Direct Potable Reuse Monitoring:

Testing Water Quality in a Municipal Wastewater Effluent Treated to Drinking Water Standards

Volume 1 of 2

FINAL

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EXECUTIVE SUMMARY

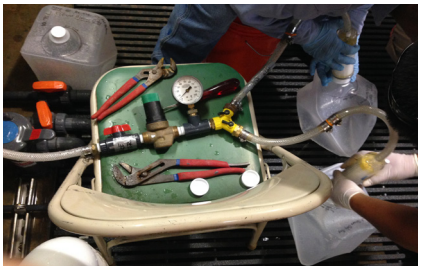
In May 2013, the Colorado River Municipal Water District (CRMWD or District) began augmenting raw water supplies with advanced treated reclaimed water from its Raw Water Production Facility (RWPF) in Big Spring, Texas. Since the implementation of direct potable reuse projects at Big Spring and Wichita Falls, many view direct potable reuse (DPR) as a viable option for increasing a community's water supply.

Study Goals

Because this newfound acceptance may lead to more DPR projects across the state, the Texas Water Development Board commissioned this study to increase confidence in the safety and effectiveness of the RWPF's DPR applications through a detailed sampling campaign. In addition, this study includes guidance focused on indicators and surrogates for improved DPR process monitoring at a reasonable cost. Both of the aforementioned goals support further developing DPR projects as a viable water supply alternative across Texas and the United States.

Sample Results

Testing was conducted in accordance with a detailed Test Protocol, and data were compiled into summary tables and graphics. Samples collected unequivocally showed that the RWPF produces water of very high quality. In fact, the water is more than sufficient to serve as a raw water source that is blended with other, conventional raw water sources before being retreated in conventional water treatment plants served by the District. This conclusion is supported by a number of facts:



Plant Operators Collecting Compliance Samples

1 RWPF compliance testing already addresses parameters with regulatory limits. Based on the data provided to the project team (see Appendix C), no regulated parameters have been exceeded.

Sampling at Moss Creek Lake Pump Station

2 Study sampling for constituents of emerging concern (CECs) indicate that concentrations of CECs in the RWPF influent are below health-based benchmarks, and concentrations in the product water are correspondingly lower. In fact, unregulated CECs in the RWPF product water were generally lower than concentrations measured in samples from Moss Creek Lake. Water from Moss Creek Lake is blended with RWPF product water. This means that the RWPF product water is actually improving the quality of the blended water provided to downstream conventional water treatment plants for final drinking water treatment and distribution to customers.

Field-Filtering for Virus

3 Pathogen testing yielded equally clear results: Protozoa (Giardia and Cryptosporidium) and bacteria (Escherichia coli) were not detected past the first treatment process in the RWPF (microfiltration). Not a single sample collected at the RWPF tested positive for enteric virus.

RESULTS OF SURROGATE TESTING

Surrogate testing provided more insight into ways to improve confidence in the treatment process. For each advanced treatment process at the RWPF, additional monitoring processes were evaluated, as follows:

1. For microfiltration (MF), effluent turbidity monitoring and particle size distribution (PSD) testing increased confidence in the integrity of the membranes. In contrast to direct integrity testing by pressure decay, PSD testing can be done while the MF skids are online, which means they can be performed more often without affecting facility production. Reducing the time between integrity tests reduces the time during which a membrane integrity issues might go undetected.

2. For the reverse osmosis (RO) process, a fluorescent tracer-based method was evaluated. It is a promising technology for monitoring membrane integrity and could be applied at the RWPF or other DPR facilities as a conservative surrogate for pathogen removal.

3. For the ultraviolet light advanced oxidation process (UV/AOP), chloramines removal correlated very well with UV dose during off-site collimated beam testing with RO permeate samples from RWPF. Because the relationship between UV dose and pathogen inactivation is well-established, chloramines removal can be a good surrogate to confirm ongoing UV inactivation of pathogens and the UV dose needed for effective UV/AOP operation. A "UV check" would be easy to conduct by periodically turning off hydrogen peroxide feed, which can interfere with chloramines measurements.

Looking Ahead

Along with providing an adequate level of pathogen inactivation, nitrogen species and disinfection byproducts should be highlighted when evaluating treatment and monitoring processes for any DPR project. Treatment for both of these chemical constituent groups is most effectively addressed not during advanced treatment, but by carefully considering the upstream wastewater treatment processes.

More generally, when considering the size of the envelope for evaluating existing and future DPR facilities, it is important to consider the upstream effects on the advanced treatment system. This includes enhanced source control with potential collection system monitoring, design integration with water reclamation facilities, and careful consideration of the operational standards and philosophies at these upstream facilities as they transition from waste management facilities to those that house the first steps in a broader system that produces drinking water.

Beyond treatment process considerations, monitoring approaches for DPR projects should be considered during the design of the advanced treatment facilities. In addition to end-of-pipe testing to confirm water quality, a monitoring program should include measures that will alert operators to any issues in real time. Both the approaches to monitoring as well as the technology and tools available to perform this type of monitoring are evolving rapidly, and future DPR projects should therefore include a review of current advanced monitoring approaches.

1 Introduction

Across the country, successful indirect potable reuse (IPR) projects create more than 200 million gallons per day (mgd) of potable water. These projects include, amongst others, those at the Water Replenishment District, Orange County Water District and West Basin Municipal Water District in California; the Upper Occoquan Service Authority in Virginia; the City of Scottsdale, Arizona; and El Paso Water Utilities in Texas. In addition, many projects in Texas classified as *indirect reuse* are implicitly potable reuse projects. These projects discharge to a Water of the State and then withdraw water downstream for potable use.

With recent droughts across the Southwest, many utilities are transitioning to direct potable reuse (DPR), which differs from IPR because it does not use a natural water body such as a river, lake, or aquifer in the treatment scheme. Beyond some potential benefits to public perception, the so-called *environmental buffers* do provide some treatment and, more critically, significant response time in case of process challenges. However, depending on the local conditions, the environmental buffer also can introduce contamination from agricultural, industrial, municipal, or natural environmental contaminants. In a transition from IPR to DPR, treatment and/or advanced monitoring and control must compensate for the lack of an environmental buffer.

In May 2013, the Colorado River Municipal Water District (CRMWD or the District) began augmenting raw water supplies with advanced treated reclaimed water from its Raw Water Production Facility (RWPF) in Big Spring, Texas. At the same time, the City of Wichita Falls, Texas, implemented a second emergency DPR project, which has since been decommissioned.

The Texas Water Development Board (TWDB) commissioned this study, titled "Testing Water Quality in a Municipal Wastewater Effluent Treating to Drinking Water Standards," for a comprehensive evaluation of the water quality produced from the nation's first DPR project in Big Spring. Additional funding for the project was received through a tailored collaboration with the WateReuse Research Foundation under Project No. 14-10 and the Texas Section of the WateReuse Association.

1.1 Project Objectives

Since the implementation of DPR projects at Big Spring and Wichita Falls, many view DPR as a viable option for increasing a community's water supply. Because this newfound acceptance may lead to more DPR projects across the state, this study has two main goals:

1. To increase confidence in the safety and effectiveness of the RWPF's DPR applications through a detailed sampling campaign.
2. To draft guidance focused on indicators and surrogates for improved DPR process monitoring at a reasonable cost.

Both goals support further developing DPR projects as a viable water supply alternative across Texas and the United States.

1.2 Project Deliverables

A Data Report that compiles the results of field testing at RWPF is being submitted concurrently with this Final Report (Appendix A).

The project team submitted a detailed Test Protocol to the TWDB on January 13, 2015 (Appendix B). A draft of this protocol had been submitted for District, TWDB, and Texas Commission on Environmental Quality (TCEQ) review on May 27, 2014, and served as a working document to determine sampling requirements for the first sample event, which was conducted in September 2015.

The goal of testing was to evaluate whether an engineered DPR system can consistently produce water of a high quality that protects public health.

2 Background

The District owns and operates the RWPF, located in Big Spring. The District serves nearly 500,000 customers in 31 counties in West Texas. In addition to other contract holders, the District serves three member cities: Big Spring, Odessa, and Snyder. Figure 2.1 shows a map of the District's service area and raw water supplies. Figure 2.2 shows the CRMWD and City of Big Spring facilities involved in direct potable reuse.

Historically, the District has relied heavily on surface water supplies from its three reservoirs on the Colorado River: Lake J.B. Thomas Reservoir, E.V. Spence Reservoir, and O.H. Ivie Reservoir. These reservoirs have a full combined capacity of 1,272 million acre-feet. To supplement this supply source, the District also operates five well fields.

Because of periodic droughts that have historically and recently reduced its reservoirs' stored volume of water to a minimum, the District has developed additional water sources. This effort included completing the Ward County Well Field (50,000 acre-foot per year (AFY) capacity) and the RWPF (1.7 million-gallon-per day (mgd) in Big Spring.

The RWPF receives cloth-media-filtered and chlorine-disinfected secondary effluent from the City of Big Spring's adjacent wastewater treatment plant (WWTP). This effluent is monitored for turbidity at the influent to the RWPF, which then treats WWTP effluent that is less than 10 nephelometric turbidity units (NTU). If WWTP effluent turbidity exceeds this value, it is returned to the WWTP.

The advanced treatment treatment train at the RWPF includes microfiltration (MF), reverse osmosis (RO), and an advanced oxidation process (AOP) consisting of ultraviolet (UV) light with hydrogen peroxide (H_2O_2) addition. The RWPF is designed to produce 1.7 mgd of raw water from a 2.5 mgd filtered secondary effluent feed flow and was designed to be expanded to twice that capacity.

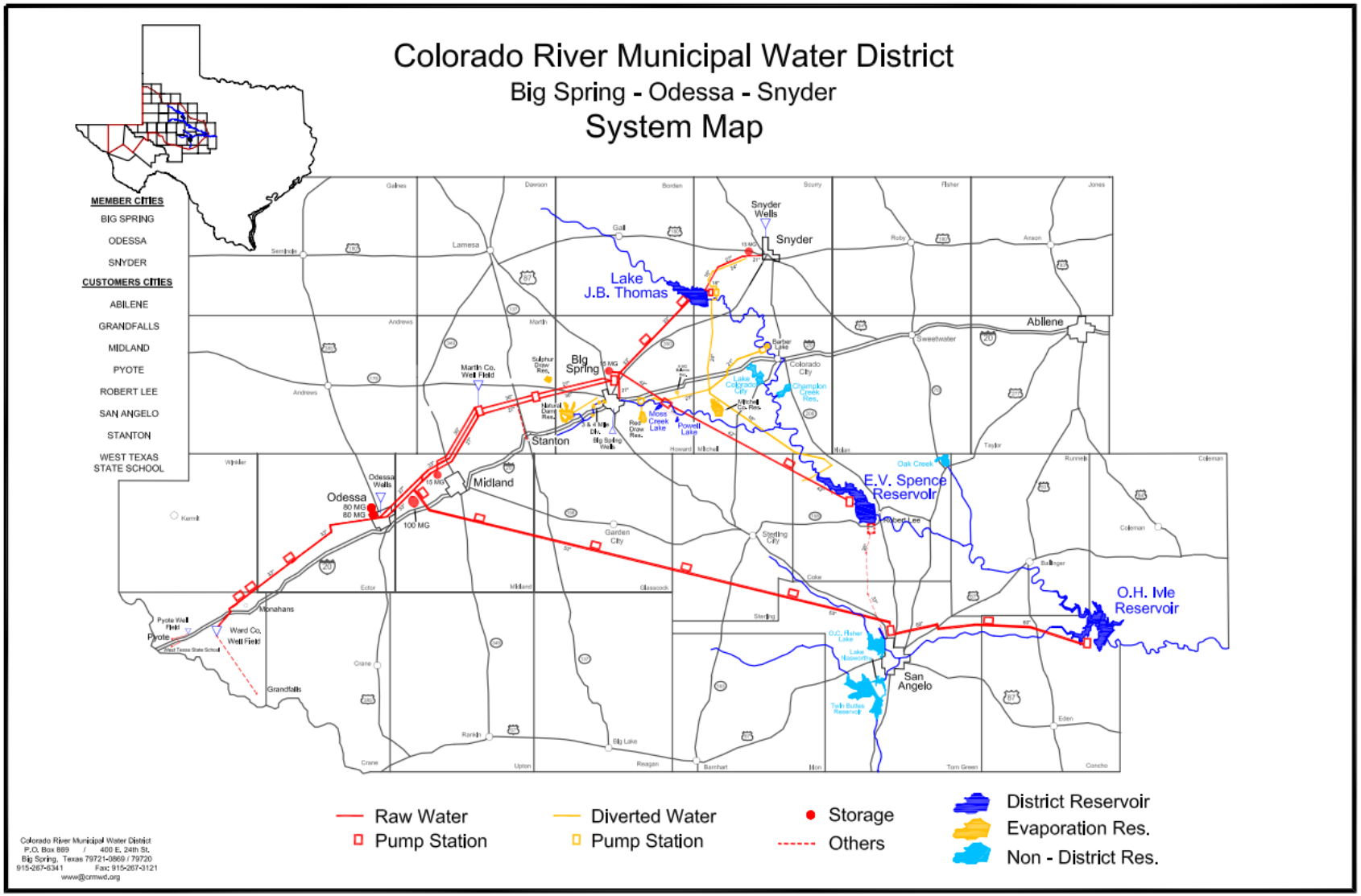


Figure 2.1 Colorado River Municipal Water District system map. (Provided by CRMWD).

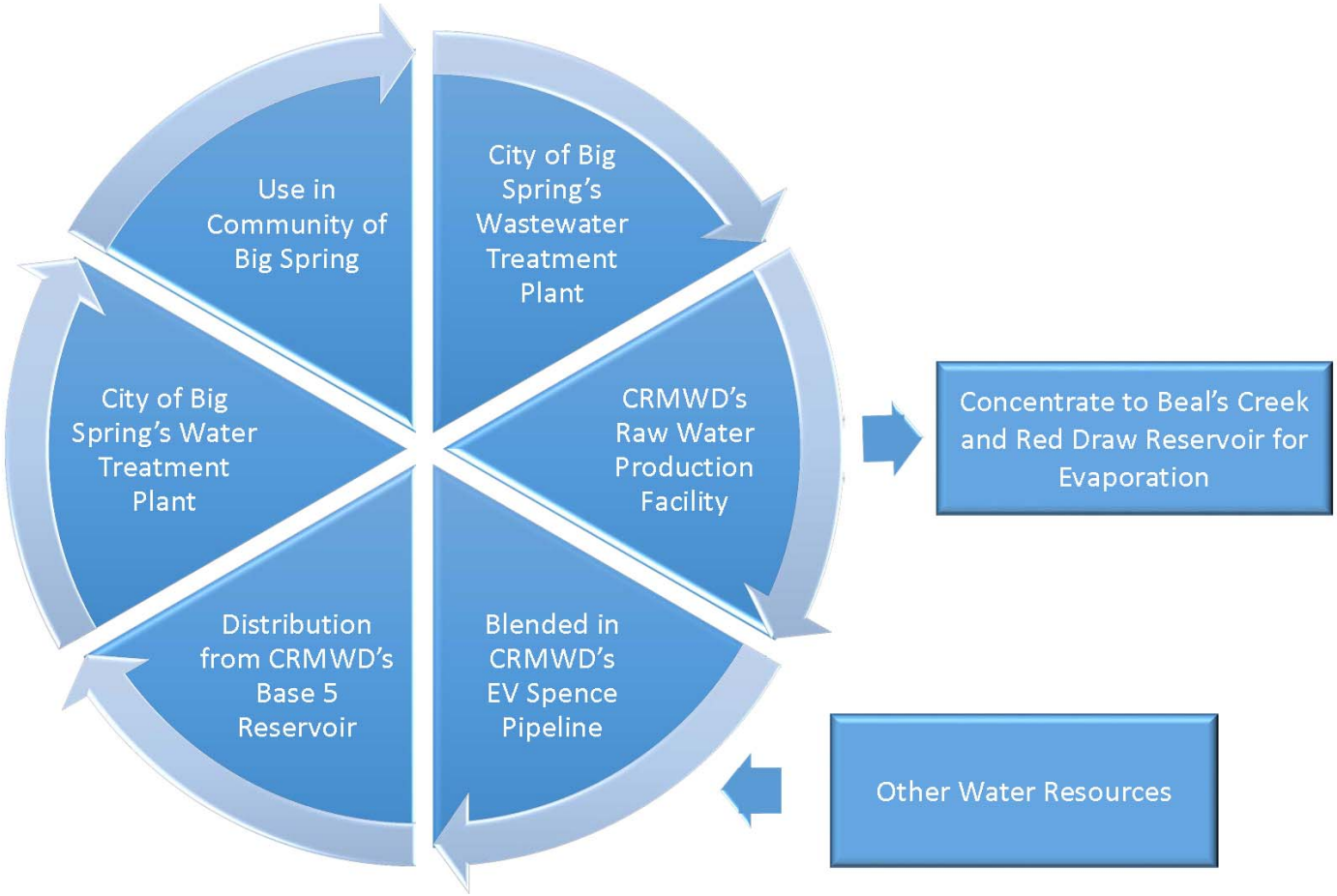


Figure 2.2 Colorado River Municipal Water District and City of Big Spring facilities involved in direct potable reuse.

2.1 Process Flow

Figure 2.3 shows a process flow diagram of the RWPF. The facility has the following major pieces of equipment:

- A source water tank.
- A diversion vault that returns water to the City of Big Spring WWTP if the influent turbidity is above 10 NTU.
- Two MF skids.
- A break tank.
- Low head transfer pumps to the RO skids.
- Two, two-stage RO skids with high-pressure feed pumps.
- AOP: UV disinfection with hydrogen peroxide addition.
- Chemical storage and mixing tanks for chemically enhanced backwash cycles on MF and clean-in-place (CIP) procedures on the RO membranes.

Both backwash water from MF and CIP waste from RO are returned to the WWTP, and RO concentrate is discharged to Beal's Creek. Finished water from the RWPF is blended in the raw water pipeline leaving the E.V. Spence Reservoir until the fraction of DPR water in the raw water reaches a maximum of 50 percent. Concentrate is discharged at the existing WWTP outfall, which flows into Beal's Creek, a naturally saline watercourse diverted to evaporation ponds.

2.2 Microfiltration

The MF system consists of two Pall AP8 racks, each with 78 UNA-620A modules and 8 blank spaces for future expansion. It is designed for a 2.5 mgd feed flow and 2.38 mgd of net filtrate, an average flux of 29.2 gallons/square foot/day at 20 ºC. The two racks are designed for duty operation, with no additional process redundancy. When one unit undergoes a backwash cycle, the other unit can be operated to a maximum instantaneous flux of 38 gallons per square foot per day (gfd), for a maximum rack flow rate of 1,107 gallons per minute (gpm). This rate equates to 1.6 mgd.

Microfilters at the Raw Water Production Facility
Photo Credit: Eva Steinle-Darling

Backwash water from the MF system is returned to the City of Big Spring WWTP.

