanket Depth	<0.3 m (<1.0 ft)	Operator checks blanket daily with a sludge judge. If sludge blanket is elevated, RAS flow is increased.
Peak MLSS Concentration	2,300 mg/L	---
Peak Day Secondary Clarifier Surface Overflow Rate (SOR)	48.8 ML/day (1,200 gpd/sf)	---
DO Setpoint	3 mg/L (Stage 1A and1B Aerobic) 2 mg/L (Stage 1C, 2A,2B and 3 Aerobic)	Each Stage is equipped with an on-line DO meter. DO is controlled by SCADA. Each Stage has a dedicated air drop line with a control valve. Control valve modulates to maintain DO setpoint. When demand drops, air requirements are set by minimum mixing requirements.

Supplemental alkalinity addition was necessary at times to prevent pH depression in the BNR system. SCADA was set to control pH by adding caustic soda (25%). The set point was set so that if Stage 1C Aerobic had a pH less than 6.4, the caustic soda pump would turn on until this same pH sensor measured the pH to be up to 6.5.

Aeration basin blowers were controlled through SCADA by using selected dissolved oxygen (DO) set points. The selected DO setpoints of the aerated zones are shown in Table 1-2.

Anoxic and swing zones were kept mixed using 1-hp vertical-shaft-type mixers. The mixing in these zones kept the mixed liquor in suspension and prevented any solids from settling out. The mixers in the swing zone could be turned off if aeration was required there; aeration provided enough mixing on its own so that both the mixer and air were not operating in the same zone at the same time.

The secondary clarifier was designed to produce an effluent that represented full scale so that the tertiary processes could be effectively investigated. Table 3 summarizes the design parameters for the pilot-scale clarifier. Similar to full scale, the sludge withdrawal mechanism is a suction type. Similarly, a flocculator centerwell was installed. The pilot plant return activated sludge (RAS) pumps were designed to mimic full scale (i.e., 50% at influent flow and a maximum of

63% at peak day flow). The effluent launders were covered to prevent algae growth that could impact downstream filtration processes.

Table 3. Summary of Pilot Secondary Clarifier Design

Parameter	Pilot Plant Specifications
Diameter, m (ft)	6.7 (22)
Sidewater Depth, m (ft)	3.7 (12)
SOR, m/day (gpd/sf)	
Average Dry Weather	23.4 (575)
Peak Day	48.8 (1,200)
Peak Hydraulic	55.2 (1,357)
RAS Ratio at Peak Day	63
RAS Pumps	
Number per clarifier	2 (1 duty/1 standby)
Capacity, each, ML/day (mgd)	1.1 (0.288)
Collector Mechanism	Suction

Sludge wasting was performed to maintain a target aerobic solids retention time (SRT) of 7.5 days (d). An algorithm was written into SCADA that would adjust the sludge wasting rate (by adjusting the waste activated sludge (WAS) pump) based on Stage Aerobic 2B mixed liquor suspended solids (MLSS), WAS total suspended solids (TSS), and aerated tank volume. This automatic sludge wasting technique was checked daily by measuring the amount of sludge wasted each day by checking how much volume was in the WAS storage tank.

Tertiary Treatment

Tertiary treatment consisted of three filtration alternatives and three disinfection alternatives. Filtration alternatives consisted of conventional granular media filter (CGMF), ozonated, biologically active granular media filter (OGMF), and ultrafiltration membrane filter (MF). Disinfection alternatives consisted of chlorine, ultraviolet irradiation (UV), and ozone. Any filtration alternative could be paired with any disinfection alternative and all combinations were tested to identify the most cost effective tertiary treatment process combination.

Preozonation Pilot Unit

Secondary effluent was ozonated and the treated effluent directed to two of the four GMF units (OGMF1 and OGMF2). A constant volume was ozonated through sidestream injection using an injector and blended with non-ozonated secondary effluent to reach the applied ozone setpoint. The sidestream flow was set at approximately 4.9 L/min (13 gpm) and the bulk non-ozonated flow varied based on the downstream demand of the GMFs. The preozone unit was designed to deliver up to 6 mg/L of applied ozone at a flow rate of up to 18.2 L/min (48 gpm).

Sidestream injection involved directly ozonating a portion of the total flow to a high ozone concentration then mixing with non-ozonated water to achieve the desired applied dose. Typically in full scale installations, 15% to 25% of the total flow is ozonated in the sidestream.

The amount of secondary effluent treated by the pilot unit varied throughout the study with each testing regime, which in turn varied the sidestream proportion between 26% and 100% of the total flow. The higher proportion is an artifact of the lower flows tested at pilot scale.

The ozone injector was connected to the pipeline flash reactor by 1.9 m (76.5) inches of 2.5 cm (1 in) diameter stainless steel piping. With the sidestream flow set at 4.9 L/min (13 gpm), the high concentration ozone water traveled at 1.6 m/s (5.3 ft/s) for about 1.2 seconds (s) before mixing with the non-ozonated water. In 1.2 s, the ozone was estimated to have decayed by approximately 0.5 mg/L, which was based on bench scale testing conducted on non-ozonated GMF effluent collected at the pilot and injected with doses of 2.5 mg/L and 5 mg/L transferred ozone. During the pilot study, ozone was dosed at a constant concentration of 4 mg/L.

A pipeline contactor was located immediately downstream of the pre-ozone unit to allow additional contact time upstream of the GMFs. The hydraulic residence time (HRT) was 16.3 minutes at 8.5 L/min (22.5 gpm) and 7.5 minutes at 14.5 L/min (38.4 gpm) as determined during the April 2012 residence time distribution (RTD) test. Sample taps were located at the inlet, outlet, and along the body of the pipeline to allow for testing at different contact times.

Rapid Mix and Flocculation

Chemical addition facilities were available upstream of all filters. For the GMF units, both rapid mix and flocculation were available. For MF, only rapid mix was available. Chemical addition was performed upstream of the GMF units only during select periods of the study. An aluminum chlorohydrate (ACH) solution was used as a flocculent aid.

Granular Media Filtration

The GMF units had dual media consisting of 1.2 m (4 ft) of anthracite (uniformity coefficient = 1.32; effective size = 1.25 mm) and 0.3 m (1 ft) of sand (uniformity coefficient = 1.37; effective size = 0.54 mm). The media was supported by 0.46 m (1.5 ft) of coarse gravel that rested on a fabricated slotted stainless steel underdrain with evenly spaced channels and air header and laterals arranged to provide even distribution of backwash air and water.

Two of the four GMFs were operated with a pre-ozonation step prior to filtration, designated as GMF 1-1 and 1-2 in SCADA, and referred to as OGMF1 and OGMF2, respectively, in this report. During disinfection testing, the filters were operated at the maximum loading condition. At the beginning of the study, both 12.2 m/hr (5 gpm/ft^2) and 18.3 m/hr (7.5 gpm/ft^2) were being tested independently. For the majority of the study, only the 18.3 m/hr (7.5 gpm/ft^2) condition was tested because there was no noticeable performance difference at the higher loading. During diurnal operation, CGMF1 and OGMF1 were operated with a maximum loading of 12.2 m/hr (i.e. when the SRWTP influent was 1,250 ML/day (330 mgd), the GMF units were at 12.2 m/hr). CGMF2 and OGMF2 were operated with a maximum loading of 18.3 m/hr during diurnal operation. At the latter portion of the project, all filters were operated with the same loading condition.

As a result of pre-ozonation, the two OGMF units were biologically active since ozonation resulted in the conversion of slowly biodegradable and non-biodegradable organic material to biodegradable material. The remaining two filters were operated without any preconditioning and were therefore conventional GMF units (designated as GMF 2-1 and 2-2 in SCADA, and referred to as CGMF1 and CGMF2, respectively, in this report.). Backwash was performed without chlorination for all filters, so it is likely that the CGMF units were biologically active to a lesser extent.

All four GMF filter columns operated with the same backwash conditions. The filters were operated in variable level mode and automatically initiated a backwash sequence once the filters reached the high level set point of 3 m (10 ft). Each filter had a separate clearwell which was filled with filtered effluent from its dedicated filter column.

Membrane Filtration

A GE-Zenon ZeeWeed® 500D pilot ultrafiltration system was used to represent MF technology. The pilot skid was a scaled-down version of a full-scale system, consisting of one cassette with three polyvinylidene fluoride (PVDF) hollow fiber membrane modules (total membrane surface area of 123 m^2 (1,320 ft^2)) suspended within the membrane tank. The membranes had a nominal pore size of 0.04 micrometers (µm). The membranes operated under a negative pressure which drew permeate through the membranes, leaving contaminants behind in the membrane tank. The MF pilot skid was preceded with an Amiad TAF automatic filter. The filter was equipped with a 500 µm stainless steel weave wire screen.

The MF system was typically operated on a diurnal flow pattern with membrane flux values ranging from 0.61 to 1.0 m/day (15 to 25 gallons per square foot per day (gfd)) with a target recovery of 90%. During disinfection testing, membrane flux values ranged from 1.2 to 1.7 m/day (30 to 42 gfd).

Chlorine Disinfection

The chlorine pilot unit consisted of sodium hypochlorite (NaOCl) addition upstream of a pipeline contactor and was operated at the design flow of 1.9 L/min (5 gpm). The pipeline contactor was designed with an HRT of 120 min and a CT value (i.e. product of concentration and contact time) of 450 milligrams per liter * minutes (mg*min/L). During RTD testing, the HRT of the contactor was determined to be 79 min at 1.9 L/min. The target total residual chlorine at the exit of the contactor was 5 mg/L and was measured with an on-line chlorine analyzer. The residual varied throughout the day as the water quality and chlorine demand of the water changed. During each sampling event, a grab sample was collected at the contactor outlet and analyzed for total chlorine to determine the residual and CT and also as a check of the online analyzer.

Ultraviolet Disinfection

The UV pilot unit was a low-pressure, high-output, open channel unit that consisted of three banks of lamps in series, with two lamps in each bank (TAK 55 manufactured by Wedeco). The UV pilot was designed for a flow range of 3.8 to 22.7 L/min (10 gpm to 60 gpm). The UV intensity was measured continuously by the UV sensor inside each bank. The lamps and channel were manually cleaned as needed to mitigate fouling. Automatic wipers were added to the lamps at the end of the study and operated for about 2 months.

UV doses ranging from about 50 to 300 milli-Joules per square centimeter (mJ/cm^2) were tested throughout the study. The desired dose was set by adjusting the number of banks in service (1 to

3), the lamp intensity (50 to 100%), and flow (3.8 to 22.7 L/min) through the channel. Performance of a filter-UV treatment train was demonstrated through regular testing of the permit parameters. All samples were collected at the end of the UV channel.