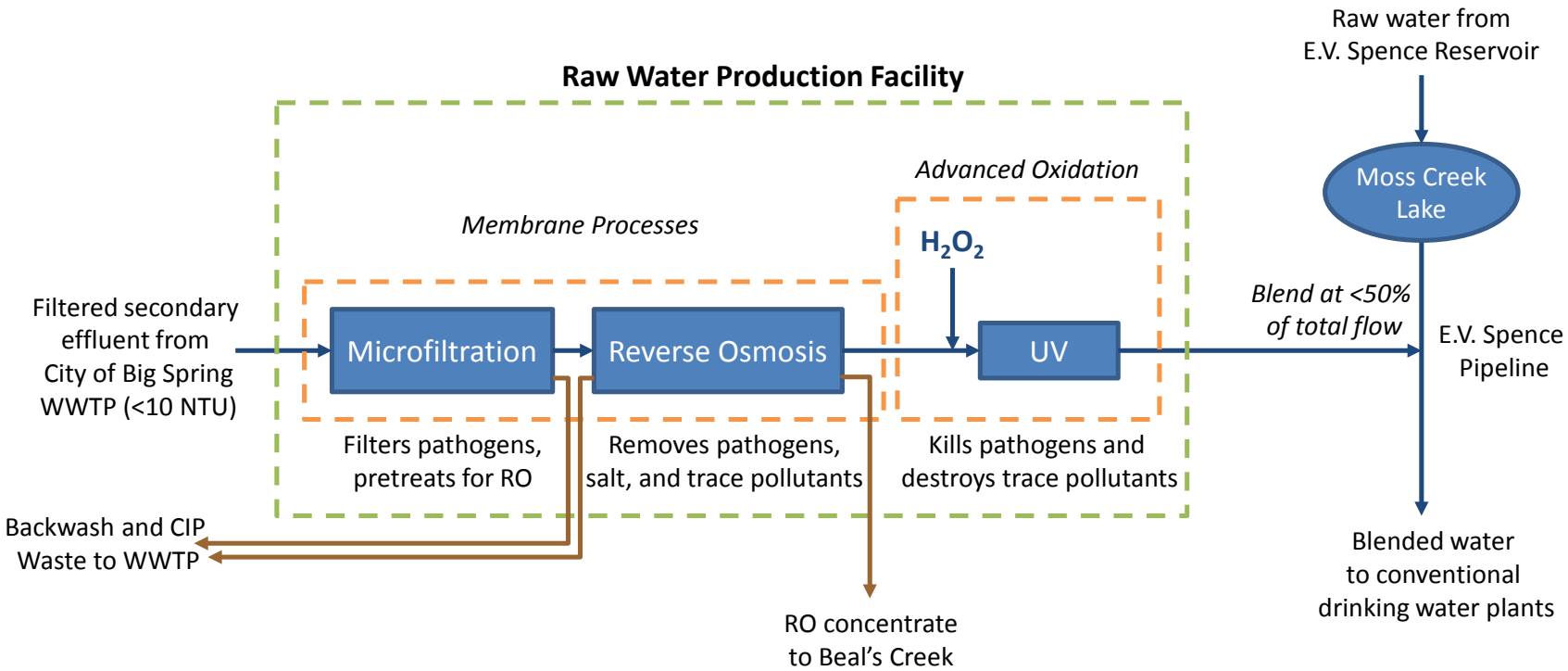


Figure 2.3 Simplified process flow diagram of the raw water production facility.

2.3 Reverse Osmosis

The RO system consists of two skids in a 24:12 array with 6 Toray TML20-400 elements per vessel. It is designed for a feed flow of 2.38 mgd, a flux of 10.5 gfd at 20 ºC, a recovery of 75 percent, and a net RO permeate flow of 1.782 mgd. Both RO skids are designed for continuous duty operation with no redundancy. During periodic cleaning events, RO system production is reduced. Concentrate is discharged to nearby Beal's Creek under an industrial discharge permit.

RO Skids at the Raw Water Production Facility
Photo Credit: Eva Steinle-Darling

2.4 Advanced Oxidation

The AOP system is composed of two Trojan Technologies UVPhox 72AL75 UV reactors in series. Each reactor contains 72 lamps with a single UVFit intensity sensor on each reactor. The two UV reactors are designed for duty operation with no additional redundancy.

Carollo validated this UV for Trojan Technologies according to the National Water Research Institute (NWRI, 2003) for a UV transmittance (UVT) range of 40.3 to 81.0 percent and a flow rate range of 0.73 to 7.39 mgd. Because the high UVT at the RWPF (>98 percent) is outside than the validated range of this UV reactor, the system's dose cannot be calculated by the validation equations and must therefore be estimated.

UV Reactors at the Raw Water Production Facility
Photo Credit: Eva Steinle-Darling

Each reactor receives credit for 2-log virus inactivation at a design dose of 100 milli-Joule per square centimeter (mJ/cm^2), which assumes a maximum 81 percent UVT. As noted, the incoming UVT is significantly higher (>98 percent) than the validated range. As a result, the actual UV dose (delivered dose) in each reactor is much higher than the 100 mJ/cm^2 for which the reactors are validated.

2.5 Direct Potable Reuse Regulatory Summary

The State of Texas regulates water reuse in several ways. These regulations include requirements for direct reuse (non-potable) described in Title 30 of the Texas Administrative Code (TAC), Chapter 210 (Use of Reclaimed Water) and Chapter 321 Subchapter P (Reclaimed Water Production Facilities). Also included are requirements for indirect reuse through the Title 2 of Texas Water Code (TWC) §11.402 governing bed and bank permits and TWC §11.406 governing return flows. For direct reuse, regulations include water quality requirements for Type I and Type II reclaimed water, which are both limited to non-potable uses. The regulations governing indirect reuse in 30 TAC §210.33 do not include water quality requirements.

Faced with an extreme need for additional water supplies in parts of the state, TCEQ has approved DPR projects, such as the RWPF, on a case-by-case basis in accordance with the innovative/alternative treatment clause in 30 TAC §290.42(g). This clause allows "any treatment process that does not have specific design requirements" listed in the chapter to be permitted.

2.5.1 Background on Pathogen Goal Concentrations in Drinking Water

Potable standards for conventional surface water treatment (USEPA, 2006a) and potable reuse standards in Texas and California are based on fundamental water quality end goals to achieve less than a 1 in 10,000 annual risk of infection for enteric virus and protozoa (Regli et al., 1991). Table 2.1 shows the drinking water pathogen goal concentrations that reflect this risk.

These concentrations are so low that direct measurement is impractical if not impossible. Therefore, both conventional surface water treatment regulations and the regulatory structures for potable reuse rely on the "log removal value" or LRV concept, which relies on each treatment process providing a certain level of pathogen inactivation or removal, measured as a certain LRV, and confirmed through periodic or online monitoring.

Table 2.1 Drinking Water Pathogen Goal Concentrations

Pathogen	Drinking Water Goal[1]	Reference
Giardia	$< 6.8 \times 10^{-6}$ cysts/L	Regli et al. (1991)
Cryptosporidium[2]	$< 3.0 \times 10^{-5}$ oocysts/L	Haas et al. (1999)
Enteric virus[3]	$<2.2 \times 10^{-7}$ MPN/L	Regli et al. (1991)

Notes

1. Drinking water goals are identified for national DPR research and as implied by California regulations and cited by Trussell et al. (2013). These are consistent with values used in Texas from personal communications with staff at the Texas Commission on Environmental Quality (TCEQ).
2. The *Cryptosporidium* goal can be inferred from the treatment requirements under LT2 for Bin 3 (USEPA, 2006a), which is the most conservative defined-boundary bin (only a lower boundary is defined for Bin 4). Bin 3 has an upper limit of 3 oocysts/L and requires 5-log treatment. The original quantitative microbial risk assessment defining this limit based on a 1 in 10,000 annual risk of infection was performed by Haas et al. (1999).
3. MPN/L = most probable number per liter. The 10^{-4} risk level concentrations of several enteric viruses are provided by Regli et al. (1991). The most conservative value listed in Table 2 of this reference is for rotavirus (at 2.22×10^{-7} MPN/L).

2.5.2 DPR Approval Process

The RWPF was permitted based on the inclusion of the three barriers now employed at RWPF (MF, RO, and UV/AOP). A log removal analysis revealed that the main pathogens of concern were viruses. Based on a survey of available literature for virus concentrations in secondary effluent, TCEQ required the RWPF's UV/AOP system to achieve a minimum 4-log virus inactivation to supplement the existing 4-log credits given to each of the downstream surface water treatment plants, for a total of 8-log virus removal achieved. For protozoa, the TCEQ assigns 4-log to the MF and 6-log to the two UV reactors in series, for a total of 10-log at the RWPF, plus 3-log at the downstream conventional surface water treatment plants, for a sum total of 13-log for *Cryptosporidium* and *Giardia*.

The TCEQ now bases its permitting requirements for DPR projects on meeting end goal concentrations as defined in Table 2.1 for pathogens (in addition to chemical parameters regulated in drinking water), and determines the treatment requirements for proposed DPR projects based on a case-by-case evaluation of *actual* pathogen concentrations in the treated wastewater *effluent* that is to be used for DPR. Project approval by TCEQ further requires validation data from operation of a pilot and a "full scale verification" step. This second step allows the TCEQ to verify that the full-scale plant is operating correctly before it begins delivering water to potable customers.

A much more detailed discussion of the steps necessary to complete a successful DPR project in Texas is provided in a recently published Texas Water Development Board DPR Resource Document (APAI, 2015).

2.5.3 Alignment with the Approach of other States

A panel of national experts convened by the National Water Research Institute (NWRI) in the context of WateReuse Research Foundation Project (WRRF) No.11-02, *Equivalency of Advanced Treatment Trains for Potable Reuse* (NWRI, 2013) recommends pathogen control that achieves at minimum 12-log virus and 10-log protozoa (*Giardia* and *Cryptosporidium*), and 9-log removal or inactivation of total coliform when treating wastewater to potable standards for DPR. These log removal targets are based on the same end goal concentrations listed in Table 2.1. Note that unlike the requirements put forth by the TCEQ, these log removal requirements are based on inclusion of the full treatment cycle from raw wastewater to finished potable water, and include the possibility of assigning treatment credits to primary, secondary, and tertiary wastewater treatment.

Therefore, while the total log removal requirements put forth by the TCEQ have lower numerical values (the 8-log virus removal required for the Big Spring case, for example), TCEQ's approval process does not allow any treatment credits to be claimed at the wastewater treatment plant. In addition, the TCEQ requires all advanced treatment processes used in potable reuse to adhere to drinking water validation standards in 30 TAC §290(F), in contrast to California regulators, who have developed a separate set of validation requirements for potable reuse projects. These differences make a direct comparison between the regulatory structures difficult. However, the stringency of the criteria developed by the NWRI and those applied by TCEQ appears to be similar.

The NWRI LRV standards are suggested by the TWDB DPR Resource Document as a way to provide additional justification to the public or stakeholders that the project meets recommendations developed by a national team of experts in potable water reuse (APAI, 2015).

2.5.4 Concentrate Management Evaluation

A significant challenge to inland desalination facilities of any type is the question of where to dispose of the RO concentrate, or brine. The same challenge exists for potable reuse projects that employ an RO (or nanofiltration) process step. The most cost-effective option, if available, is surface water discharge, either in conjunction with an existing TPDES discharge permit for the wastewater treatment facility or a separate discharge permit. Other alternatives, in general order of increasing cost, include deep well injection, evaporation in large pond systems, or zero liquid discharge systems that further concentrate the brine and then crystallize it into a solid.

The RWPF benefits from its proximity to Beal's Creek, which is also the receiving stream for the City of Big Spring's effluent under a TPDES permit. The creek has a background salinity of approximately 20,000 mg/L TDS. This means that the CRMWD was able to obtain an industrial discharge permit for the RO concentrate from the RWPF. The highly brackish water in Beal's Creek has historically been diverted into an evaporation reservoir (see Figure 2.2); thus, the CRMWD was able to take advantage of that existing infrastructure for their concentrate disposal with minimal added cost to the project.

Beal's Creek Concentrate Discharge Point
Photo Credit: David Sloan

3 Description of Testing

Testing progressed in general accordance with the Test Protocol (Steinle-Darling et al., 2015).

3.1 Scope and Schedule of Testing

Four major sampling events were conducted on July 7-8, 2014, February 9-10, 2015, June 1-2, 2015, and September 15-16, 2015. With very few exceptions, the samples were collected and analyzed for the proposed constituents during the sample events. Table 3.1 provides a sampling matrix that summarizes the samples collected.

In addition to the four large sampling events, the District conducted monthly sampling for *Cryptosporidium* and *Giardia* in the plant influent and product water. The project team supported this testing, as described in the Test Protocol (Steinle-Darling et al., 2015). Sampling began in November 2013 and continued through May 2016, with seven monthly events missed during that time. The final sample was the 24th sample collected.

Appendix A is the stand-alone Test Protocol for Testing Water Quality in a Municipal Wastewater Effluent Appendix B includes the results from all sampling events conducted for this study. Treating to Drinking Water Standards. In addition, Appendix C includes the summary of compliance testing results from product water sampling conducted by the TCEQ between January 2013 and March 2016. Analytes for the testing included inorganics, metals, and trihalomethanes. Appendix D provides a stand-alone report prepared by Trussell Technologies based on the results of collimated beam ultraviolet advanced oxidation process (UV AOP) testing. This testing was conducted in Trussell's Pasadena, California laboratory. Appendix E contains results from off-site RO challenge and tracer testing.

3.2 Testing Locations

The process flow diagram in Figure 3.1 and the photos in Figure 3.2 show the six test locations. These locations are as follows:

1. RWPF Influent - hose bib in influent sample panel.
2. RO Feed - collected directly after MF skids (2a) at the tap on the MF skid, or after the inter-process storage tank at the influent sample panel (2b).
3. AOP Feed – tap on permeate collector tube.
4. RO Concentrate - tubing on wall mounted rack
5. RWPF Product water - hose bib after AOP.
6. Moss Creek Lake - at pump station (not shown in Figure 3.2).

Table 3.1 Sampling Summary Matrix as Implemented

Parameter	Locations Sampled at Each Sample Event[1]			
	Jul 2014	**Feb 2015**	**Jun 2015**	**Sep 2015**
Trace Chemicals[2]				
Pharmaceuticals	all	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
Hormones	all	1,2,3,6	1,2,3,5,6	none
Perfluorochemicals (PFCs)	all	1,2,3,6	1,2,3,5,6	all
Disinfection Byproducts (DBP)				
Nitrosamines	all	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
Trihalomethanes (THMs)	all	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
Haloacetic Acids (HAA5)	all	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
DBP Formation Potentials (FPs)				
N-Nitrosodimethylamine FP	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
THM FPs	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
HAA5 FPs	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6	1,2,3,5,6
Bioassays				
Yeast Estrogen Screen (YES)[4]	1,2,3,5,6	1,2,3,5,6	none	none
Total Nitrosamines (TONO)	all	1,2,3,5,6	none	1,2,3,5
Chloramines[5]	2,3,4	2,3,4,5	2,3,4,5	2,3,4,5
Excitation Emission Matrix (EEM)	all	all	1,2,3,6	1,2,3,6
PSD Analysis	1,2	1,2	1,2	1,2
Adenosine Triphosphate Testing	none	1,2,3,5	1,2,3,5	1,2,3,5
Collimated Beam	none	3	none	none
Trasar® Testing	See Note 3.			
Microbial Parameters				
Giardia & Cryptosporidium	1,2,3,5,6	1,2,5,6	1,2,5	1,5
MS2 Phage (indigenous)	none	1,2	none	none
Enteric virus	1,3,6	none[6]	none[6]	1,3
E. coli *by SM9223*	all	1,5,6	1,5,6	1,5,6

Notes:

1. Sample locations are numbered as follows: (1) RWPF influent, (2) RO Feed, (3) AOP Feed, (4) RO concentrate, (5) Product Water, and (6) Moss Creek Lake.
2. Appendix A provides the full list of trace chemicals.
3. Trasar® testing was conducted off-site and outside the formal scope of this project in July 2015.
4. YES Assay results were given only as present/absent, with the threshold of detection in the low ng/L range.
5. Chloramines tests were conducted using HACH test kits and included monochloramine, ammonia, and total chlorine. Selected samples were also field-tested for pH.
6. Samples for enteric virus analysis were collected during each of the four major events. However, no results are available for the second and third sampling events due to sampling equipment malfunctions that rendered the samples unusable.
7. Analytical methods for measured parameters available in lab reports in Appendix A.

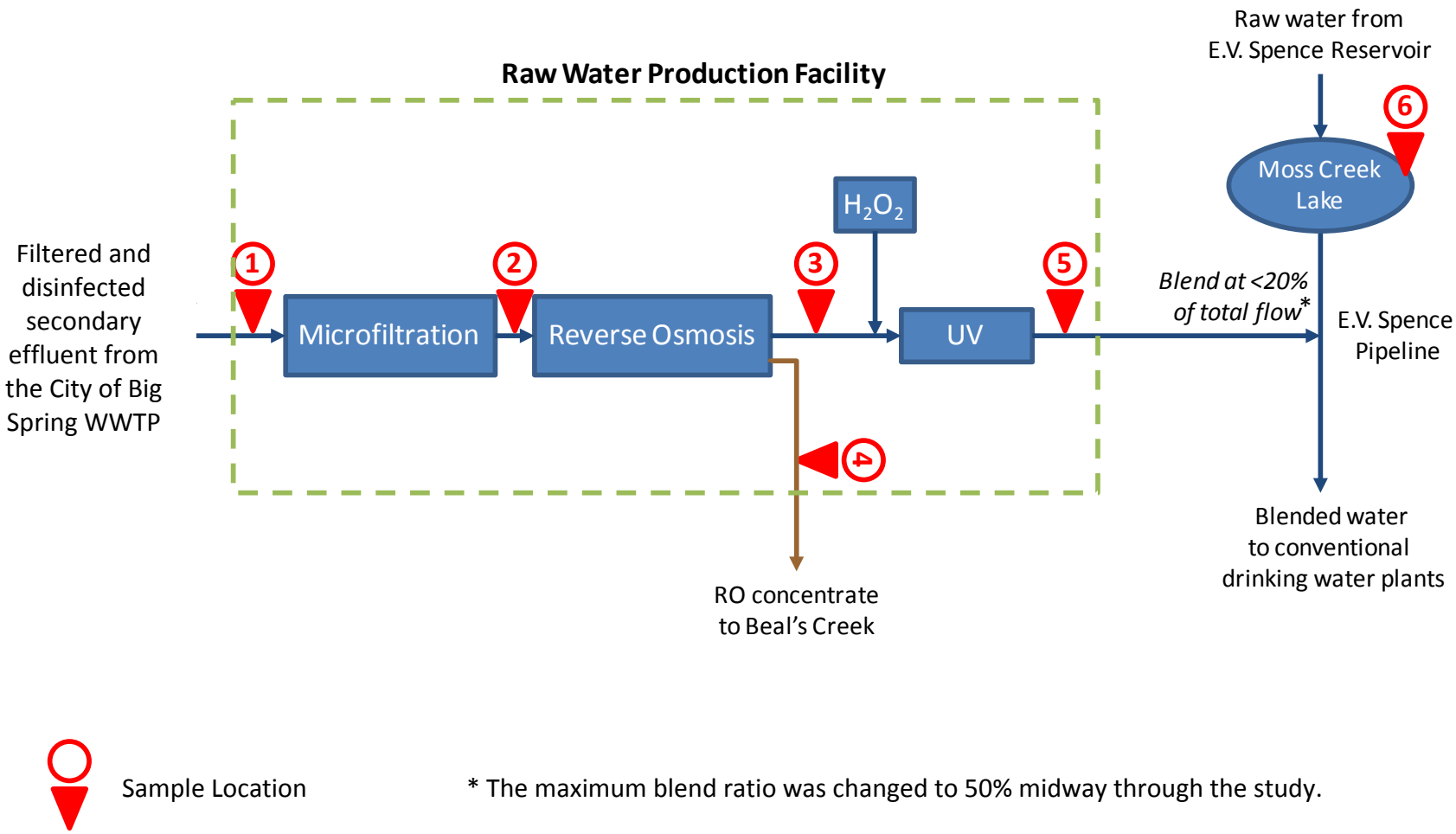


Figure 3.1 Conceptual process flow diagram with study sample locations.