Ozone Disinfection

The ozone disinfection pilot skid was designed for a constant flow of 3.8 L/min (10 gpm) and a maximum dose of 20 mg/L applied ozone. The filter treated water was ozonated using mainline injection via an injector. A pipeline contactor designed for an HRT of 15 minutes was located downstream of the ozone unit. The actual HRT was measured to be 15.7 minutes at 3.9 L/min. The contactor was manually cleaned as needed by filling it with a high concentration sodium hypochlorite solution and soaking for 6 to 24 hours (h).

Applied ozone doses varying from 2 to 20 mg/L were tested during the study. All samples were collected from the contactor outlet.

Sampling Schedule

The BNR was in service for the entire testing period (April 2012 – February 2013). Throughout the study, filter effluent was routed to the disinfection pilot units such that different unit process configurations could be tested. Sampling was performed to mimic a plant demonstrating compliance with the SRWTP permit. Additional sampling was performed to better understand the different process trains. Special sampling helped determine if certain process trains were capable of meeting potential future permit requirements, such as trace organic compounds (TOrCs). During the special studies, sampling to demonstrate meeting permit requirements was occasionally postponed because of modifications to the process for special studies (such as adding viruses or chemicals to the process, changing flow rates, etc.).

Composite Samplers

ISCO 4700 Refrigerated Composite Samplers were used on this project. Two different modes of operation were used, depending on sample location. The first (and most common) mode of operation was the Flow-Paced Constant Volume, Variable Time sampling mode. This mode of operation collected a flow proportional composite sample and took a set sample volume after a specified flow interval (e.g. a sampler was programmed to collect 100 milliliters (mL) of sample for every 18.9 m^3 (5,000 gallons) of flow through a flow meter). The flow-pacing interval (gallons) was programmed based on the expected daily flow such that the sampler collected approximately 120 samples over a 24-h period to mimic the sampling scheme implemented at the SRWTP. The sample aliquot volume was programmed based on the sample volume required for all analyses and the minimum sample aliquot volume the sampler could deliver. Typically this value was between 50 to 80 mL per sample, to target a total 24-h sample volume of 7 to 10 liters (L). Each sampler received an analog flow signal from the corresponding flow meter(s) through SCADA, as shown in Table 1-4.

Table 4. Composite Sample Locations

Sampler ID	Sample Description	Mode of Operation	Sampler Flow Pacing Signal	Sampler Flow Pacing Signal Full Scale (20mA)
SMP 100	Pilot Influent (WWTP Primary Effluent)	Constant Volume, Variable Time	Pilot influent + wet weather influent (FIT 101 + FIT 205)	1250 gpm
SMP 129	MLSS	Time-Paced	No flow signal, time based only	NA
SMP 130	Secondary Effluent	Constant Volume, Variable Time	Pilot Influent + sidestream influent + wet weather influent – WAS effluent (FIT 101 + FIT 175 + FIT 205 – FIT 151)	1250 gpm
SMP 140	WAS (Stage 3 Aerobic)	Time-Paced	No flow signal, time based only	NA
SMP 178	Sidestream Storage Tank	Constant Volume, Variable Time	Sidestream influent (FIT 175)	20 gpm
SMP 213	Microfilter Effluent	Constant Volume, Variable Time	Microfilter effluent (FIT 217)	70 gpm
SMP 237	OGMF1	Constant Volume, Variable Time	GMF 1-1 Influent (FIT 231)	45 gpm
SMP 238	OGMF2	Constant Volume, Variable Time	GMF 1-2 Influent (FIT 233)	45 gpm
SMP 247	CGMF1	Constant Volume, Variable Time	GMF 2-1 Influent (FIT 241)	45 gpm
SMP 248	CGMF2	Constant Volume, Variable Time	GMF 2-2 Influent (FIT 243)	45 gpm
SMP 255	Ozone Disinfection Effluent	Time-Paced	NA	NA
SMP 256	Chlorine Effluent	Time-Paced	Chlorine Influent (FIT 252)	NA
SMP 257	UV Effluent	Time-Paced	UV Influent (FIT 260)	NA

Not all samplers used the aforementioned mode of operation. The MLSS sampler (located in Stage 2B Aerobic) operated with no flow signal and only took time-based samples. All three final effluent samplers were on time-based sampling because each disinfection unit was fed a constant flow rate. Table 4 shows all sampler locations, the mode of operation used, and flow signal origin. The location of the samplers is illustrated in Figures 1 and 2.

Monitored Parameters

To assess the treatment effectiveness of the tested tertiary treatment process combinations of filtration and disinfection, the ability to meet California Title 22 unlimited reuse reclaimed water performance standards was assessed. The Title 22 water quality performance standards include limits on turbidity and total coliform and a demonstrated ability to reduce seeded MS-2 bacteriophage virus by at least 99.999% (≥5-log).

The limits on turbidity are:

- ≤ 2 NTU (daily average)
- ≤ 5 NTU (5% of the time within 24 hr)
- ≤ 10 NTU (always)

The limits on total coliform are:

- ≤ 2.2 MPN/100 mL (7-day median)
- ≤ 23 MPN/100 mL (max month)
- ≤ 240 MPN/100 mL (always)

Total coliform was measured by the SRWTP laboratory using Standard Methods #9221B. Male specific bacteriophage was enumerated by Biovir Laboratory (Benecia, CA) using Adams 1959 method. Turbidity was continuously monitored by online turbidimeters (Hach Filter Trak 660) located at the effluent of all filters and disinfection processes.

Life Cycle Cost Analysis

A life cycle cost analysis was conducted to assess the cost for each tertiary treatment process combination to meet the Title 22 standards. Values used for unit cost variables are presented in Table 5.

Table 5. Unit Cost Variables

Description	Unit	Variable Value
Technology Life-Span	Years	60
Nominal Discount Rate	%	5
Inflation Rate:		
General	%	3
Labor	%	3
Energy	%	5
Chemical	%	3
Base Year	Year	2012
Labor	$/hr	93
Energy	$/kWh	0.90
Chemicals:		
Sodium hypochlorite (12.5%)	Gallon	0.60
Citric acid (50%)	Gallon	5.43
Sodium hydroxide (25%)	Gallon	1.19
Sodium bisulfite (25%)	Gallon	0.98
Polymer (100%)	Pound	2.00
Coagulant (alum, 48%)	Pound	0.13
Chlorine	Pound	0.075
Sulfur Dioxide	Pound	0.093

The operations and maintenance requirements for labor, energy, and chemicals were determined based on pilot study requirements to meet water quality standards and on information from other operating treatment plants utilizing the tested treatment processes. Capital costs were determined by professional estimators from the SRWTP project management office.

Trace Organic Compounds

Twelve indicator TOrCs were selected to represent a range of physical and chemical characteristics found in compounds present in municipal wastewater. The goals of the indicator TOrC selection were to represent the various categories of TOrCs and target those that provide treatment efficacy information based on the removal, or lack thereof, within a particular unit process. Selection criteria for these indicator compounds consisted of readily available analytical techniques for analysis, available occurrence data, and representation of a range of characteristics of other compounds. The selected compounds and their reported reactivities are presented in Table 6.

Table 6. Indicator Target Analytes.

	Compound	Bio-degradability	Reactivity to Ozone	Reactivity to Pre-Ozone/GMF	Reactivity to Chlorination	Reactivity to UV Disinfection
1	Carbamazepine	Recalcitrant	High	High	Low	Low
2	DEET	Moderate	High	High	Low	Low
3	Ibuprofen	Rapid	High	High	Low	Low
4	NDMA	Moderate	Formation Potential	Formation Potential	Formation Potential	High at High Doses
5	Sucralose	Low	Low	Low	Low	Low
6	Sulfamethoxazole	Moderate	High	High	High	Moderate
7	Triclosan	Rapid	High	High	High	Moderate
8	Atenolol	High	High	High	Moderate	Low
9	Gemfibrozil	Moderate	High	Moderate	Low	Low
10	Iopamidol	Low	Low	Low	Low	Low
11	Meprobamate	Recalcitrant	Moderate	Moderate	Low	Low
12	TCPP	Low	Low	Low	Low	Low

DEET = N,N-Diethyl-meta-toluamide
NDMA = N-Nitrosodimethylamine
TCPP = Tris (1-chloro-2-propyl) phosphate

RESULTS AND DISCUSSION

Filtration

The granular media filters, both conventional and biologically active, were operated under both diurnal flow varying conditions and maximum loading conditions [18.3 m/hr (7.5 gpm/ft^2)]. The filtered effluent turbidity from the preozonated biofilters and conventional granular media filters did not exceed 2 NTU for the duration of the testing when operating at 18.3 m/h, which is presented in the probability plots in Figures 3 and 4. These results indicate that operation at 18.3 m/h produced an effluent that is in compliance with Title 22 turbidity requirements for granular media filter performance.

Figure 3. Probability plot of OGMF effluent hourly average turbidity data.