Figure 3.2 Photos with numbered sample locations marked by white arrows.

3.2.1 Raw Surface Water Sample Location

The surface water with which RWPF product water is blended is held in Moss Creek Lake, a small open recreational reservoir upstream of the blending point. All water from the E.V. Spence pipeline enters this reservoir before being pumped to the 15 million-gallon Base 5 Reservoir near Big Spring. RWPF Product Water is blended in the E.V. Spence pipeline between Moss Creek Lake and the Base 5 Reservoir (see Figure 2.2). From there, it can go to up to five different conventional surface water treatment plants operated by District customers, including the City of Big Spring.

For testing, samples were collected from a sample tap in the pump station immediately downstream of Moss Creek Lake. This location was chosen because it provided sufficient head for field-filtered samples.

Moss Creek Lake near Big Spring, TX. Photo Credit: Eva Steinle-Darling

3.3 Deviations from the Test Plan

One significant deviation from the Test Plan was removing the proposed evaluation of a fluorescent tracer method from the TWDB project scope. Instead, testing was conducted at an alternative site (Ventura, California) with funding from a Tailored Collaboration with the WateReuse Research Foundation (Project No. 14-10) and the Water Research Foundation (Project No. 4536) for which the pilot was being operated.

The results from this testing are provided as an in-kind contribution to the TWDB project and are therefore included in this report. Appendix E provides full tabulated results and the associated laboratory results.

In addition, small changes were made to the analyte lists as dictated by laboratory availability and capability. These changes are addressed in the respective sections where results are discussed, but do not materially affect the overall scope of the study.

4 Summary of Testing Results

4.1 Regulated Chemicals

Maximum contaminant levels (MCLs) define the acceptable end concentration for many chemical parameters. However, the study did not focus on these parameters since the RWPF compliance sampling program, conducted periodically by the TCEQ, already collects and analyzes RWPF product water samples for parameters of regulatory importance.

Appendix C provides data collected by the TCEQ or by others on their behalf for samples collected from the RWPF product water. The TCEQ sampling focuses on general water quality parameters as well as on select inorganic constituents (Table C.1), metals (Table C.2), disinfection byproducts, organic constituents, and radionuclides (Table C.3).

In general, no constituents were recorded at concentrations exceeding their respective MCL (or Action Level). In fact, all but two constituents were found at concentrations well below (a factor of 10 or more) the MCL. The only exceptions were nitrate (MCL = 10 mg/L as N, maximum concentration measured = 2.83 mg/L) and total trihalomethanes, or TTHM (MCL = 80 μg/L, maximum concentration measured = 33.1 μg/L; see Table C.3).

Conventional disinfection byproducts (DBPs) were included in the study's scope for several reasons: they were expected to form during chlorination/chloramination processes, the "formation potential" for a range of DBPs can provide insight into general water quality that feeds the downstream water treatment plant, and this project includes DBP and DBP formation potential testing of the existing raw water supply, allowing further comparisons to the product water from the RWPF.

The product water from the RWPF improved the existing raw water quality (through dilution), and the vented pipeline experienced some volatilization when the maximum blend ratio was achieved. As a result, the TTHM concentrations measured in the pipeline after blending were much lower that those found in the product water (see Table C.3) and thus should not cause issues downstream.

4.2 Background on Constituents of Emerging Concern (CECs)

Constituents of emerging concern (CECs), including pharmaceuticals, personal care products, and hormonally active agents, are present in treated wastewater. It is known from recent experience that the processes employed at the RWPF remove most of these constituents to below detectable levels at the nanogram per liter (ng/L)-level, though some trace constituents have been known to pass through RO membranes and were found in the RO permeate.

Trace pollutants at the levels found in the finished water from the RWPF, in the low part per trillion range or below (if even detected), have been demonstrated in the literature to not be a public health concern (National Research Council, 2012). Nonetheless, the public has a negative perception of CECs in potable reuse projects. This perception grew from a landmark study published by the U.S. Geological Survey in 2002 showing that wastewater-derived CECs were prevalent in U.S. surface waters (Kolpin et al., 2002).

Because of this perception, the project team performed a detailed evaluation of CECs at the study sample locations. This evaluation provided conclusions about CEC fate at the RWPF, and it

compared the existing surface water source's relative contributions to total CECs in raw water sent to downstream drinking water treatment plants with RWPF product water.

The National Water Research Institute (NWRI) convened an Expert Independent Advisory Panel for WateReuse Research Foundation (WRRF) project 11-02. This panel issued the "Equivalency of Advanced Treatment Trains for Potable Reuse" report that recommended monitoring a list of CECs in potable reuse projects based on specific criteria. In order of most to least preferred, criteria included the U.S. Environmental Protection Agency (USEPA) MCL, World Health Organization Drinking Water Goal, State MCL, State provisional level (e.g., California Notification Level or "NL"), *de minimus* concentration, *de minimus* dose, medical benchmark, and *de minimis* benchmark from secondary source (NWRI, 2013).

The NWRI panel concluded that individual CEC concentrations below 1 µg/L (1,000 ng/L) in reclaimed water are acceptable for use in DPR applications. The only exceptions are three classes of compounds that require lower concentrations to ensure public safety when using reclaimed water from DPR projects. These are (1) nitrosamines, (2) perfluorochemicals (PFCs), and (3) steroid hormones (NWRI, 2013). The groups are discussed in following sections.

The final list of CECs (and conventional disinfection byproducts) evaluated in samples from the RWPF was selected from the NWRI panel's recommendations and from analyses that the SNWA Laboratory was equipped to perform. The analyte list and results are provided in Appendix A.

4.2.1 Nitrosamines and N-Nitrosodimethylamine (NDMA)

N-nitrosodimethylamine, or NDMA, is a disinfection byproduct that the USEPA has classified as a likely human carcinogen with a lifetime excess cancer risk of 10^{-6} at 0.7 ng/L in drinking water (USEPA, 2014). While neither the USEPA nor any states have instituted regulatory limits for NDMA, California developed a 10 ng/L Notification Level (NL) and a 200 ng/L Response Level, at which the California Department of Drinking Water (DDW) recommends removing the source from service.

NDMA and other nitrosamines are primarily formed through chloramination. This process is used at the RWPF to limit biological fouling on RO membranes and is ubiquitous, though at varying levels, at many facilities. RO membranes remove NDMA poorly because of its small, hydrophilic chemical structure (Steinle-Darling et al., 2007; Plumlee et al., 2008). NDMA also is susceptible to direct photolysis, independent of oxidant addition to create AOP. For reference, a UV dose of 50 mJ/cm^2 is recommended to inactivate 99.999% of poliovirus in RO permeate (NWRI, 2012), whereas the most resistant virus to UV, adenovirus, can be reduced by 6-log at a dose of 235 mJ/cm^2 (Gerba et al., 2002). The RWPF was modeled after the Groundwater Replenishment System (GWRS) at the Orange County Water District, which employs a high UV dose for NDMA reduction.

4.2.2 Perfluorinated Compounds (PFCs)

Perfluorinated compounds (PFCs), also referred to as perfluorinated alkyl substances (PFASs), are used in stain-resistant coatings readily present in our everyday lives (e.g., Gore-Tex, Stainmaster, and Teflon brands). The USEPA (2016) describes PFCs as follows:

"Perfluorinated chemicals are a diverse group of compounds resistant to heat, water, and oil. For decades, they have been used in hundreds of industrial applications and consumer products such as carpeting, apparels, upholstery, food paper wrappings, fire-fighting foams and metal

plating. PFCs have been found at very low levels both in the environment and in the blood samples of the general U.S. population.

These chemicals are persistent, and resist degradation in the environment. They also bioaccumulate, meaning their concentration increases over time in the blood and organs. At high concentrations, certain PFCs have been linked to adverse health effects in laboratory animals that may reflect associations between exposure to these chemicals and some health problems such as low birth weight, delayed puberty onset, elevated cholesterol levels, and reduced immunologic responses to vaccination."

PFCs have been found as far as the Canadian Arctic (Martin et al., 2004) and are found in wastewater, where they are present in secondary effluent (Higgins et al., 2005; Schultz et al., 2006) and tertiary-treated recycled water (Plumlee et al., 2008). Previous studies have shown that nanofiltration (Steinle-Darling et al., 2008), RO (Tang et al., 2005 and 2006), as well as ion exchange and granular activated carbon (Appleman et al., 2014) provide robust removal of these compounds.

Interest in the health impacts of these constituents is increasing. Thus, the scope of this study includes an evaluation of their removal at the RWPF.

In May 2016, the USEPA issued a health advisory (HA) level of 70 parts per trillion (ppt, or ng/L) for two perfluorinated compounds (perfluorooctane-sulfonate [PFOS] and perfluorooctanoic acid [PFOA]) in drinking water. Per the USEPA, their combined concentration should not exceed 70 ng/L. The new level is nearly 10 times more stringent than the sum of the individual HA values for PFOS and PFOA issued by the USEPA in 2009. This level provides a margin of protection for the most vulnerable human populations based on a lifetime of exposure to both chemicals in drinking water. This new HA is used as the benchmark in Table 4.1.

4.2.3 Hormones and other Endocrine Disrupting Compounds

A major public perception challenge comes from an increasing body of literature suggesting that conventionally treated wastewater effluent discharged to rivers and streams can negatively affect aquatic life. These effects are from natural and synthetic hormones and from other endocrine-disrupting compounds (EDCs) in the discharged effluent (Pickering and Sumpter, 2003).

Effective removal of hormones during wastewater treatment has been reported (Andersen, 2003; Baronti, 2000; Joss, 2004). However, because EDCs are biologically active at low concentrations (low nanogram per liter range), the chemicals can still have measurable impacts at very low effluent and downstream environmental concentrations (Pickering and Sumpter, 2003). Furthermore, although other EDCs, such as alkylphenols, are significantly less biologically active on a per mass basis, they are not removed as well during conventional wastewater treatment and might contribute to the total estrogenic effect of treated wastewater discharged to the environment.

This potentially significant issue with effluent discharges is not yet the subject of regulation in the United States, although it is starting to be addressed in Europe. Still, it is less problematic in potable reuse projects for two reasons. One, significant additional treatment is provided in most potable reuse scenarios, which removes hormones to below detectable (and below environmentally relevant) concentrations. Two, while hormones in general are biologically active at low concentrations, aquatic species, which "breathe" them in through their water

environment, are considerably more sensitive to the presence of EDCs at a given concentration than are their terrestrial counterparts, including humans.

Regardless, the NWRI panel concluded that total estrogenic activity in drinking water should be limited to the "low nanogram per liter" level (as estradiol). Thus, samples from RWPF and Moss Creek Lake were tested for a number of hormones. These samples also were tested with the Yeast Estrogen Screen (YES) Assay, which assesses a water sample's total estrogenic effect.

4.3 Testing Results for Constituents of Emerging Concern (CECs)

Samples from all collection locations were analyzed for a large suite of CECs, including pharmaceuticals, personal care products, nitrosamines, PFCs, and hormones, as well as for conventional disinfection byproducts and their formation potentials. Tables A.1 through A.8 provide the full set of results from this testing.

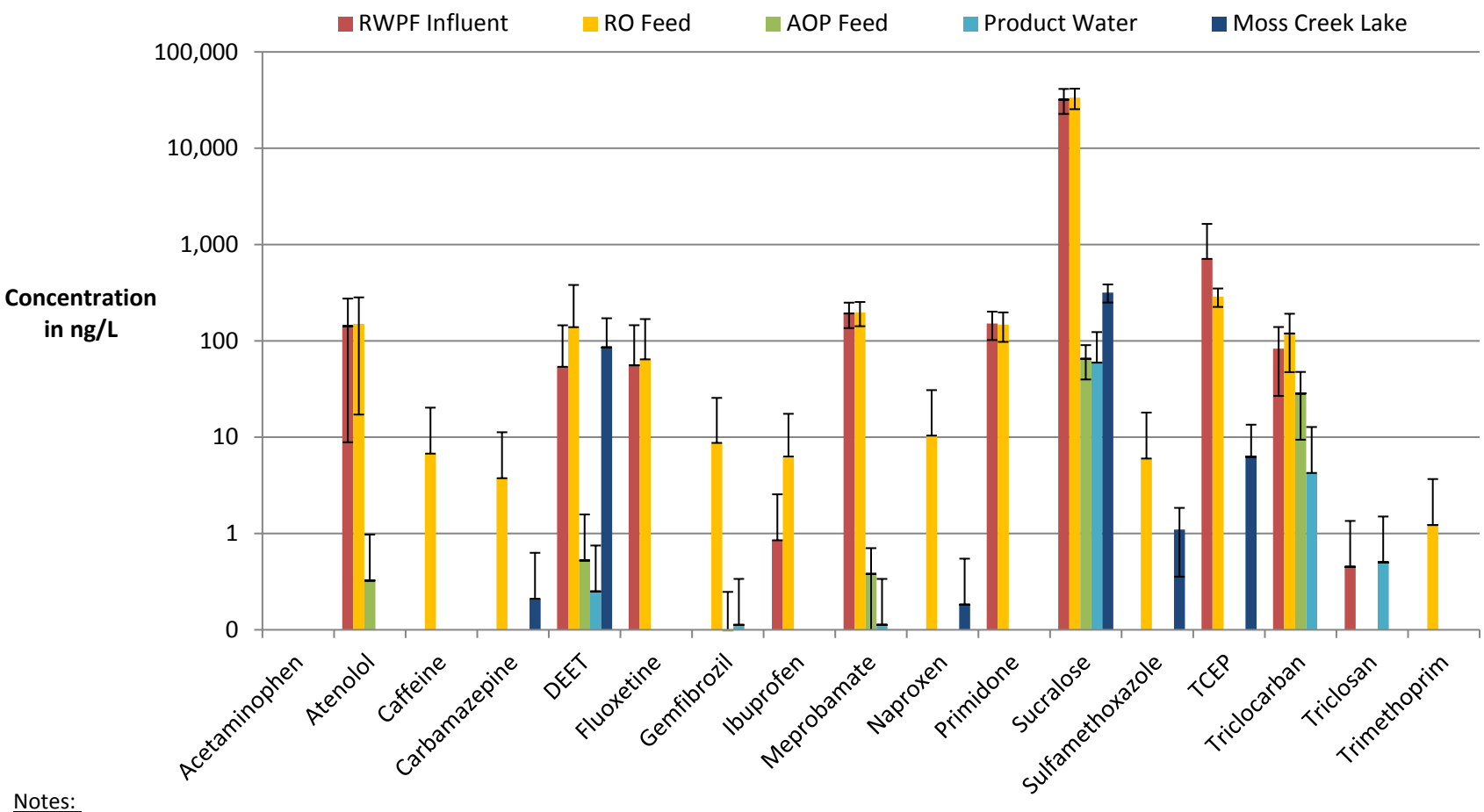
Figures 4.1 through 4.5 show the fate of various chemicals, grouped by type, across the treatment train. The figures show the average of the results collected during the four major sample events, with the error bars indicating one standard deviation. Note that some plots have a logarithmic ordinate axis to display every result at a meaningful scale. For consistency across datasets, non-detects are counted as "zero concentration".

General observations of the results are as follows:

1. Concentrations of chemicals were generally low, in the nanogram per liter (ng/L) range, except for conventional disinfection byproducts and the artificial sweetener sucralose.
2. In most cases, the influent concentrations (red bars) and the RO feed (yellow bars) were not much different. This was expected, since the microfilters remove only particulates and no dissolved materials.
3. RO membranes remove most of the CECs. Where detected, concentrations were significantly lower in the AOP feed (green bars) than the RO feed.
4. Generally, the AOP process did not significantly remove CECs. Where detected in the product water (turquoise bars), concentrations were not significantly different than those in the AOP feed.
5. With no exceptions of significance, the concentrations of the measured constituents were lower in the product water than in Moss Creek Lake (dark blue). This was determined by comparing the concentrations in both sources to represent the surface water blended with the product water before conveyance to downstream conventional water treatment plants.

For additional reference, Table 4.1 lists a number of trace constituents that DPR treatment processes are to be evaluated from, as determined by the NWRI panel (NWRI, 2013). The table lists the health-based reference limit for each compound and the ***highest*** concentrations found in the RWPF plant influent and the RWPF product water. As shown in the table, in no case did concentrations in the product water exceed any health-based thresholds. In fact, with only two exceptions (the conventional disinfection byproduct groups, HAA5 and TTHM), the concentrations in the RWPF *influent* did not exceed health-based thresholds.

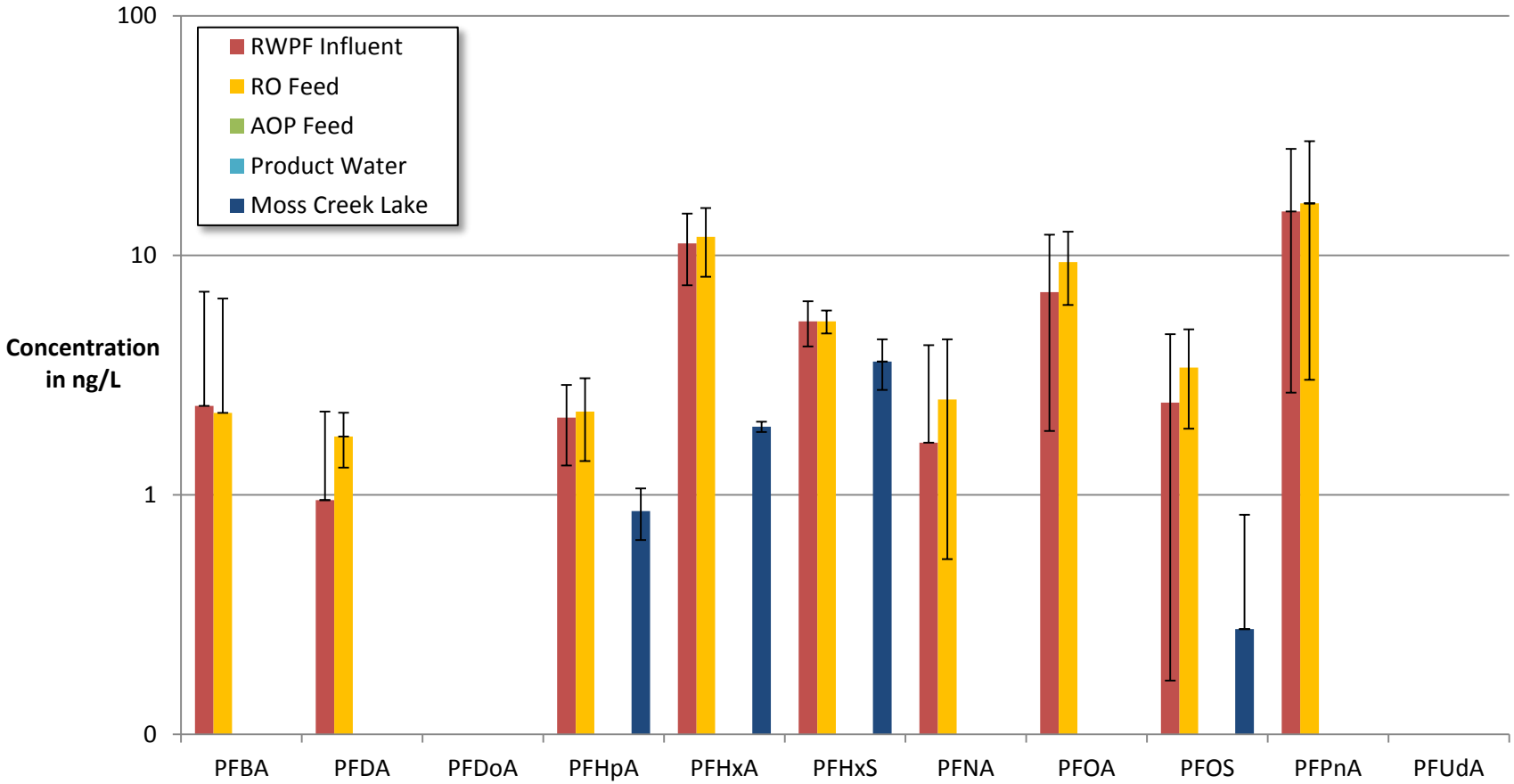
Because of the excellent RWPF treatment processes, the formed DBPs are reduced to below regulatory thresholds. However, this outcome highlights that, ***similar to existing surface water treatment plants, meeting the need for disinfection while limiting the level of disinfection byproduct formation might be the biggest treatment challenge DPR projects will face.***



Notes:

1) This graph compiles results from four sample events, with samples collected in July 2014, February 2015, June 2015, and September 2015.
2) Colored bars denote average concentrations, and the error bars indicate one standard deviation. Where only an upper error bar is shown, the lower error bar is larger than the average value and can therefore not be plotted on a logarighmic axis.
3) Non-detects were handled as a zero concentration due to significant inter-event variability in reporting limits that would have skewed the results if a reporting limit-based value for non-detects had been used.
4) Abbreviations: DEET = N,N-Diethyl-meta-toluamide, TCEP = Tris(2-chloroethyl) phosphate.

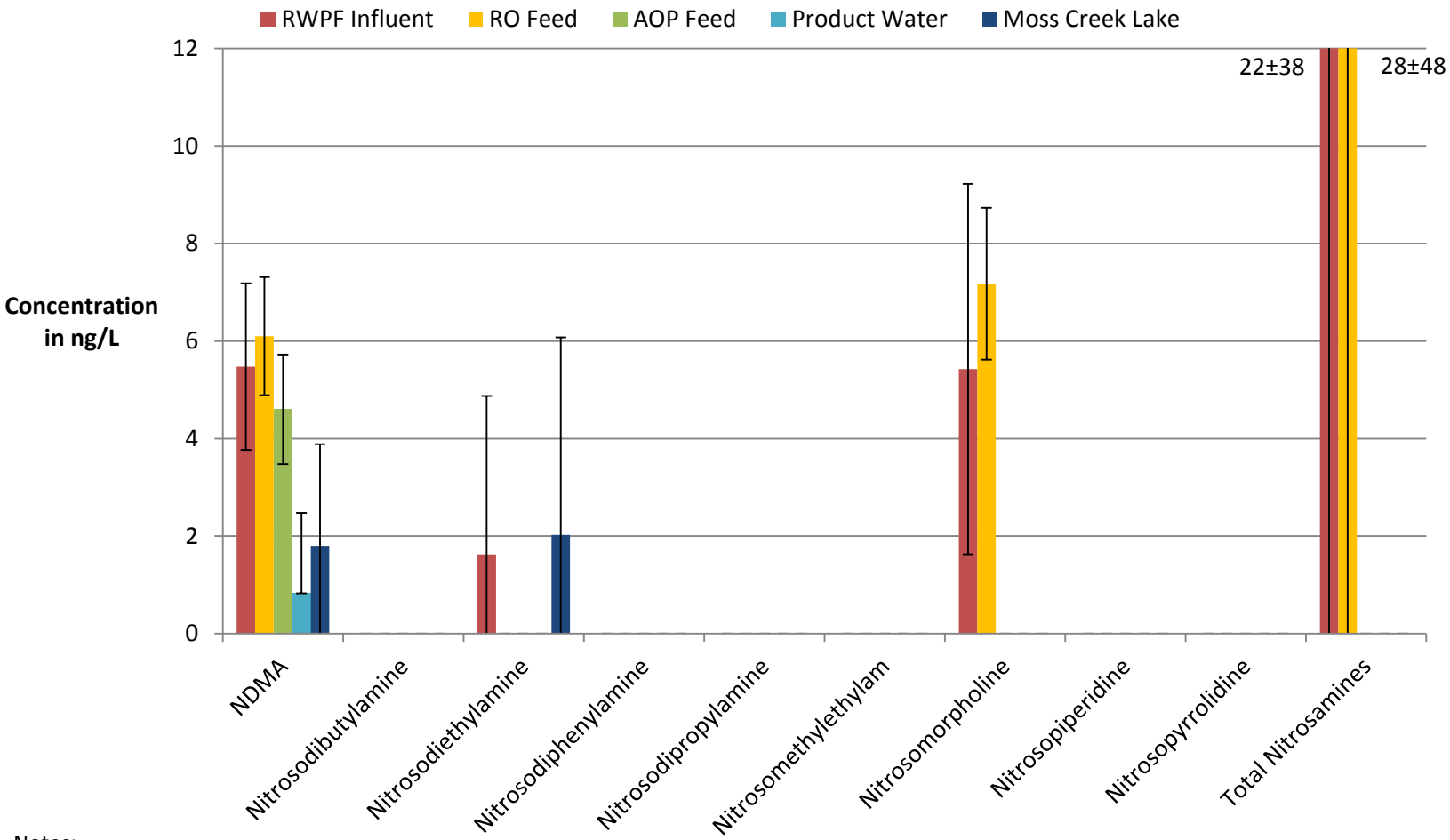
Figure 4.1 Pharmaceuticals and personal care products through the treatment train.



Notes:

1) This graph shows a compilation of results from four sample events, with samples collected in July 2014, February 2015, June 2015, and September 2015.
2) Colored bars denote average concentrations, and the error bars indicate one standard deviation.
3) Non-detects were handled as a zero concentration for consistency with other CECs data graphing.
4) Abbreviations: PFBA = perfluorobutanoic acid, PFDA = perfluorodecanoic acid, PFDoA = perfluorododecanoic acid, PFHpA = perfluoroheptanoic acid PFHxA = perfluorohexanoic acid, PFHxS = perfulorohexanyl sulfonate, PFNA = perfluorononanonoic acid, PFOA = perfluorooctanoic acid, PFPnA = perfluoropentanoic acid, PFUdA = perfluoroundecanoic acid.

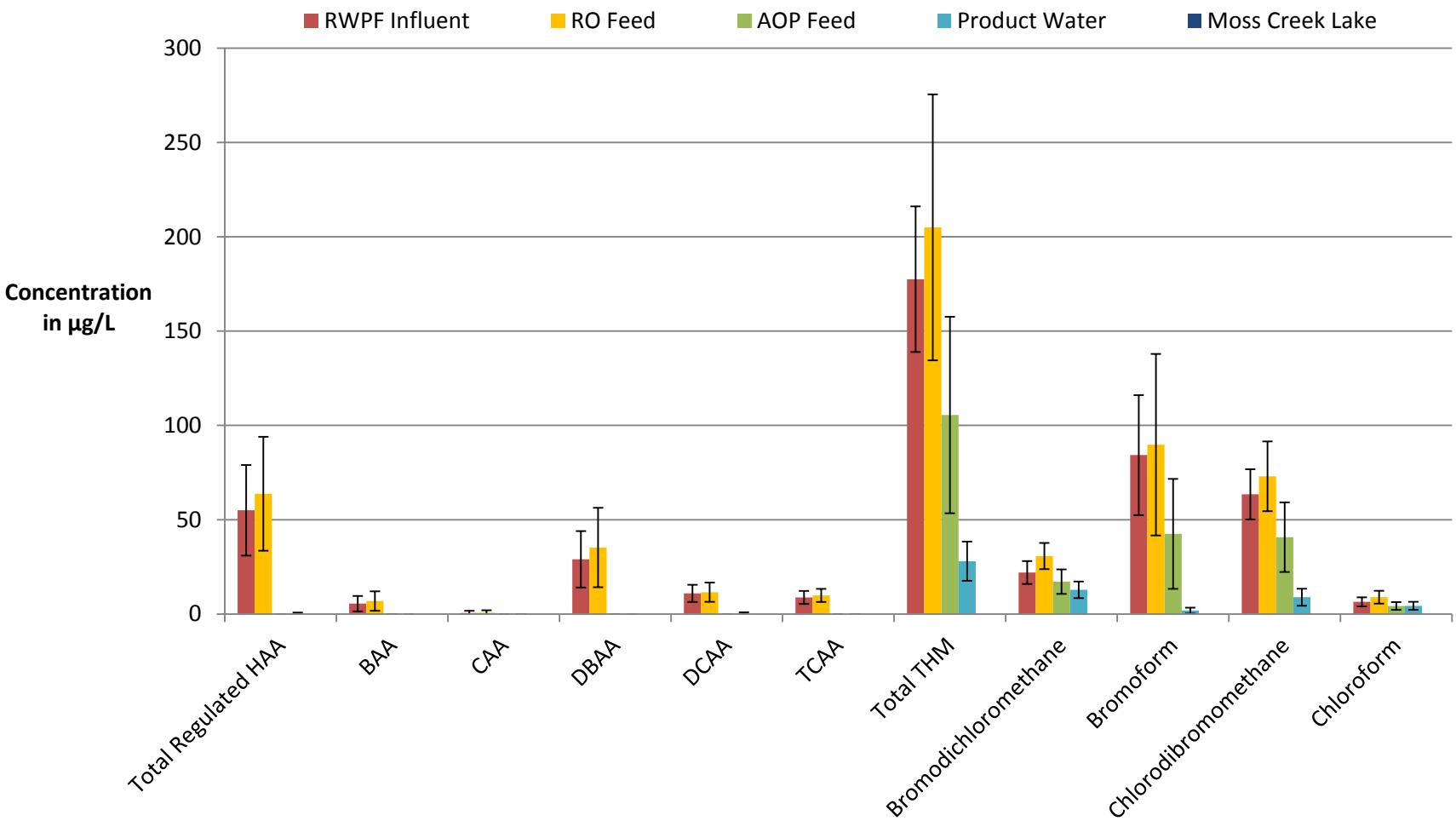
Figure 4.2 Perfluorinated compounds through the treatment train.



Notes:

1) This graph compiles results from four sample events, with samples collected in July 2014, February 2015, June 2015, and September 2015.
2) Colored bars denote average concentrations, and the error bars indicate one standard deviation.
3) Non-detects were handled as a zero concentration for consistency with other CECs data graphing.
4) No analysis for total nitrosamines was completed in June 2015.
5) Abbreviation: NDMA = *N*-nitrosodimethylamine

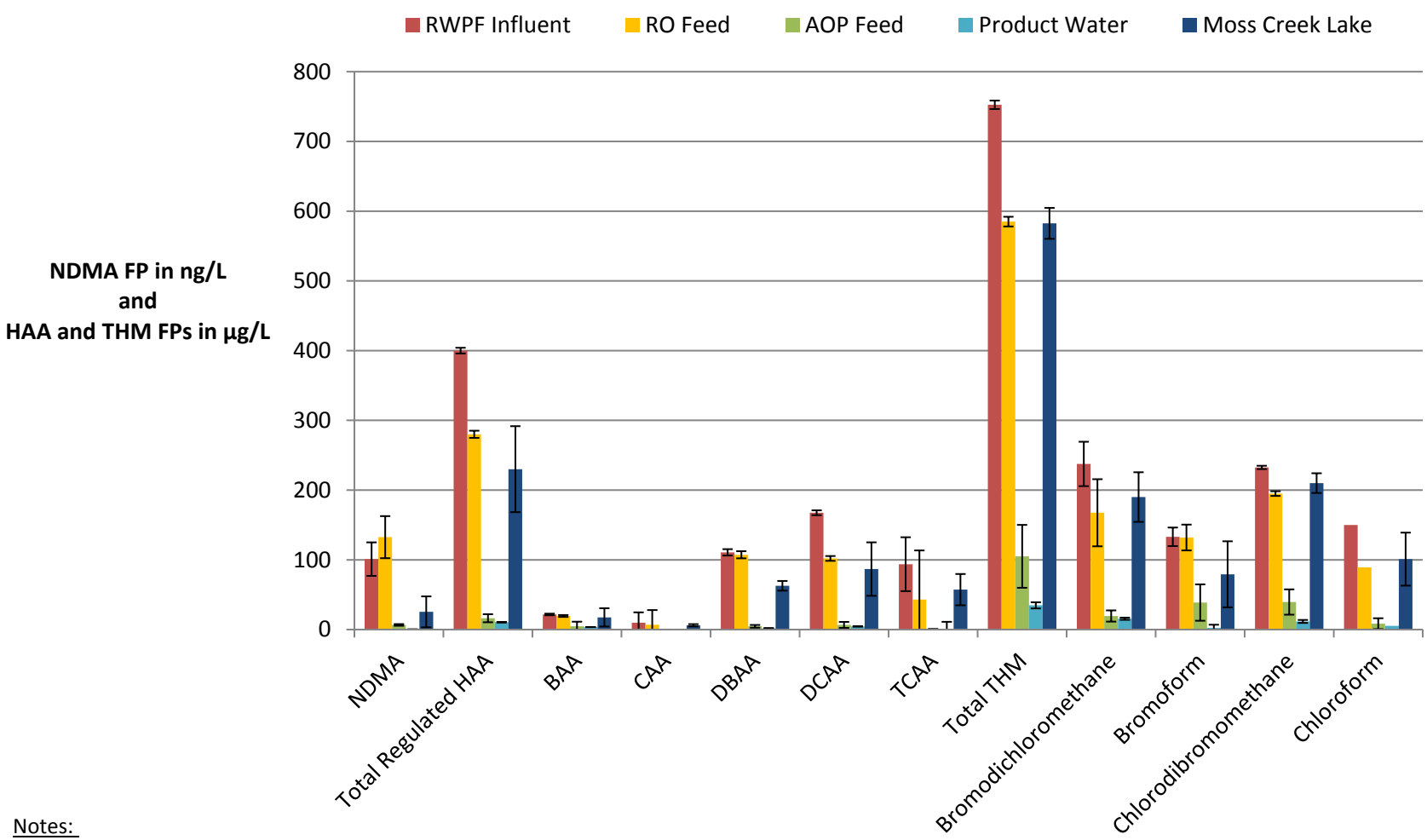
Figure 4.3 Nitrosamines through the treatment train.



Notes:

1) This graph compilesresults from four sample events, with samples collected in July 2014, February 2015, June 2015, and September 2015.
2) Colored bars denote average concentrations, and the error bars indicate one standard deviation.
3) Non-detects were handled as a zero concentration for consistency with other CECs data graphing.
4) Abbreviations: HAA = haloacetic acid, BAA = bromoacetic acid, CAA = chloroacetic acid, DBAA = dibromoacetic acid, DCAA = dichloroacetic acid, TCAA = trichloroacetic acid, THM = trihalomathane.

Figure 4.4 Conventional disinfection byproducts through the treatment train.



Notes:

1) This graph compiles results from four sample events, with samples collected in July 2014, February 2015, June 2015, and September 2015.
2) Formation potentials shown are for uniform formation condition (UFC) test conducted by SNWA for samples collected from the locations indicated.
3) Colored bars denote average concentrations, and the error bars indicate one standard deviation.
4) Non-detects were handled as a zero concentration for consistency with other CECs data graphing.
5) Abbreviations: NDMA = N-nitrododimethylamine, HAA = haloacetic acid, BAA = bromoacetic acid, CAA = chloroacetic acid, DBAA = dibromoacetic acid, DCAA = dichloroacetic acid, TCAA = trichloroacetic acid, THM = trihalomathane, FP = formation potential.

Figure 4.5 Disinfection byproduct formation potentials through the treatment train.

Table 4.1 Chemical Constituents: Health-Based Criteria and Measured Concentrations

Chemical Classification	Chemical[1]	Criterion[2]	Highest Concentration in RWPF Influent	Highest Concentration in RWPF Product Water
Disinfection byproducts (DBPs)	HAA5	60 µg/L (MCL)[3]	**75 µg/L**	1 µg/L
	NDMA	10 ng/L	7.6 ng/L	3.3 ng/L
	THMs	80 µg/L (MCL)[3]	**230 µg/L**	37 µg/L
Unregulated chemicals of interest	Carbamazepine	10 µg/L	<0.01 µg/L	<0.0005 µg/L
	Estrone	320 ng/L	<0.2 ng/L	<0.2 ng/L
	Meprobamate	200 µg/L	0.23 µg/L	0.00045 µg/L
	Atenolol	4 µg/L	0.33 µg/L	<0.001 µg/L
	Primidone	10 µg/L	0.19 µg/L	<0.0005 µg/L
	PFOA	70 ng/L[4]	12 ng/L	< 5 ng/L
	PFOS	70 ng/L[4]	5.4 ng/L	< 1 ng/L
	1,4-dioxane	1 µg/L	0.36 µg/L[5]	<0.07 µg/L[5]
Other chemicals of interest	DEET	200 µg/L	0.19 µg/L	0.15 µg/L
	Triclosan	2.1 mg/L	0.0018 µg/L	< 0.01 µg/L
	Sucralose[6]	150 mg/L	0.041 mg/L	0.000150 mg/L
	TCEP	5 µg/L	2.1 µg/L	< 0.01 µg/L

[1]-The list of chemicals was taken from NWRI (2013). This study did not test for bromate, chlorate, or perchlorate, so these were omitted from the table. Sampling conducted by the TCEQ (Appendix C) indicates an absence of bromate in the product water.

[2]-Health-based criteria for the evaluation of DPR treatment as determined by NWRI (2013).

[3]-MCL = maximum contaminant level. These criteria correspond to regulated limits in drinking water.

[4]-Values for PFOS and PFOA are based on a recently published EPA Health Advisory level of 70 ng/L, which supersedes the values published by the NRWI Panel. The 70 ng/L applies to both compounds individually and together.

[5]-Analysis for 1,4-dioxane was added at the end of the test schedule due to an original omission from the analyte list. Since it was detected in the influent in April 2016, a full set of sample analyses was conducted across the treatment train in May 2016.