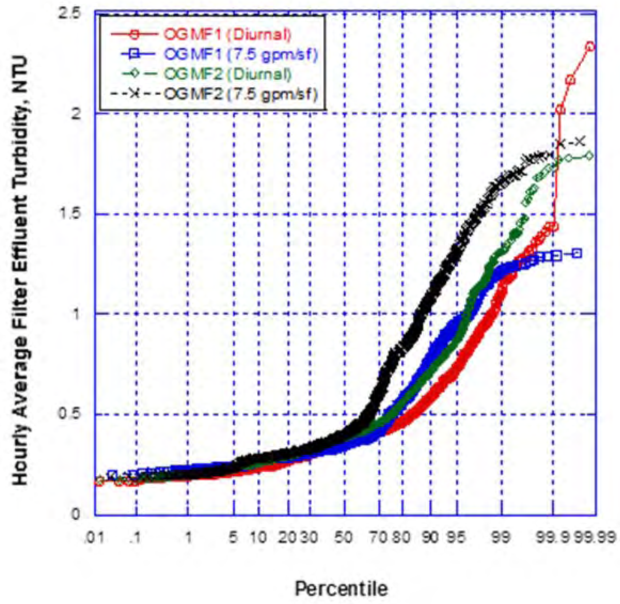
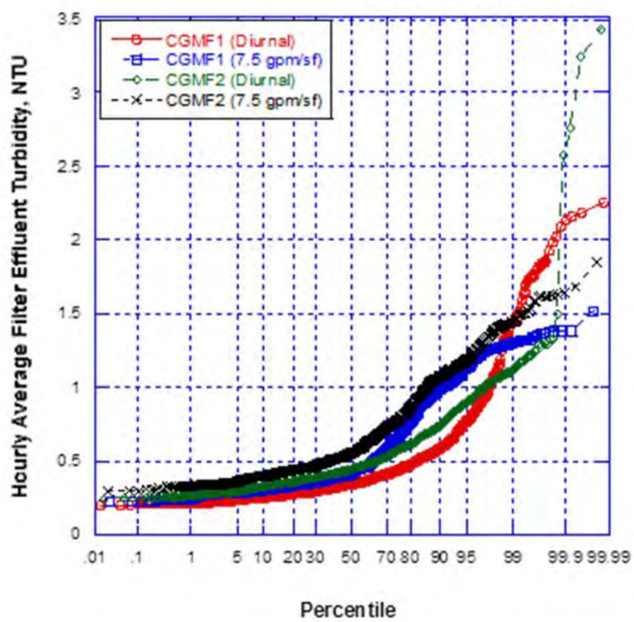
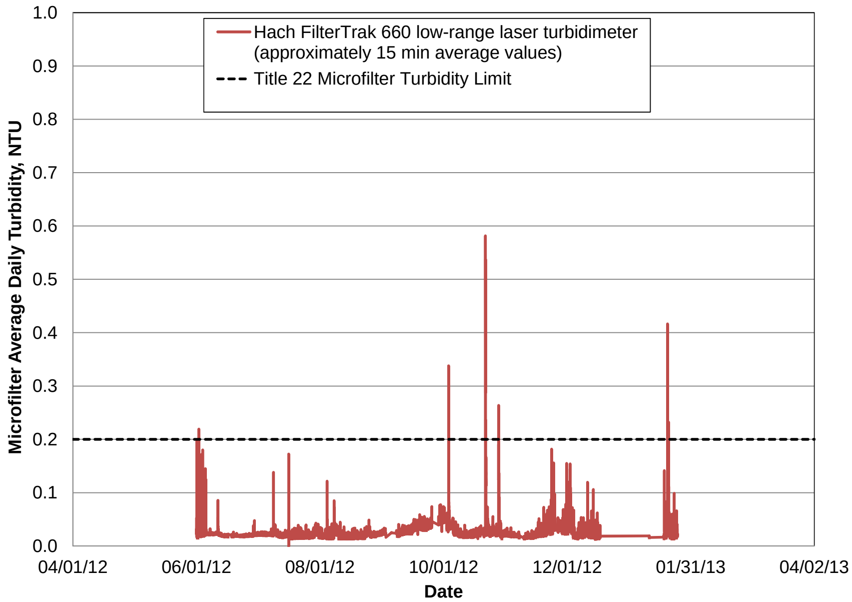


Figure 4. Probability plot of CGMF effluent hourly average turbidity data.



The Title 22 turbidity limit for membrane filters is 0.2 NTU. The data presented in Figure 5 illustrate that the test MF system met the Title 22 turbidity requirements.

Figure 5. Average Daily Turbidity from On-line Turbidimeter for MF



Recovery rates for filters, the percentage of filtered water that becomes product water, translates directly to cost. Recoveries for the biofilters and conventional filters are presented in Table 7. In general, the conventional filters had higher recoveries than the biofilters. This difference may be due to a higher backwash frequency required by the biofilters due to additional filtration capacity attributed to the biomass that grew on the preozonated filters.

Table 7. GMF recovery statistics over the length of the project

Filter	Diurnal Flow Recovery (percent)			Recovery at 7.5 gpm/sf (percent)		
	Median	95th Percentile	5th Percentile	Median	95th Percentile	5th Percentile
OGMF1 (max of 5 gpm/sf at diurnal condition)	95.8	97.5	93.3	94.4	96.2	89.9
OGMF2 (max of 7.5 gpm/sf at diurnal condition)	95.4	96.8	92.7	92.0	96.0	83.4
CGMF1 (max of 5 gpm/sf at diurnal condition)	97.0	97.8	96.3	95.9	97.8	94.9
CGMF2 (max of 7.5 gpm/sf at diurnal condition)	96.6	97.7	95.1	95.7	97.5	94.3

Disinfection

Disinfection processes had to reliably meet two performance criteria, the total coliform limit and the virus reduction requirement in the SRWTP NPDES permit. The total coliform testing was conducted on the final filtered, disinfected product water. Virus reduction performance was measured by seeding the secondary effluent with a known concentration of virus and measuring virus concentrations of filtered, disinfected effluent from the tested process trains. By including the filtration process in the virus reduction measurements, the disinfection benefit gained from the pre-filtration ozonation process was included in the virus reduction performance testing for the OGMF process train.

Figure 6 presents total coliform results with regard to chlorine CT values. All coliform results met permit requirements. CT values ranged from 217 mg*min/L to 1,150 mg*min/L. All total coliform values were under 2.2 MPN/100 mL at CT values above 386 mg*min/L.