[5]-Sucralose is a food additive and as such, the criterion listed above corresponds to the approximate concentration in a can of diet soda.

4.4 Pathogens

Pathogenic microorganisms should be a particular focus for any DPR project because of their acute human health effects. Small levels of pathogens in a drinking water source can cause immediate gastrointestinal illness and large-scale epidemics. Viruses are of particular concern because they have a low infectious dose, are small in size, and are resistant to certain types of disinfection.

This is in direct contrast to other contaminants such as salts, which can dramatically affect agriculture long-term, and industrial chemicals such as 1,4-dioxane, which can affect human health long-term. Thus, in DPR applications, the primary public health concern should be to protect against pathogens, and emphasis and resources should be on pathogen sampling (National Research Council, 2012).

4.4.1 Virus Testing Results

Samples were collected at various points in the treatment process and analyzed for enteric virus (norovirus and enterovirus) using USEPA method 1615. Quantitative real-time polymerase-chain reaction (qPCR) and culture methods, where possible, were used. ***None of the quantification methods detected virus in any sample collected from the many sample locations and sampling events*** (see Table A.9). The significance of the results, therefore, lies in the detection levels achieved.

Field-Filtered Virus Sample Collection at Moss Creek Lake
Photo Credit: Eva Steinle-Darling

Enteric virus samples were field-filtered, meaning detection limits were determined by the total volume that could pass through the field filtration apparatus before other constituents in the water clogged the filter. With sample volumes of over 2,000 L for RO permeate samples (AOP Feed), detection limits of less than 0.00005 organisms per liter (MPN/L) were achieved. Then, the permeate samples were divided into three aliquots for culture and two types of qPCR analyses, resulting in final reporting limits of $<2x10^{-3}$ MPN/L for the culture results.

With a minimum 4-log inactivation provided by the downstream UV reactors per the RWPF's permit, the RO permeate samples represent as close as is practically achievable to direct evidence of attaining the 2.2×10^{-7} MPN/L virus concentration goal for finished drinking water.

4.4.2 Protozoa: Giardia and Cryptosporidium

Tables A.11 and A.12 summarize the results for *Giardia* and *Cryptosporidium*, which were collected and analyzed according to EPA method 1623. These protozoa were detected only in the RWPF influent; no protozoa were detected in samples past the first treatment step (microfilters) at the RWPF. Samples from Moss Creek Lake also were analyzed for protozoa in July 2014 and February 2015. Protozoa were not detected in those samples either.

In addition to the samples collected at the treatment plant during the major sampling events, CRMWD staff, under the project scope, conducted sampling of the plant influent and product water for analysis by USEPA 1623 for 24 monthly events. ***Neither organism was detected in the product water.***

Incoming pathogen loading is the focus of Texas Commission on Environmental Quality's (TCEQ's) permitting process for DPR systems. Surface waters used as a source of drinking water are classified into bins under the Federal Long Term 2 Enhanced Surface Water Treatment Rule (LT2). Table 4.2 shows the bin classification scheme and the associated level of treatment under LT2.

Table 4.2 Bin Classifications as a Function of *Cryptosporidium* Concentrations[1]

Bin	Mean *Cryptosporidium* Concentration in 24 Monthly Source Water Samples	Additional (and Total) *Cryptosporidium* Treatment Requirement at Filtration Plants
1	<0.075 oocysts/L	None (3-log total)
2	from 0.075 to < 1.0 oocysts/L	1-log (4-log total)
3	from 1.0 to < 3.0 oocysts/L	2-log (5-log total)
4	≥ 3 oocysts/L	2.5-log (5.5-log total)

[1]-Per the Long Term 2 Enhanced Surface Water Treatment Rule or LT2 (USEPA, 2006a), for conventional filtered treatment

4.4.3 Evaluation of Results

Figure 4.6 shows results from monthly plant influent sampling. Based on the results of the influent water testing conducted at the RWPF, which had a maximum arithmetic mean *Cryptosporidium* concentration of 12.6 oocysts/L for any twelve consecutive months in the monitoring period, the filtered effluent from the City of Big Spring's WWTP would be classified as a Bin 4 source water. This is the most impaired classification, requiring a total 5.5-log inactivation of *Cryptosporidium*, under LT2.

Interestingly, the mean *Cryptosporidium* concentration recorded in the first 14 months of sampling was 0.37 oocysts/L, which would have resulted in a Bin 2 classification. During this time, *Cryptosporidium* was detected in less than one in three samples. However, starting with the 15th month of sampling in August 2015, *Cryptosporidium* was detected in 100 percent of the samples collected through April 2016, with a mean of 17 oocysts/L and a maximum concentration recorded in November 2015, of 65 oocysts/L. Discussions with plant operators at RWPF, who are in regular contact with the City of Big Spring WWTP operators, did not offer any reasonable explanation of this sudden change in *Cryptosporidium* concentrations.

A different trend is evident in the results for *Giardia*, which sporadically showed significantly elevated concentrations (a maximum of 325 cysts/L was recorded in March 2015). Other than those samples, however, detections were more evenly distributed, with a mean of 18 cysts/L.

4.4.4 Comparison to Goal Concentrations

Looking beyond the requirements codified in LT2, comparing the maximum measured concentrations of protozoa (325 cysts/L Giardia and 65 oocysts/L Cryptosporidium) to the goal concentrations listed in Table 2.1 results in treatment targets for a potable reuse system of 7.6-log *Giardia* and 6.3-log *Cryptosporidium*.

A comparison to the treatment provided by the RWPF, of 13-log *Giardia* and *Cryptosporidium* (see Section 2.5) determines that the facility provides more than adequate treatment to address these incoming protozoa concentrations, even at the highest level measured over 24-monthly samples.

For virus, the RWPF is validated as providing a minimum of 4-log (2 reactors with 2-log each) inactivation. Per the Ultraviolet Disinfection Guidance Manual (UVDGM; USEPA, 2006b), the dose needed to achieve this level of inactivation is very low (22 mJ/cm^2), whereas the installed UV system is providing a dose that is likely more than 20 times greater than this value (as described in Section 4.6.3).

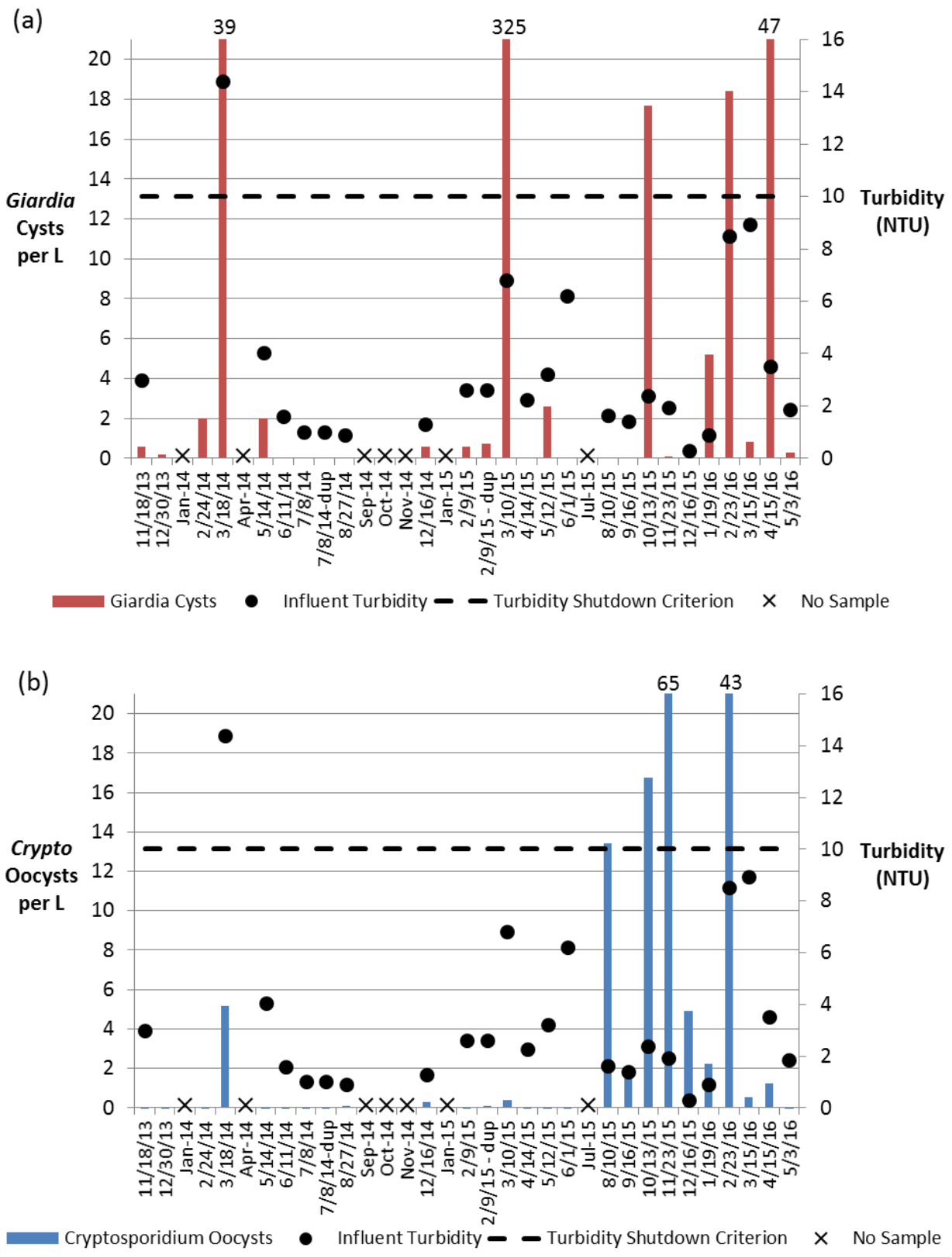


Figure 4.6 Results of monthly (a) *Giardia* and (b) *Cryptosporidium* raw water production facility influent samples.

Thus, one can at the very least rely on the maximum value provided in UVDGM per each of two reactors, 3-log, as a very conservative treatment estimate for RWPF alone. The value per reactor can be added to the 4-log treatment applied at downstream water treatment plants for 10-log of *validated* treatment provided. As discussed in Section 4.6.3, the actual UV dose achieved at the RWPF is well beyond the range defined in the UVGDM, even for virus. Thus, the inactivation actually achieved is still much higher.

Add to this fact that no detections of enteric virus were recorded in any sample from the plant, and the fact that the two RO permeate samples, when followed by 4-log virus inactivation in the downstream UV reactors at RWPF (see Section 4.4.2), were shown to meet drinking water standards even before treatment at the downstream conventional water treatment plants.

Thus, the water produced by the RWPF more than meets the necessary standards for microbial water quality.

4.4.5 Discussion of Influent Variability

Having successfully addressed and dispelled any concerns related to potential health risks posed by the variable and intermittently high influent concentrations of protozoa, the next step is to explain the level of variability encountered.

Except for samples collected in March 2014 when the RWPF operated intermittently because of problems with the tertiary filters at the City of Big Spring WWTP, treatment upsets did not correlate with elevated concentrations of either protozoan. With the same exception, elevated concentrations of protozoa do not correlate with each other or with elevated turbidity levels in the RWPF plant influent.

In fact, operators at the RWPF reported a Big Spring WWTP upset during the March 2014 sample event, corroborated by an elevated incoming turbidity (18.5 NTU). However, as shown in Figure 4.6, this was the first sample in which both *Giardia* and *Cryptosporidium* were at their lowest in three months. *Cryptosporidium* was at its lowest in eight months.

If higher influent concentrations cannot be traced to treatment problems at the wastewater treatment plant, one must look for explanations upstream, such as within the community that sources the wastewater, which was outside the scope of this study. Thus, the origin of the higher influent concentrations remains unknown.

What is certain, however, is that the level of treatment the RWPF provided in conjunction with the downstream WTP should be more than sufficient to dispel any concerns about the quality of the water produced. In fact, interpreting the influent protozoa dataset as representative of both baseline and outbreak conditions can lead one to conclude that the RWPF provides treatment well in excess of the level required even during outbreak conditions.

4.5 Water Quality Indicators

In addition to the direct measurement of chemicals and microbial species of health concern, the Test Plan also included a number of indicator and surrogate parameters that could be monitored more frequently, easily, and/or cost effectively in a future ongoing monitoring plan than previously discussed parameters. Indicator organisms and chemicals are generally harmless constituents whose presence is correlated with the presence of organisms and chemicals of health concern.

4.5.1 E. coli *as an Indicator for Enteric Bacteria*

As summarized by Trussell et al. (2013), "in general, bacteria are considered less resistant pathogens compared to the viruses and protozoa [therefore] treatment that inactivates the more resistant viral and protozoan pathogens is assumed to also inactivate bacteria." Nonetheless, because it is frequently used as an indicator for (bacterial) pathogens, *E. coli* were included as an indicator for enteric bacteria, such as *Salmonella* spp.

Table B.13 summarizes bacteria results. As shown in the table, *E. coli* were detected only in the surface water (Moss Creek Lake) and the RWPF influent. *E. coli* were detected in fewer than 50 percent the RWPF influent samples. However, no samples past the first treatment step (MF) were positive for *E. coli*.

4.5.2 MS2 Bacteriophage as an Indicator for Viruses

The MS2 bacteriophage is a virus that infects *E. coli* and other members of the *Enterobacteriaceae* family of Gram negative bacteria (van Duin et al., 2006). The MS2 viral particle is about 27 nm in diameter (Strauss et al., 1963) and has an isoelectric point of 3.9 (Dowd et al., 1998). This means that, like many viruses, it carries a negative surface charge at a neutral pH. Its repulsion by a negatively charged RO membrane surface would therefore be expected to be similar to that of other viruses.

MS2 is commonly used as an indicator species for human pathogens for several reasons: it is commonly found in wastewater effluent; it is easy to measure and to seed; its presence in water correlates with the presence of enteric viruses (Ventkatesan et al., 2008) and its susceptibility to inactivation through UV and chemical disinfection is known. The most critical characteristic of MS2 for use as an indicator organism and treatment efficacy surrogate is that it is not a human pathogen. Therefore, MS2 does not represent a human health threat (Havelaar et al., 1990; Schijven et al., 1999).

During the February sample event, samples from the RWPF influent and the RO feed (i.e., before and after MF) were analyzed for indigenous MS2 (see Table A.10). As shown in Figure 4.7, no significant removal was observed between the plant influent and RO feed, with results ranging from 6 to 12 organisms (PFU) per 100 mL, which represents very low influent concentrations. Other work conducted at the Orange County Water District (OCWD) showed significant (approximately 1-log) removal of MS2 and somatic phage during microfiltration when feed concentrations were higher (Leddy, 2013). Thus, the results obtained for this study might reflect the effectiveness of the upstream disinfection from the chloramines feed more than the inability of the MF membranes to retain viruses.

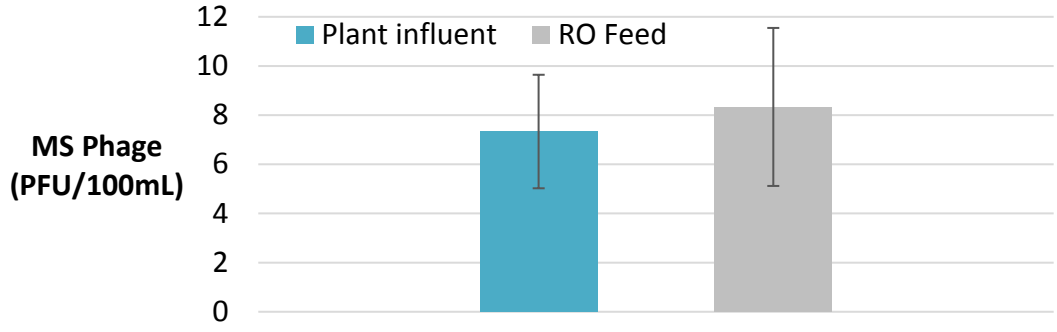


Figure 4.7 Indigenous MS2 phage before and after microfiltration at the raw water production facility.

4.5.3 Fluorescence Excitation-Emission Matrices (EEMs)

Fluorescence spectroscopy can generate fluorescence excitation-emission matrices (EEMs), which are a tool for evaluating differences in organic matter between water sources as well as changes resulting from treatment. These EEM graphs are produced by plotting the changes in fluorescence intensity generated as an individual water sample is excited through a spectrum of light wavelengths (240-470 nm) against the corresponding fluorescent emissions over a similar wavelength range (280-580 nm) (Chen et al., 2003).

Some types of natural organic matter (NOM) exhibit fluorescent properties when exposed to ultraviolet and visible light (McKnight et al., 2001; Hua et al., 2010). Fluorescing NOM emits light when electrons that have been promoted to an excited state after absorbing UV light fall back to their ground state. The portions of NOM molecules that both absorb and emit light vary based on the chemical structure; thus, three dimensional EEM spectroscopy is an excellent means for characterizing the type and source of NOM present in a water sample (McKnight et al., 2001).

Several methods have been developed to mine EEM data and characterize the NOM content of a sample. Peak picking within the fluorescence excitation-emission matrix, as well as fluorescence regional integration, can be used to operationally define fluorescence spectra regions of various organic matter types (Chen et al., 2003; Johnstone et al., 2009). Five regions were originally described by Chen et al. (2003); this was later reduced to three regions (Table 4.3; Figure 4.8), roughly correlated to microbial byproducts, humic acids, and fulvic acids (Stanford et al., 2011).

Table 4.3 Regions of excitation-emission spectra with corresponding compound type

Region	Excitation (nm)	Emission (nm)	Compound Type
Region I	240 - 300	280 - 390	Proteins
Region II	240 - 300	390 - 580	Fulvic-like Compounds
Region III	300 - 470	300 - 580	Humic-like Compounds
First-order Raleigh scattering	300 - 380	300 - 380	Colloidal/Particulate
Second-order Raleigh scattering	250 - 300	500 - 600	Colloidal/Particulate

In general, analysis of water samples to generate EEMs provides details about the contributions of components of different origin and character to the NOM makeup in a water sample and can correlate to disinfection byproduct formation potentials (DBP-FP).

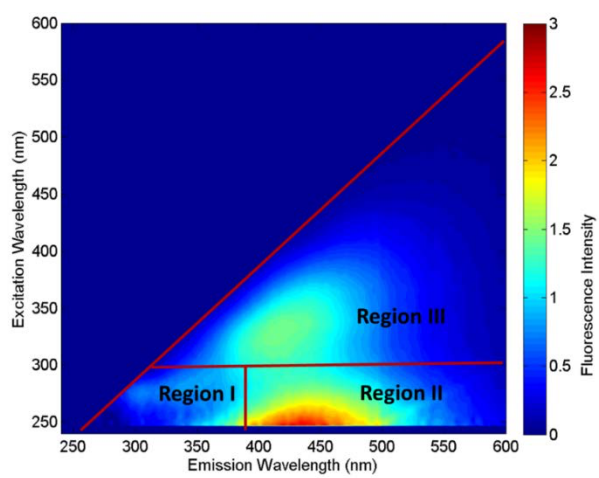


Figure 4.8 Example excitation-emission matrix (EEM) with 3 regions identified for regional integration.

In particular, fluorescence at longer wavelengths associated with terrestrially derived NOM such as humic and fulvic acids correlates very strongly with DBP-FP (Hua et al., 2010; Hao et al., 2012).

Figure 4.9 shows representative EEMs for four sample locations (note the rotation of the axes compared to Figure 4.8): (a) RWPF Influent, (b) RO Feed, (c) AOP Feed, and (d) Moss Creek Lake, for samples collected in February 2015. Appendix A provides additional EEM plots for samples of the product water, samples of the RO concentrate, and samples from all locations collected during the other major sample events.

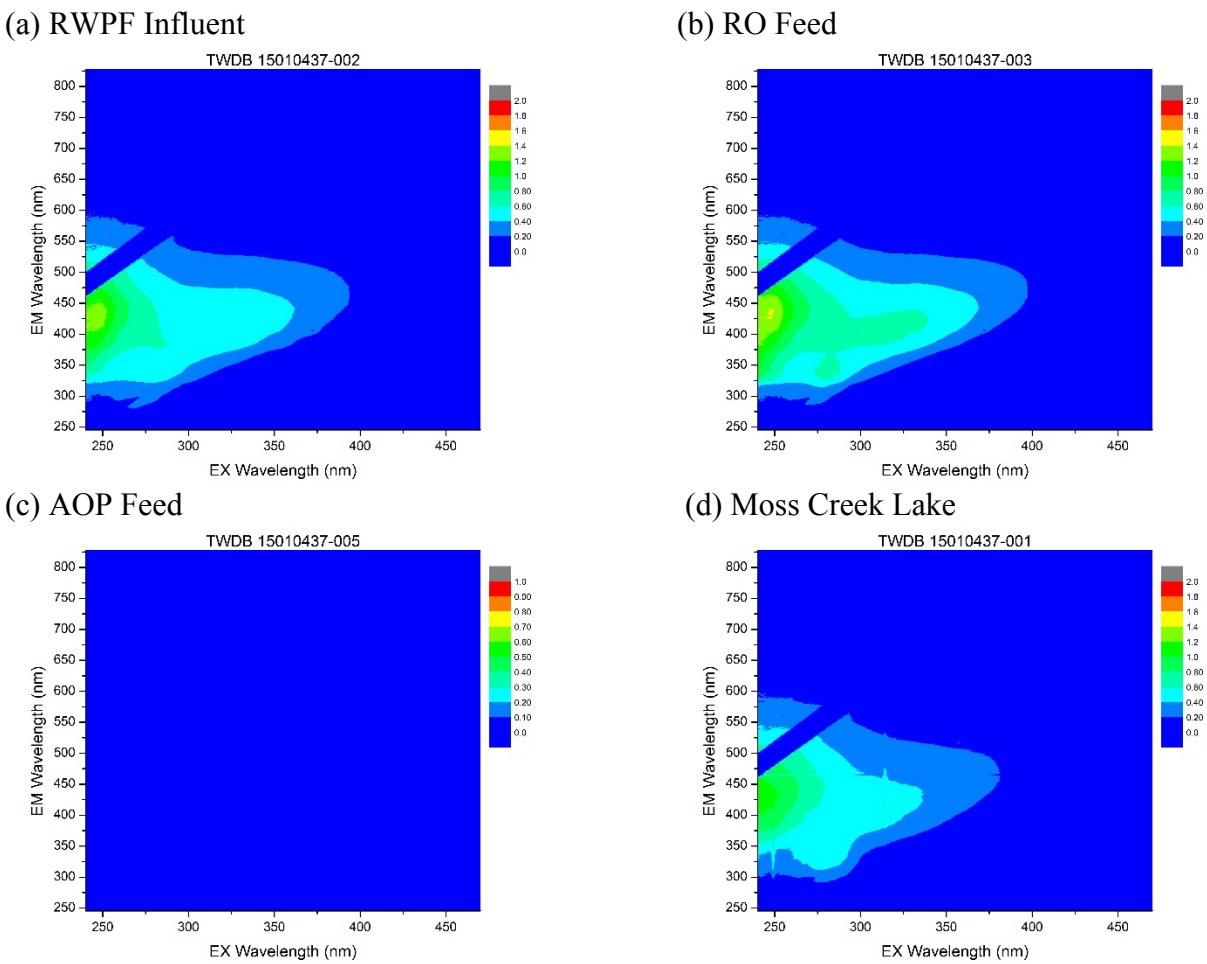


Figure 4.9 Representative fluorescence excitation-emission matrices.

EEMs provide a useful visual metric for communicating water quality. In the example shown in Figure 4.9, it is easy to see that the organic matter in Moss Creek Lake has a similar fingerprint to the organic matter in the RWPF influent. That is to say, the surface water source has similar types and amounts of organic matter as the treated wastewater effluent before being sent through the RWPF. The RWPF product water, with much lower organic carbon levels, is then blended with the Moss Creek Lake surface water before being sent to the WTPs. The RO process (as observed in the AOP Feed EEM, Figure 4.9-c) provides an excellent barrier for removal of much of the organic matter present in the RWFP influent.

4.5.3.1 Preliminary Data Analysis

A total of 19 water samples were collected and analyzed by fluorescence spectroscopy to produce EEM data. The samples were collected from the six locations listed in Section 3.2.

The first step of the analysis was a visual inspection of the EEM plots. The visual inspection served two purposes: as a basic confirmation that the data appeared to be plausible and within range, and as a comparison between intensities for the different sampling locations. Based on the visual inspection, it was apparent that the samples from the AOP feed and product water were below the detection limits of the fluorescent instrument. It also was apparent that there were seasonal variations in the NOM characteristics of the water, and that NOM was removed during the RO process.

Following the visual analysis, the samples were post-processed to remove the first- and second-order Rayleigh scattering regions. The Rayleigh scattering lines represent artifacts of the measuring technique, and are typically omitted unless the flurophores of interest lie close to the Rayleigh scattering regions (Rinnan et al., 2005). The original EEM dataset also was reduced to excitation/emission pairs for every 10 nm.

Following these post-processing steps, potential correlations between individual excitation/emission pairs and DBP-FP (TTHM-FP and HAA5-FP) were examined. Table 4.4 and Figure 4.10 contain the results of this analysis, which was based on the excitation/emission pairs previously identified in Water Research Foundation Project No. 4336 (Carptenter et al., 2013), as well as the data pair from this study (excitation = 350 nm; emission = 380 nm, last line of Table 4.4) that showed the strongest correlation for the DBP-FP parameters.

Table 4.4 Single excitation-emission pair and disinfection byproduct formation potential (DBP-FP) linear regression correlation coefficients (n=19)

HAA5 FP Single Pair Correlations		**TTHM FP Single Pair Correlations**	
Wavelength Pair	**R2 TTHM FP**	**Wavelength Pair**	**R2 HAA5 FP**
250/390	0.68	250/390	0.56
280/510	0.59	280/510	0.45
250/450	0.68	250/450	0.58
310/420	0.65	310/420	0.53
280/320	0.43	280/320	0.36
350/380	**0.69**	**350/380**	**0.74**

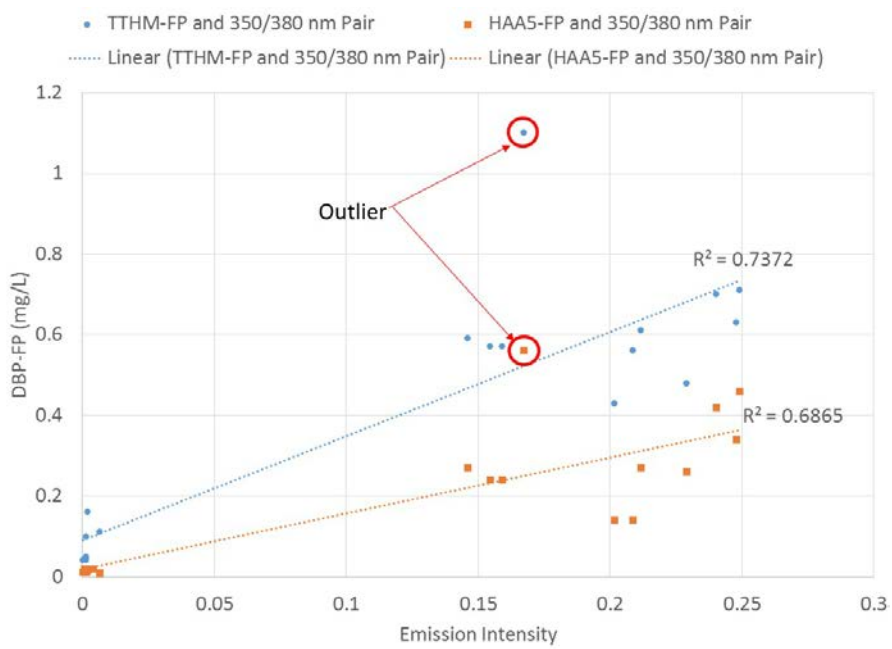


Figure 4.10 Disinfection byproduct formation potential (DBP-FP) parameters vs excitation/emission at 350/380 nm.

4.5.3.2 Advanced Data Analysis

The next step of the data analysis was to model the DBP-FP concentrations using partial least-squares regression (PLSR). PLSR is a powerful technique for decomposing a high-dimensional data set into a low-dimensional subspace of principal components (PC). The individual PCs are linear combinations of the original explanatory variables (Giancarlo, 2002), which are then utilized together in a linear regression to model the explanatory variable. An important feature of the PLSR model is that the individual PCs are not co-linear, and are calculated to maximize the explained variance in the target variable (i.e., DBP-FP) with each successive component.

Once a PLSR model is formed, it is important to validate that model to ensure it has not been over fit and will accurately predict future data sets that were not used for the training. The validation method used for this study is termed "leave-one-out" (LOO) validation. Essentially, this method takes the full sample set and fits the regression model on all but one of the observations. This one "left-out" observation then serves as the testing set to assess how well the model predicts "novel" data. This validation process is repeated so that all of the samples are used as the testing data, and statistics on model performance are compiled. The root mean square error prediction (RMSEP) is often used in conjunction with LOO validation as a metric for how well the model will perform on novel data. A higher RMESP indicates that the model has become over-fit to the existing data, and will not do well at handling new predictions. The final number of selected components to use in the model then becomes a balance between a high degree of correlation (R-squared) and the lowest possible RMSEP. The LOO validation method does not work well on autocorrelated data; however, due to the low frequency of sample collection (i.e., monthly) it is not expected that the data sets for this study are autocorrelated. For this study, the PLSR models were developed in the statistical software R using the "plsr" function from the "pls" library.

Prior to forming the PLSR models, the excitation-emission spectra were post-processed to reduce the dimensionality of the EEM by "moving" all excitation/emission pairs into a single row for each sample. This processing step is commonly referred to as "unfolding," and allows the EEM to be processed in the same manner as a two-dimensional dataset.

As the sample size for this study was relatively small (n=19), there were concerns that a PLSR model would overfit the data. To help alleviate these concerns, the data from this study were combined with the EEM and DBP-FP data from Wright et al. (2016) to form a larger data set (n = 123). Prior to fitting the PLSR model, the dataset was standardized to an average of zero and standard deviation of one. Figure 4.11 illustrates the correlation between the laboratory DBP-FP values and the values predicted by the calibrated PLSR model.

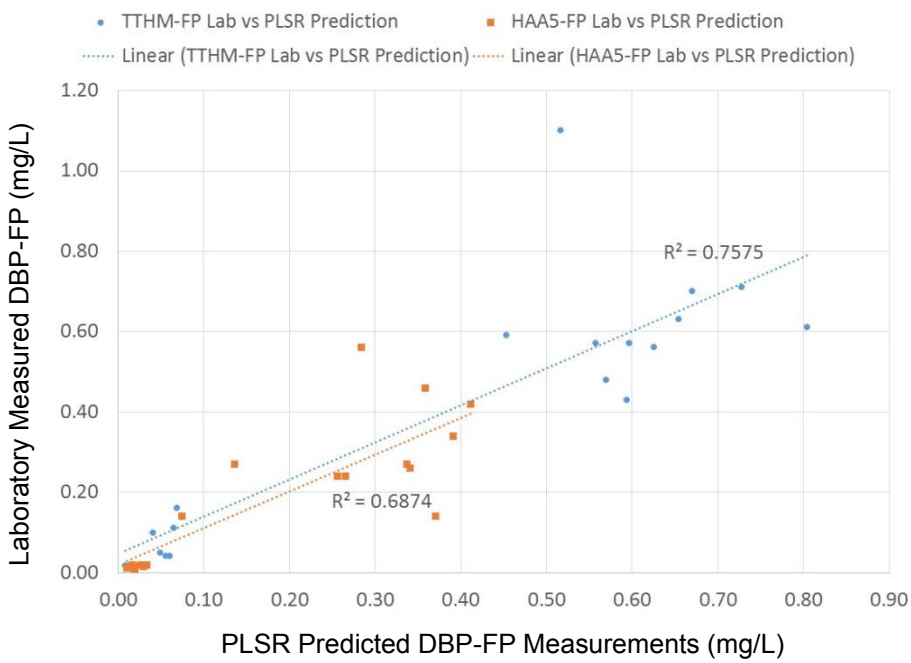


Figure 4.11 Correlation between actual disinfection byproduct formation potential (DBP-FP) values and partial least-squares regression (PLSR) model predicted DBP-FP values.

4.5.3.3 Discussion

The data analysis shows that the fluorescent spectroscopy data can readily differentiate between the samples that have very little to no DBP precursors, and the samples that have high levels of these compounds in this study. The analysis of the single excitation-emission pairs shows that many of the pairs identified by Carpenter et al. (2013) prove to be good DBP-FP surrogate parameters for this dataset. However, in the case of TTHM-FP, a wavelength pair different from those identified by Carpenter et al. (2013) proved to be the best indicator (based on R-squared). Interestingly, utilization of the full EEM dataset did not significantly improve the predictive power compared to single wavelength pairs. This might be due to the relatively small dataset, and differences between the NOM character in these water samples versus the samples collected by Wright et al. (2016).

The analysis conducted here indicates that while a good correlation between EEM data and DBP-FP data can be achieved, it requires a larger training dataset. This may lend itself to an in-depth characterization of an existing effluent proposed for a DPR project, but that it may not be a good tool for ongoing monitoring at DPR facilities.

4.5.4 Yeast Estrogen Screen (YES) Bioassay

Assays measure a sample's total *functional* content for a given characteristic instead of providing a list of the individual chemicals detected. Assays have the advantage of measuring the total *effect* of what is in water, which might be caused by unknown compounds.

The Yeast Estrogen Screen (YES) bioassay assesses the sum of all constituents contributing to the estrogenic activity of the water as a whole and is given in units of estradiol equivalency (EEQ).

Because of analytical challenges at the SNWA Laboratory, no quantitative YES assay results were reported. However, the estrogenic activity of samples collected in July 2014 and February 2015 was analyzed. These samples were collected from RWPF influent, RO feed, AOP feed, product water, Moss Creek Lake, and field blanks. The estrogenic activity of these samples was reported as "present" or "absent" (see Table A.14).

The results for all but one sample (Moss Creek Lake on July 17, 2014) showed no estrogenic activity. While a precise reporting limit does not apply to these samples, per communications with the SNWA laboratory staff, a "present" result indicates an estradiol equivalency in the low ng/L range.

These results provide additional confirmation of the analyses conducted for individual hormones during the first three sample events (see Tables A.1-A.3). In the samples collected from Moss Creek Lake, estrone was detected in all three (at an average of 0.6 ng/L), and progesterone was detected in one (at 0.65 ng/L, February 2015). In contrast, only a single detection of any hormone was found in *any* sample from the RWPF. Specifically, in the June 2015 sample, progesterone was detected at 0.4 ng/L in the influent. Because hormones were generally not detected, this analysis was omitted during the last major sampling event.

4.5.5 Turbidity

Turbidity is measured as the amount of light scattered by particles in the water. The particles' size, color, and shape will affect this scattering response, making it at best a very indirect measurement of microbial concentrations. Nonetheless, the industry has developed a large empirical dataset over many years of operation for conventional water treatment processes (coagulation, flocculation, sedimentation, and filtration) on traditional surface water sources. Surface water treatment regulations rely on these empirical data to define log removal values (LRVs) for various treatment technologies as a function of the turbidity of the water produced. However, the empirical relationships between pathogen removal and turbidity developed for conventional treatment of conventional surface water might not translate to membrane treatment for the RWPF plant influent.

As shown in Figure 4.6 (see Table A.11 for tabulated data) and discussed previously, turbidity does not correlate quantitatively with protozoa concentrations in the RWPF influent. Unusually

high turbidities in March 2014 and March 2015 appeared to be associated with higher protozoa concentrations when compared to the baseline of more than a year of low turbidity samples spanning November 2013 through July 2015. Low or non-detect protozoa results also accompanied this baseline.

However, for several months starting in August 2015, high turbidities and higher protozoa concentrations were not associated with each other. During this time, consistently higher *Cryptosporidium* concentrations and intermittently higher *Giardia* concentrations were detected, despite low influent turbidities.

The trend continued until February 2016, when an otherwise unrelated treatment upset was reported at the City of Big Spring WWTP. This upset caused higher turbidities and a number of RWPF shut-downs in February and March 2016. Ironically, the March 2016 protozoa concentrations were significantly lower than those of previous months, despite continued elevated influent turbidities. Thus, a long-term direct correspondence between turbidity and protozoa concentrations cannot be concluded.

In effect, much like its role in conventional water treatment, RWPF influent turbidity can still be a useful *surrogate* of proper *treatment* at the City of Big Spring WWTP, which no doubt serves to reduce protozoa concentrations in the water that this plant ultimately delivers to the RWPF. However, the data collected for this study confirms that influent turbidity should not be used as a direct indicator of pathogen concentrations. This is because measuring turbidity alone would not detect higher incoming pathogen concentrations and, in effect, a higher ratio of pathogens to solids.

4.5.6 Particle Size Distribution

A very similar argument can be made for particle size distribution (PSD) testing, which is described in detail in Section 4.6.1. An additional analysis evaluated influent protozoa concentrations from monthly sampling compared to 5-15 µm particle count data, which were only intermittently available. Figure 4.12 shows this comparison.