Figure 6. Chlorine CT value vs. Total Coliform Results in Chlorine Final Effluent

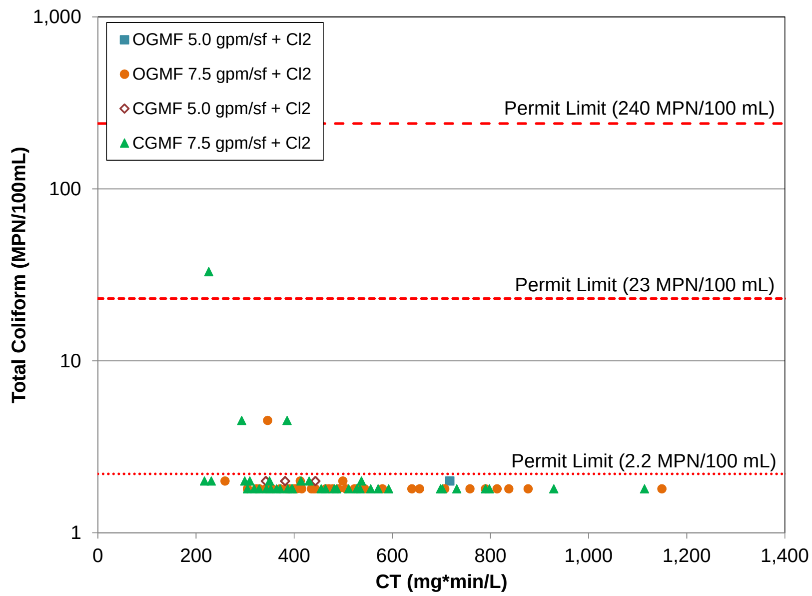
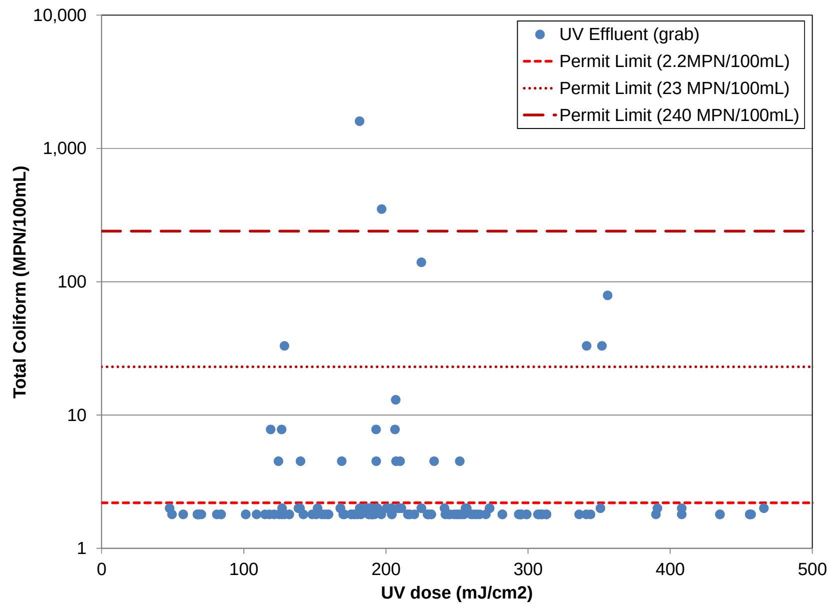


Figure 7 presents the total coliform results for UV disinfection. As shown, several UV coliform samples exceeded permit limits. This was attributed to sampling methodology and channel contamination. This situation was improved by modifying sampling methodology and increasing frequency of channel cleaning. Initially, grab coliform samples were collected from a tap at the end of the UV channel. Due to concerns with regrowth, sampling taps were installed on the side of the UV channel immediately after each bank. Starting at the end of August, grab samples were collected from the effluent of the last bank in service and the UV channel was cleaned every four to six weeks depending on the frequency of testing. Compliance with the total coliform requirement improved markedly after these changes were implemented.

Figure 7. UV Dose vs. Total Coliform Results in UV Final Effluent



Huitric et al. (2008) reported that poliovirus and MS2 removals were similar in the presence of free chlorine. In this study, MS2 bacteriophage was used as a surrogate for poliovirus for all virus seedings. During virus challenges, GMF units were operated at a loading of 7.5 gpm/sf . The maximum GMF flux specified by Title 22 is 5.0 gpm/sf; however, recent research by Williams et al. (2007) demonstrated that Title 22 requirements can be met at elevated filtration flux rates. Table 8 presents the results of pilot-scale virus challenge of MF and CGMF effluents. CT values between 315 and 500 mg*min/L were tested for MF filter effluent. For CGMF filter effluent, a target CT of 450 mg*min/L was tested. The test results showed that greater than 5-log inactivation of MS2 bacteriophage is possible at CT values at 315 mg*min/L and 412 mg*min/L, respectively for MF and CGMF filter effluents.

Table 8. Summary of virus seeding results for chlorine disinfection treating filter effluent

Date	Filter in Service	Modal Contact Time (min)	Total Residual Chlorine (mg/L)	CT (mg*min/L)	Virus Log Inactivation	Sample Count
6/21/12	MF	48	6.6-7.0	315-334	6.60-6.90	3
6/21/12	MF	55	6.0-6.5	330-358	6.52-7.08	3
6/21/12	MF	79	5.9-6.2	463-491	6.30-6.40	3
6/19/12	CGMF2	79	5.2-5.8	412-460	6.11-7.20	6
1/30/13	CGMF2	79	5.4-5.8	423-461	6.82-7.02	6

Virus challenges were performed on the preozonation system and showed that as much as 5-log removal of MS-2 could be realized. Therefore, by providing virus removal in the pre-filtration ozonation step, downstream disinfection processes can potentially be sized smaller, assuming the coliform limit can be met.

Collimated beam testing of total coliform destruction at UV doses below the Title 22 prescriptive dose of 100 mJ/cm^2 were conducted to assess the efficacy of reducing UV disinfection doses following pre-filtration ozonation. Results from the testing are presented in Table 9. The results indicate that UV dose below 100 mJ/cm^2 can meet Title 22 total coliform limits, making reduced UV disinfection sizing feasible when preceded by pre-filtration ozonation. The combined processes can meet both the virus reduction and total coliform requirements of the permit.

Table 9. UV irradiation by collimated beam to measure total coliform inactivation.

UV Dose (mJ/cm^2)	Influent Total Coliform (cfu/100 mL)	Effluent Total Coliform (cfu/100 mL)
0	9.3E+03	---
40.1		<1
60.2		<1
80.3		<1
100.4		<1
120.4		<1

Data from the on-line UV Transmittance (UVT) analyzers during a "first flush" storm event are presented in Figure 8. A significant UVT drop occurred in response to the addition of storm water to the plant influent. Secondary effluent UVT declined nearly 20% during this "first flush" storm event and is believed to be due to impacts from the portion of the Sacramento collection system that is a combined collection system. Although preozonation improved UVT during the storm event, preozonated GMF effluent UVT was less than 65%, the allowable lower limit for effective virus inactivation specified in the NWRI guidelines. Subsequent testing of UVT response to ozone treatment illustrated that UVT can be increased nearly 20% with ozone doses of 12 mg/L (Figure 9). This means that preozonation facilities would be required to make UV disinfection feasible for this treatment facility, increasing the cost for the UV disinfection alternative.

During the "first flush" storm event, a virus challenge was performed and showed that at the routine ozone dose of 3 mg/L, only 2-log removal was observed. The UVT decline implies that some of ozone was consumed by competitive demands and was not available for virus destruction. The correlation between UVT decline and reduced virus destruction implies that UVT may be able to be used as a surrogate measurement of ozone demand. This could be very beneficial because UVT measurement occurs in real time and is much less expensive and time consuming than conducting virus counts.

Figure 8. Impact of rainfall on filtered effluent UVT (OGMF units are GMF 1-1 and 1-2; CGMF units are GMF 2-1 and 2-2)

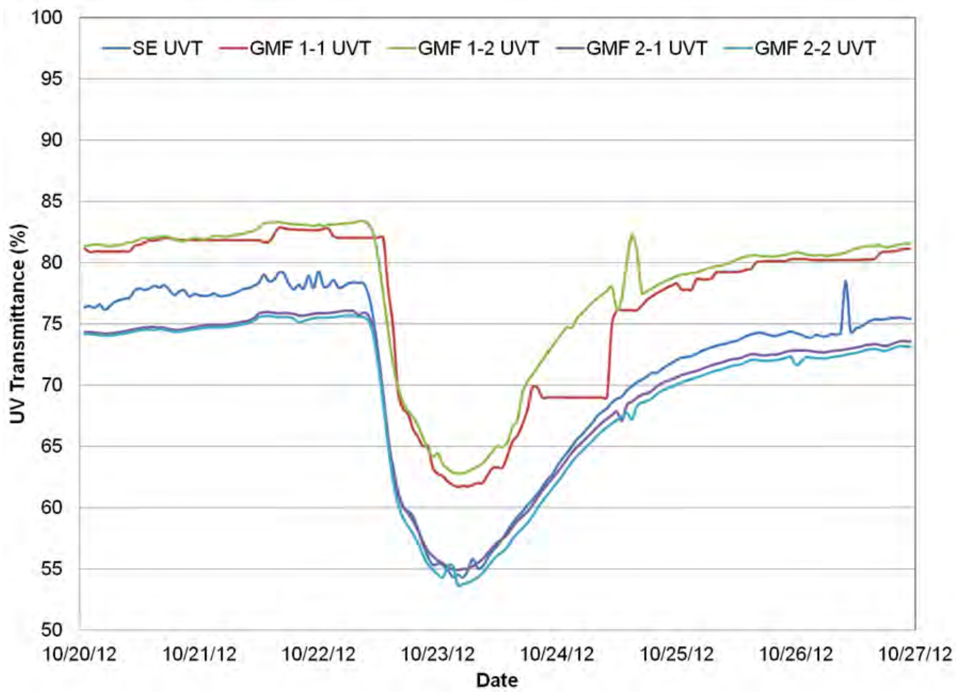
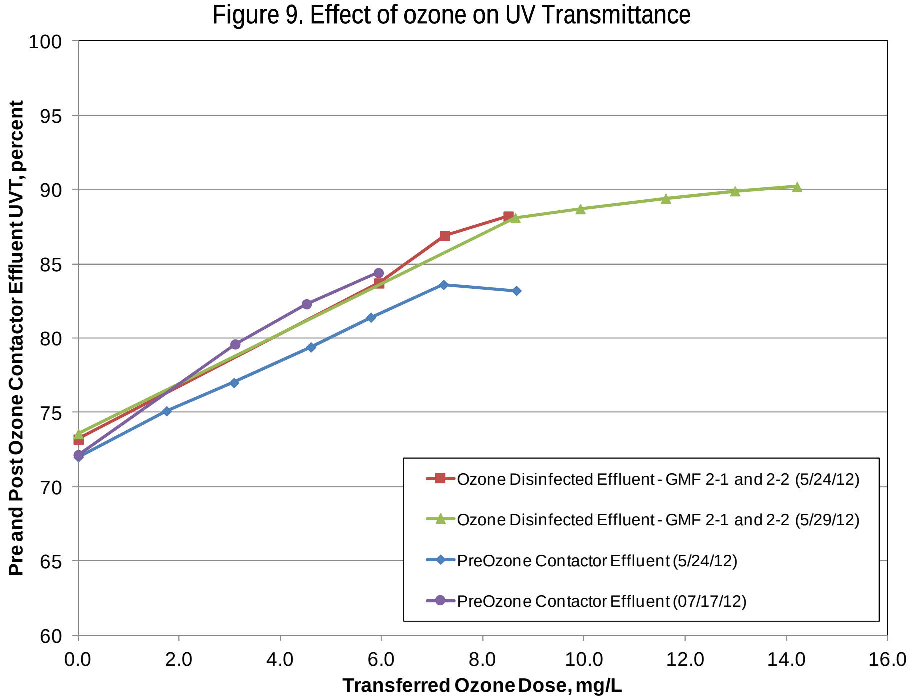