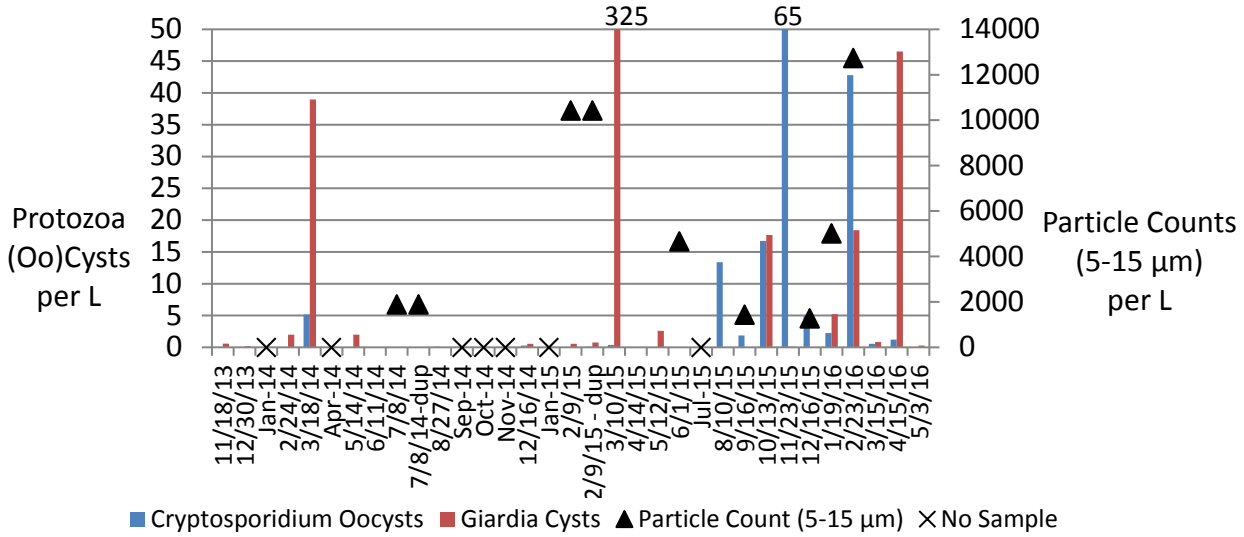


Figure 4.12 Monthly protozoa results compared to available 5-15 µm particle count data.

As shown in the figure, no direct link between particle counts and incoming protozoa concentrations is discernable. PSD results should not be used as a direct indicator of pathogen concentrations. Like turbidity, and other measures of *process* performance, such as pressure decay tests on MF membranes, PSD results can show whether the MF treatment process is performing properly.

4.5.7 Adenosine Triphosphate (ATP) Testing

Microorganisms primarily store energy in the form of adenosine triphosphate (ATP) (Madigan et al., 2012). Because of its high turnover rate, this biomolecule is a good indicator of cell viability (Harber, 1982). A number of studies show that bacterial levels of ATP correlate with cell numbers (e.g., Chapelle and Levon, 1968; D'Eustachio and Johnson, 1968; Deininger and Lee, 2001). Bacterial levels of ATP can be quantified in 15 minutes using a kit that that produces light from a reaction between ATP, dissolved oxygen, and luciferin. Luciferase, a naturally occurring firefly enzyme, catalyzes the reaction. The light is measured as Relative Luminescence Units (RLU), which are detected by a luminometer, with light output correlating directly to the sample's ATP content.

Using a luminometer and test kits, samples were field-tested for ATP (LuminUltra, Fredericton, N.B.) during the February, June, and September 2015 sample events (see Table A.15). Duplicate measurements were made at each sample point during each sample event. Figure 4.13 shows the average of these six sample results for each point where samples were collected. In the figure, the error bars denote the standard deviation.

As shown in Figure 4.13, and noting the logarithmic scale, ATP content is significantly reduced across the RO membranes, with downstream RLU levels below the "background" threshold. For reference, see the on-site laboratory deionized water (DI) sample shown at the far right in the figure. The reduction in ATP content is consistent with the idea that RO membranes are a robust barrier to microorganisms.

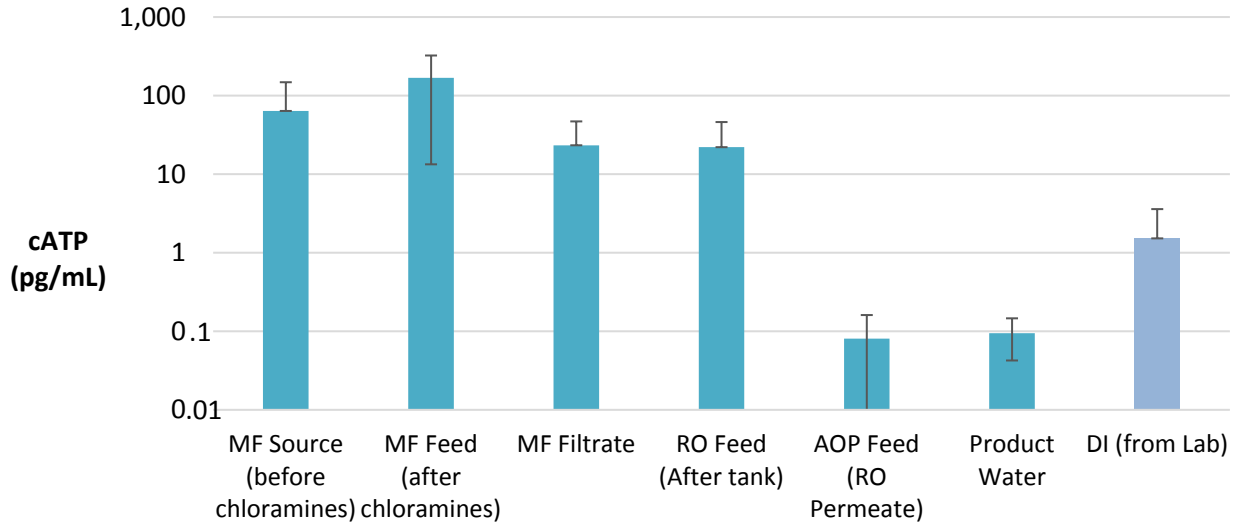


Figure 4.13 Average cellular adenosine triphosphate (cATP) results at each sample point.

4.6 Monitoring Surrogates

In addition to indicators for specific groups of pathogens and chemical groups, surrogate parameters were chosen specifically to monitor the effectiveness, or integrity, of each of the three advanced treatment processes. Surrogates are parameters that are not generally of health concern, but that are used to test the efficacy of treatment processes.

4.6.1 Microfiltration Integrity Monitor

Pressure decay tests (PDTs) demonstrate membrane integrity (Reardon et al., 2005, CDPH 2011), but only for one finite time period per day, and not in terms of viruses. Thus, there is no continuous and accurate online measurement of MF performance. Although there are online particle counters, they are prone to calibration and maintenance challenges and are not used at the RWPF. Benchtop particle counts were performed at the Carollo lab but could be implemented on a more frequent periodic basis to confirm integrity in between routine PDTs.

By tracking the reduction in particles in the appropriate size ranges, true pathogen reduction performance can be more accurately determined (Linden et al., 2012). For this reason, PSD analyses were conducted on samples collected from the RWPF influent and RO feed (i.e., before and after MF). These samples were collected during each major sample event and several additional monthly samples after higher protozoa concentrations were detected in the RWPF influent, beginning in December 2015. Particle counts were conducted offsite by Carollo on 500 mL grab samples using an Accusizer 780 syringe injection sampler (Particle Sizing Systems, Santa Barbara, CA).

PSD results are provided in terms of the total number of particles in a given size range per volume of sample. Results for particles in the size range of protozoa (5-15 µm) and bacteria (1-5 µm) can be used as surrogates for microbial concentrations across processes that remove microorganisms based on particle size, such as MF. Table A.16 summarizes the results from this testing.

Figure 4.14 is a representative plot of the PSDs for the four replicates (A-D) collected of MF feed and filtrate samples in February 2015. Appendix A (Figures A.24-A.31) provides the remaining PSD plots showing individual data points.

Based on four replicate samples each in the MF feed and filtrate collected during each major sample event, and an additional six replicate samples each in the feed and filtrate collected in December 2015 - February 2016, LRVs ranged from 1.96-log to 3.08-log for protozoa-sized particles and 1.22- to 3.17-log for bacteria-sized particles.

In general, samples were relatively consistent between replicates but were highly variable between individual events. Variability was seen for the influent particle concentration (ranging approximately from 900 to 13,000 per mL for protozoa-sized particles and from 2,500 to over 100,000 per mL for bacteria-sized particles) and for the filtrate concentrations (0 to 81 per mL, with one single sample outlier at 257 per mL for protozoa-sized particles and 4 to 1,000 per mL for bacteria-sized particles).

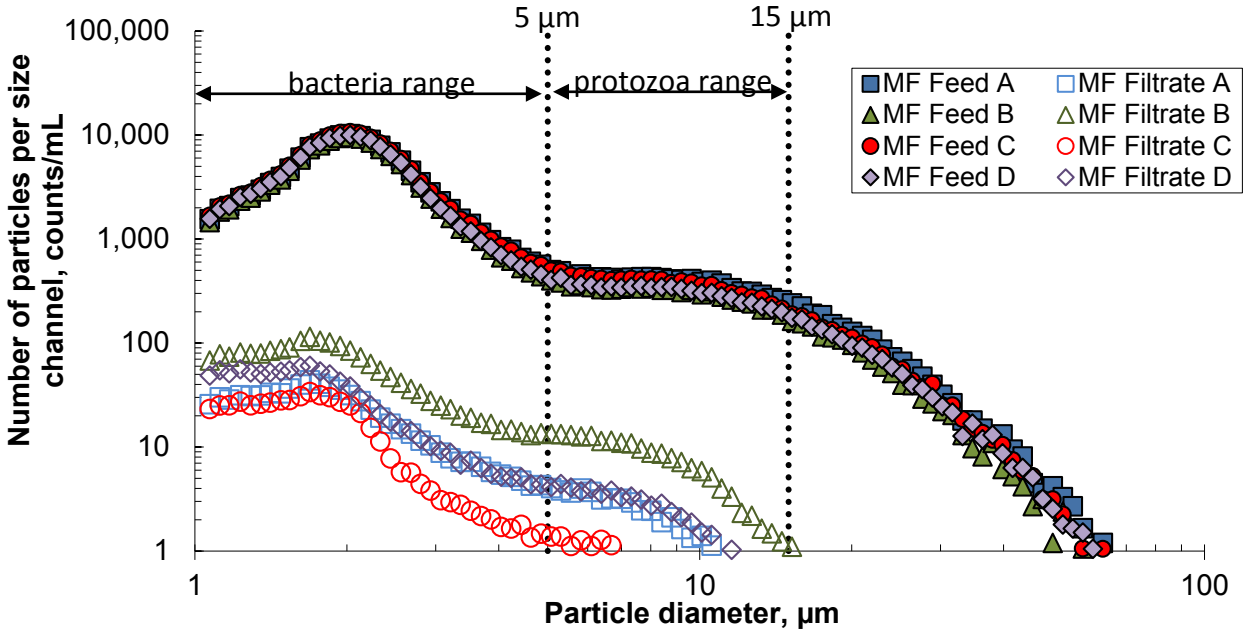


Figure 4.14 Representative particle size distribution data (February 2015).

In general, LRVs for protozoa-size particles were higher than for bacteria-sized particles. However, this was not always the case, indicating some statistical scatter in the data. As shown in Figure 4.15, and removing the outlier noted above, LRVs in each particle size range correlated reasonably well with one another within the range of data shown. Also note that at higher LRVs (3-log), the differences between protozoa and bacteria-sized particles all but vanish. Conversely, at lower LRVs (1.5-log on Bacteria axis), there is more than a 0.5-log difference, with greater removal of protozoa-sized particles as expected.

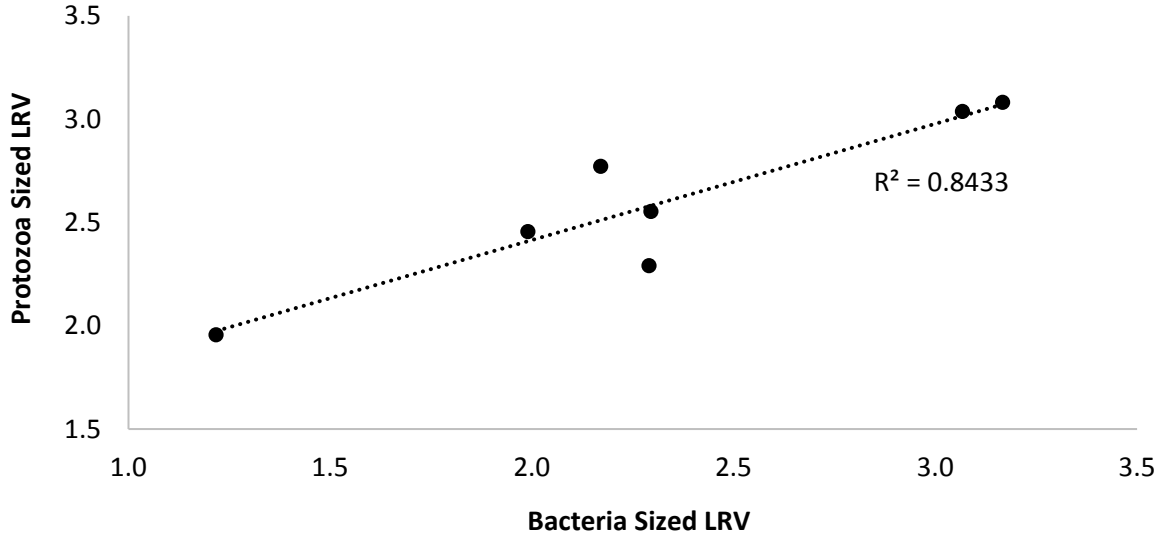


Figure 4.15 Correlation between average log removal values for bacteria-sized and protozoa-sized particles for each sample event (with one outlier removed).

As a side note, this observation is a good reminder of the problems with extrapolating any correlation beyond the data range from which it was developed: extrapolating to higher LRVs based on this correlation would predict that bacteria-sized particles are removed better than protozoa-sized particles, which is not realistic.

Samples were not collected at a specific time relative to the periodic cleaning cycles on the membranes, which likely induced variability in the LRVs. In addition, filtrate particle counts might include particles sourced from biofilms in the MF filtrate, resulting in a lower apparent LRV.

Direct integrity tests (DITs) performed routinely at the RWPF indicated no issues with membrane integrity when the samples were collected and showed that the membranes consistently achieved a minimum of 4-log removal for protozoa. Thus, the particle counts reported here should be understood as providing a conservative estimate of the LRV provided by the membranes and might be useful for periodic interim checks between DITs once a larger and more consistent baseline dataset is established.

Future applications of particle counting to demonstrate membrane integrity should aim to collect samples from immediately before a cleaning cycle, which would give the system as long as possible to flush out particles left over from the previous backwash.

4.6.2 Reverse Osmosis Integrity Monitor

Texas has not yet approved pathogen removal credit for RO membranes. California guidelines provide 2-log or less removal credit for pathogens in RO installations at potable reuse facilities, based on the removal of online surrogates like electrical conductivity (EC) or total organic carbon (TOC). This credit is awarded based on the assumption that the removal of both EC and dissolved organic carbon (DOC) are lower than the removal of the target pathogens.

Challenge testing has shown that RO membranes are capable of 6-log or more virus removal. This result was expected because of the significantly large size of viruses compared to the effective pore size of RO membranes.

4.6.2.1 Background on 3D TRASAR® Technology

One component of this project included testing to see whether a fluorescent tracer-based method could be used as an online surrogate to demonstrate higher LRVs for RO membranes for all pathogen classes. Developed by the Nalco Company (an Ecolab Company), the 3D TRASAR® (Trasar) tracer compound is an organic molecule NSF-certified as a fluorescent dye, which can be detected at a level of 10 μg/L with an online sensor.

Currently, Trasar is used as an additive in Nalco's antiscalants for precise dosing in RO operations. By dosing the Trasar compound to the RO feed at a concentration of up to 6-log higher than the detection limit, and measuring its concentration in the feed, concentrate, and permeate, the removal performance can be determined.

The molecular weight of the Trasar molecule (614 grams per mole [g/mol]) is similar to trace organic compounds commonly found in wastewater and is large enough that it should not penetrate RO membranes (thus demonstrating up to 6-log removal), but is much smaller than

enteric viruses (20-85 nanometer (nm) diameter). It also carries a negative charge, thus mimicking some of the charge repulsion experienced by negatively charges virus particles encountering the negatively charged RO membrane surface, but the size differential is large enough that size exclusion is likely to be the dominant factor in differentiating their retention by RO membranes. Thus the Trasar molecule acts as a conservative surrogate for even the smallest of the pathogens of interest.

4.6.2.2 Reverse Osmosis Challenge Testing Setup

Testing was conducted at an off-site pilot location. A 2-stage (2:1 array with six four-inch elements per pressure vessel) demonstration-scale RO pilot system with membranes donated by CSM was operated at a recovery of 80 percent (75 percent recovery in each stage), using tertiary effluent from a Ventura, California, WWTP. Table 4.5 summarizes the pilot setup operating conditions and other specifications.

Table 4.5 Ventura Reverse Osmosis Pilot Specifications

Component	Design Criteria & Comments
Hydraulic Design	Production Rate Range: 15-18 gpm; Feed Flow Rate: 16 to 30 gpm; Concentrate Flow Rate: 2 to 30 gpm
Array	Two stage array, 2:2:1:1
Cartridge Filter	Type: glass fiber wound or polypropylene; Length: 10 inch; Number of elements: 6; Nominal pore size: 5 micron
Booster Pump	1.5 hp, 480 V, 3 ph, 60 Hz, 3 FLA
Feed Pump	Grundfos model CRN10-16 (15 hp, 480 V, 3 ph, 60 Hz, 21 FLA), VFD controlled
Interstage Boost Pump	Grundfos model CRN3-11 (2 hp, 480 V, 3 ph, 60 Hz, 3.4 FLA), VFD controlled
Pressure Vessels	Codeline, 4-inch diameter, maximum pressure: 300 psi; Three 3-element and three 4-element vessels to simulate full scale 6 or 7-element vessels
Membrane Type	CSM RE4040-FE
Membrane Elements	4-inch diameter x 40-inches long; Stage 1: Up to 14 elements; Stage 2: Up to 7 elements, 85 ft^2 per element
Chemical Feed Pumps and Tanks	Acid Pump: LMI model A971-352SI (0.42 gph); Scale inhibitor: LMI model P131-392SI (0.42 gph); 30-gallon scale inhibitor tank with low level switch; Acid and scale inhibitor dosage are manually set. Used drums for acid.

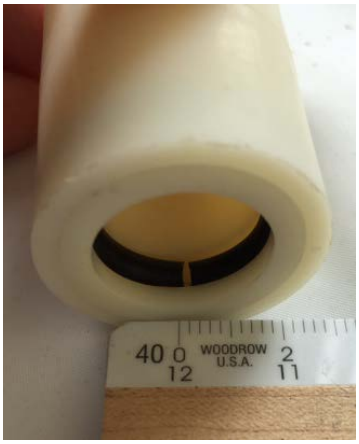
Tests were prepared and conducted in general accordance with the Test Plan (see Appendix B and Appendix E for details). However, they were scaled down to accommodate a smaller pilot-scale size than the RWPF's full-scale RO trains, which the Test Plan had anticipated. While a full-scale evaluation was preferred, operating at the pilot scale allowed for additional replicates to be collected and for the RO process to simulate long term membrane degradation as well as short-term failure.

Virus removal by the RO membranes was evaluated using MS2 seeded to the RO feed and compared to EC and the Trasar system response. Removal of MS2, EC, and the tracer compound were compared using intact membranes, oxidized membranes, and defective o-rings.

Reverse Osmosis Skid at VenturaWaterPure Demonstration Facility
Photo Credit: Justin Sutherland

4.6.2.3 Summary of Reverse Osmosis Challenge Testing Results

For each set of tests, LRVs for MS2 were established using six replicates of feed and permeate grab samples each. Results in subsequent figures are shown as averages, with error bars indicating one standard deviation of the LRV, based on a simplifying assumption of paired feed/permeate samples with no independent measurement error.