Figure 9. Effect of ozone on UV Transmittance



Similar testing of chlorine disinfection efficacy for meeting total coliform requirements at CT values below the prescriptive Title 22 values was inconclusive and follow up testing is scheduled. Due to the inconclusive results, it is currently being assumed that CT values for chlorine disinfection must be designed at Title 22 prescriptive levels and savings can't be realized by pre-filtration ozonation for virus reduction.

Cost

Of the three filtration technologies tested, all met the performance criteria and were evaluated for life cycle cost comparison. Two of the disinfection technologies tested, chlorine and UV irradiation, met performance criteria and were evaluated for life cycle cost comparison. The third tested disinfection technology, ozone, could not reliably meet total coliform requirements and was therefore not included in the economic analyses. The estimated program costs for each viable treatment process train are presented in Table 10.

Table 10. Estimated program costs for treatment train alternatives

Alternative	Capital	Annual O&M
BNR + CGMF + Chlorine	$1.5 billion	$49 million
BNR + CGMF + UV	$1.6 billion	$45 million
BNR + OGMF + UV	$1.7 billion	$46 million

Trace Organic Compounds

Table 11 presents the results of the TOrC testing. These results show that of the 12 compounds selected for study, most have at least partial removal by the BNR process and many are nearly completely removed. Of the tertiary processes, ozonation proved to be most effective, whether applied as pre-filtration treatment or as post-filtration disinfection. A few of the compounds reacted to UV and to chlorine.

Table 11. Summary of TOrC Parent Compound Removal (%).

Constituent	Removal through BNR		Reactivity to Pre-Ozone		Reactivity to Free Chlorine		Reactivity to UV		Reactivity to Post-Ozone	
	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
Iopamidol	11	0 - 31	19	0 - 33	46	0 - 70	6	0 - 31	55	21 - 90
Atenolol	85	76 - 95	9	4 - 14	2	0 - 8	3	0 - 12	10	2 - 19
Sucralose	33	0 - 80	20	0 - 36	7	0 - 33	6	0 - 32	4	0 - 8
Meprobamate	4	0 - 41	28	18 - 41	2	0 - 15	1	0 - 10	56	29 - 84
Sulfamethoxazole	24	0 - 41	70	61 - 84	23	0 - 52	44	0 - 99	41	5 - 78
Carbamazepine	1	0 - 8	98	93 - 99.9	1	0 - 5	4	0 - 19	50	0 - 99.9
DEET	94	82 - 99.8	4	0 - 12	0	0 - 1	0	0 - 1	3	1 - 6
TCPP	1	0 - 9	0	- -	0	- -	0	0 - 3	0	- -
Ibuprofen	99.9	99 - 99.99	0	0 - 1	0	- -	0	- -	0	- -
Gemfibrozil	96	80 - 99.99	4	0 - 9	0	0 - 1	2	0 - 20	1	0 - 1
Triclosan	89	57 - 98	9	4 - 32	2	0 - 11	4	0 - 22	4	1 - 7
NDMA	75	0 - 95	0*	- -	32	0 - 95	8	0 - 67	0**	- -

* NDMA was formed when reacted with ozone, but was removed by subsequent biologically active filtration

** Ozone disinfection produced NDMA.

CONCLUSIONS

- To produce secondary effluent to feed the tested tertiary processes, it was necessary to construct and operate a secondary BNR treatment facility due to significant water quality characteristic differences between the existing high purity oxygen activated sludge process and a BNR process.
- All tested filtration alternatives, CGMF, OGMF, and membrane met the required water quality requirements. CGMF was the most cost effective filtration alternative.
- Chlorine and UV disinfection met the performance requirements, but UV transmittance dropped significantly during large storm events, necessitating pre-filtration ozone treatment to increase UVT before UV disinfection. Chlorine disinfection was not affected by the reduced UVT.
- Chlorine was the most cost effective disinfection alternative.
- BNR treatment removed many of the 12 trace organic compounds tested.
- Pre-filtration ozone treatment was the most effective tertiary treatment process tested for removing the 12 trace organic compounds tested.

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