Cut O-Ring Used in Testing
Photo Credit: Justin Sutherland

Trasar and conductivity were recorded once per minute in the feed and at one of two permeate sample locations (Stage 1 or Combined Permeate). The average and standard deviation values for the LRVs of these parameters were calculated from between 100 and 300 feed/permeate data pairs to show the stability of Trasar operations. For MS2, the data are based on six pairs of grab samples for each condition collected during the window in which Trasar and EC data were recorded.

As shown in Figure 4.16, LRVs for MS2, Trasar, and conductivity using intact membranes (Stage 1) averaged 6.2, 4.3, and 1.7, respectively. The results indicate that the tracer compound is a conservative surrogate compared to actual MS2 removal under normal operating conditions.

Figure 4.16 also shows the results from samples taken from the combined permeate of both stages. Because the pilot system had been operated before, the second-stage membranes were fouled with inorganic constituents, which autopsy reports confirmed, and had sustained some significant damage, as evidenced by Trasar and conductivity results. However, as shown in Figure 4.16, this damage did not affect virus removal.

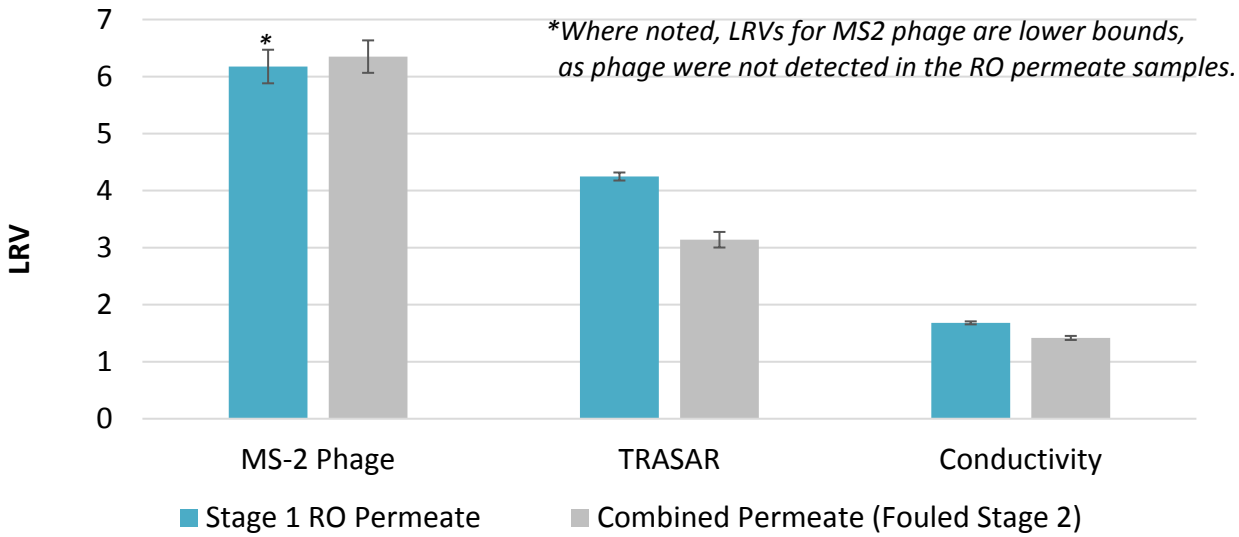


Figure 4.16 Log removal values (LRVs) for MS2, TRASAR, and electrical conductivity for stage 1 and the combined permeate of two stages.

Figure 4.17 compares the results of the cut o-ring test with the intact Stage 1 results. All three parameters, MS-2, Trasar, and conductivity, detected similar LRVs of ~1-log, which were expected under a bulk flow breach. The Trasar system detected this breach within seconds of starting the damaged o-ring, demonstrating its effectiveness as a real-time monitor similar to the response time of online conductivity.

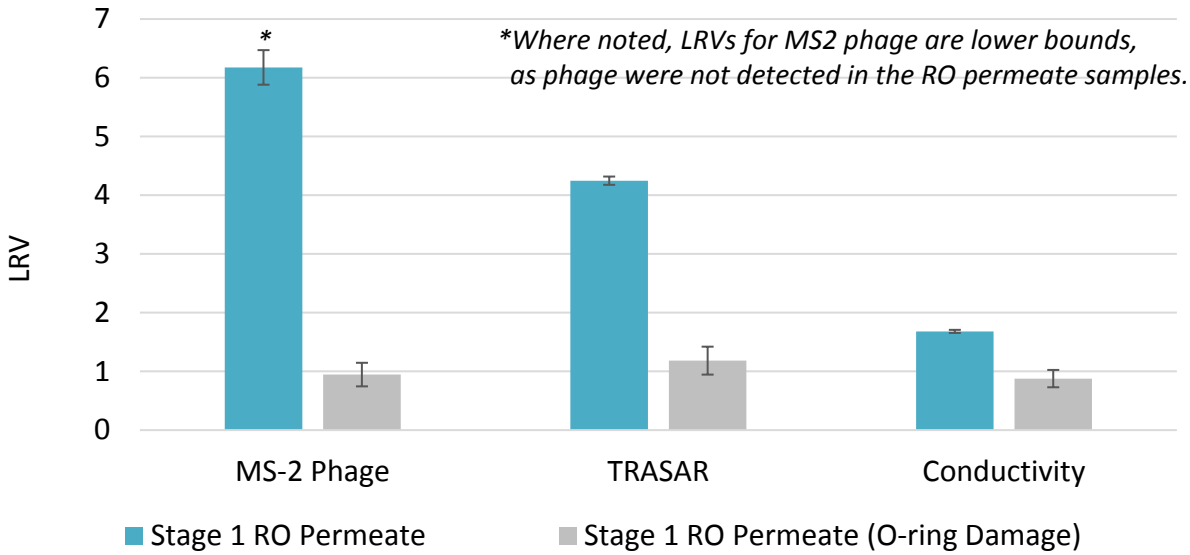


Figure 4.17 Log removal values (LRVs) for MS2, Trasar, and electrical conductivity for Stage 1 under intact conditions and with a cut o-ring.

For the third test condition, a membrane oxidation procedure developed specifically for this study was applied to select membrane elements before they were installed at the pilot site. The test had two purposes:

1. Simulating a common membrane degradation mechanism from prevalent use of chloramines to control biofouling in reuse applications.
2. Developing a set of conditions to determine whether the Trasar system is a conservative surrogate to measure virus removal, even under compromised conditions.

For the test, the membrane elements were exposed to several pulses of feed water containing free chlorine until steady-state salt passage increased from a nominal 1 percent to approximately 20 percent under standard operating conditions. The increased salt passage represents a 20-fold reduction in selectivity and thus indicates significant oxidative damage. Two oxidized membrane elements were inserted into one of two parallel Stage 1 pressure vessels, replacing two of six intact elements in that vessel. With this, two out of 12 total elements in Stage 1 were substituted.

Figure 4.18 illustrates the results of this test. As the figure shows, the system with the oxidized membranes did not demonstrate any reduction in MS2 LRV, which remained at more than 6-log. Tracer compound removal was reduced from 4.3 to 3.6 log, providing immediate feedback on the membrane degradation. However, the tracer compound still demonstrated a significantly higher LRV than the 1.1-log that conductivity achieved under damaged conditions. With this result, a treatment plant could likely continue to meet pathogen reduction targets until the damaged membranes are replaced.

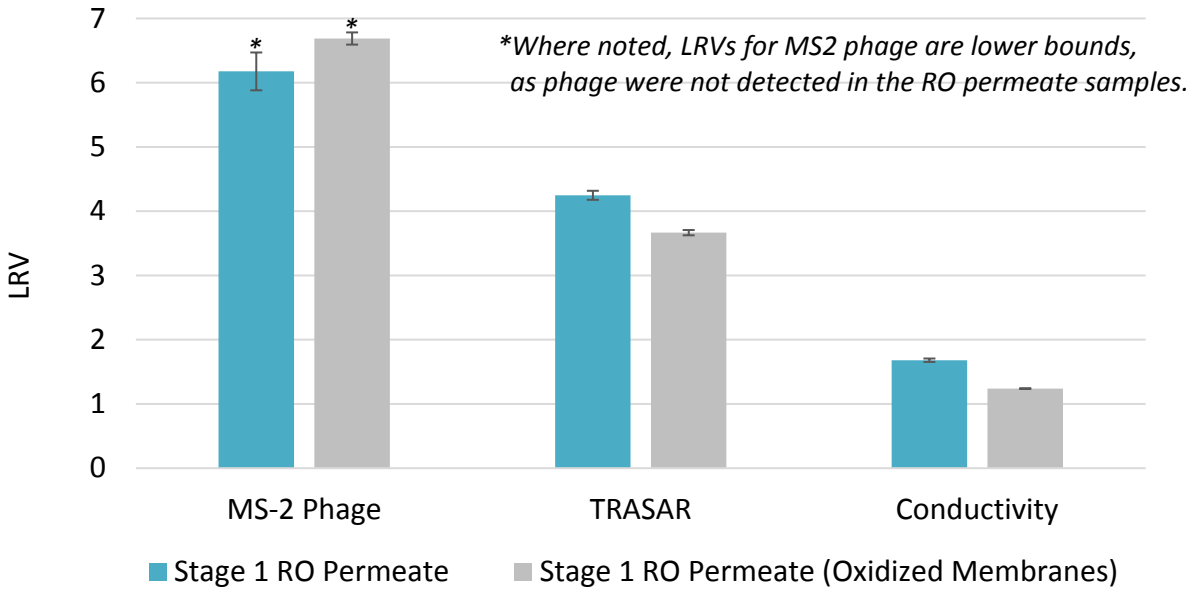


Figure 4.18 Log Removal Values (LRVs) for MS-2, Trasar, and electrical conductivity for Stage 1 under intact conditions and with the two lead elements out of six in one of two Stage 1 pressure vessels substituted for oxidized elements.

Under normal operating conditions, oxidative damage would likely occur slowly over time. In this case, the Trasar system would indicate a gradually increasing level of damage that could determine when further assessment or replacement of one or more membrane elements is necessary. During this time, the system could continue to maintain a significant LRV (>3-log) until maintenance or replacement occurred. This could significantly extend the lifespan of membranes used in reuse applications, where the use of chloramines for biofouling control contributes to faster "aging" of membranes with respect to salt rejection but where salt removal itself might not be the driving factor for using RO.

4.6.2.4 Conclusions from Reverse Osmosis Challenge Testing

In summary, the data demonstrate that the 3D Trasar® system constitutes a viable online option for detecting membrane failure modes and the fluorescent Trasar molecule acts as a conservative indicator of microbial removal by RO membranes. Application of this technology to DPR projects would provide greater confidence in pathogen removal by RO systems.

4.6.3 Ultraviolet Light/Advanced Oxidation Surrogates

In the last treatment process, UV/AOP, two related but separate physical treatment mechanisms are at work. UV light inactivates pathogens by damaging the nucleic acids that encode all the functions of the cells. It also can transform chemicals, such as NDMA, which are susceptible to direct photolysis. AOP is achieved by adding hydrogen peroxide, which the UV light cleaves into hydroxyl radicals. These hydroxyl radicals act as strong oxidizing agents that break down many different chemicals.

Thus, to adequately monitor the effectiveness of this process step, one must monitor for UV dose and AOP effectiveness. UV dose determines the level of pathogen inactivation and direct photolysis. AOP effectiveness is measured by tracking the destruction of a surrogate, such as 1,4-dioxane, that is not susceptible to direct photolysis.

Research conducted at the West Basin Municipal Water District in California has shown chloramines to be a good surrogate for UV dose (see Appendix D). Like many other advanced treatment facilities that employ RO for potable reuse, chloramines are fed ahead of the RWPF's RO membranes to reduce biofouling. Because chloramines pass through the RO membranes, they are available as a potential surrogate for UV AOP performance at the facility.

4.6.3.1 Collimated Beam Testing Summary

Collimated beam testing was performed on AOP feed samples (RO permeate) from the RWPF at the Trussell Technologies Lab in Pasadena, California. This testing was done for two reasons: (1) to verify the effectiveness of the UV/AOP process for inactivating pathogens and destroying CECs, NDMA photolysis, and 1,4-dioxane oxidation and (2) to develop correlations between that effectiveness and a potential surrogate (chloramines) for ongoing monitoring. The testing protocol was part of the project's Test Protocol (Steinle-Darling et al., 2015). Appendix D provides a detailed report of Trussell Technologies' testing. A summary of the findings is provided in the following sections.

4.6.3.2 Nitrosamines Destruction

NDMA concentrations in the AOP feed were not high enough to develop correlations between UV dose and NDMA destruction. Sampling at the RWPF corroborates this, since NDMA was only detected once in a product water sample, at 3.3 ng/L on 7/7/14, and 5.8 ng/L was the highest concentration measured in samples collected from the UV AOP feed (see Section 4.3 and Tables A.1 through A.4).

From a public health perspective, this is an excellent outcome, since NDMA is considered a likely human carcinogen. Furthermore, while not regulated in the State of Texas, it has a California Notification Level of 10 ng/L. Concentrations measured in all locations at the RWPF, except for one RO concentrate sample, were lower than this threshold.

4.6.3.3 Chloramines Residual

Chloramines residual was measured in the AOP feed and product water during three sampling events (see Table A.17). The UV/AOP system achieved an average chloramines (as monochloramine) LRV of 0.63-log, with a standard deviation of 0.15-log.

Collimated beam (CB) testing conducted by Trussell Technologies (summarized in Appendix D) resulted in development of a linear relationship between log removal of chloramines and UV dose, specific to RO permeate from the RWPF, that would allow operators to estimate UV dose delivery based only on chloramine destruction. Based on the linear correlation shown in Figure 4.19, a chloramine destruction of 0.63-log corresponds to a UV dose of more than 1,200 mJ/cm^2.

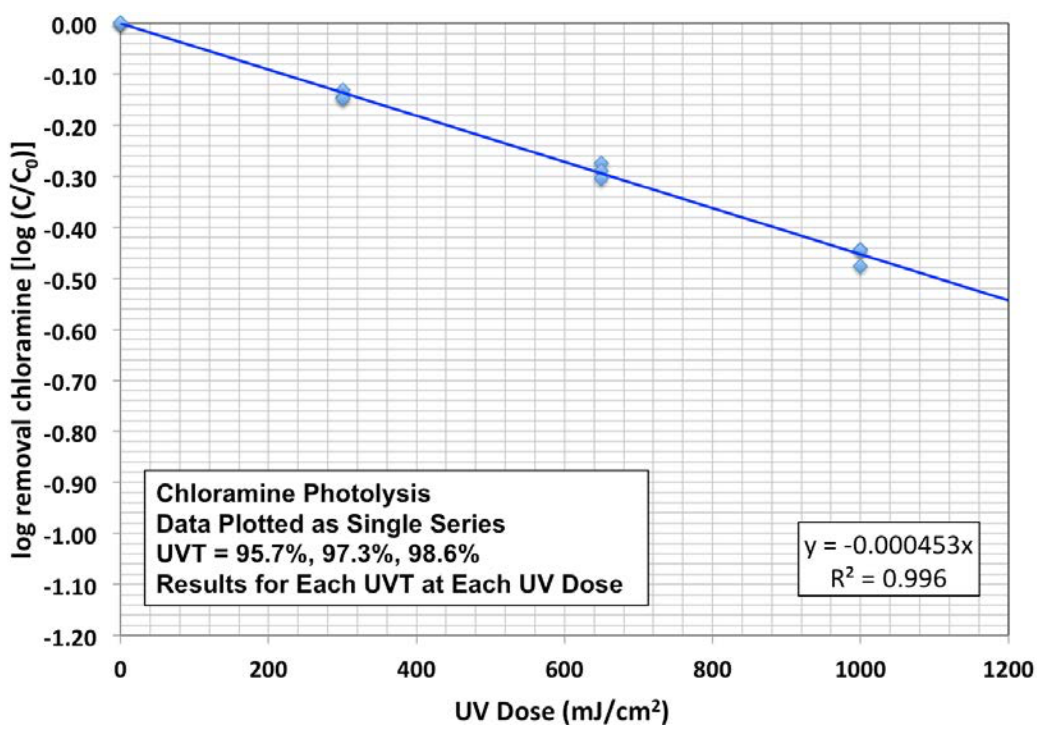


Figure 4.19 Chloramine log-removal during NDMA destruction collimated beam testing.

However, the addition of hydrogen peroxide (H_2O_2) interferes with chloramine measurements, so a robust verification of UV dose would require a short-term stoppage of H_2O_2 addition. This test was not performed at the RWPF and thus the extrapolated UV dose above should not be considered a precise value of the actual dose achieved at RWPF. However, this kind of "UV check" could be implemented on a periodic basis similar to direct integrity tests performed on the MF units.

4.6.3.4 Advanced Oxidation Process Benchmarking Based on 1,4-Dioxane Destruction

Separate testing was conducted to determine the effectiveness of the AOP process, as measured by the destruction of 1,4-dioxane. In California, AOP processes used in potable reuse projects must achieve a minimum 0.5-log destruction of 1,4-dioxane, so this is a common design benchmark for UV/AOP systems.

The benchtop CB tests conducted by Trussell Technologies (see Appendix D for details) were done on samples spiked with 1,4-dioxane because the background concentrations in the RO permeate samples sent to the lab were too low for quantification. Other samples from RWPF analyzed for 1,4-dioxane (Table A.18) corroborated this finding, which showed low concentrations in the influent (maximum 0.36 μg/L) and non-detects in the AOP feed and product water samples.

Assuming a UVT of 98.6 percent, which was the amount measured in the samples collected at RWPF, and a hydrogen peroxide dose of 5 mg/L, the Trussell Technologies tests indicate that 0.5-log removal is achieved at a dose of approximately 720 mJ/cm^2. This level is well below what appears to be applied based on the chloramines destruction (as discussed above).

At lower hydrogen peroxide feed concentrations, additional UV dose is required to achieve the same level of 1,4-dioxane destruction and at lower UVTs, additional energy is required to maintain the target dose. The CB results in Appendix D clearly show the impact of higher chloramine concentrations to 1,4-dioxane destruction efficiency and to UVT in the RO permeate (both have negative effects).

4.6.3.5 Summary of Ultraviolet Light/Advanced Oxidation Process Surrogate Evaluation

The UV dose that RWPF reactors provided when samples were collected seems *well* in excess of the minimum UV dose needed for the TCEQ to credit the 4-log virus inactivation to the process. This provides a significant safety factor for the RWPF.

In addition, ongoing monitoring of UV_{254}, which is UV light at a 254 nm wavelength, and total chlorine in the AOP feed and product water could be another online monitor of UV effectiveness at the RWPF and other DPR facilities. This would require relatively low additional investment in equipment.

5 Monitoring Approaches for Direct Potable Reuse

The Texas Water Development Board's recent publication "Direct Potable Reuse Resource Document" (APAI, 2015) provides an overview of technical and regulatory guidance for DPR to date. This overview includes water quality performance targets, treatment strategies, pilot study information, public outreach, and regulatory considerations for DPR.

However, the report does not address the advanced monitoring necessary for verifying and maintaining the effectiveness of advanced treatment for DPR. It states, "there is currently a significant amount of ongoing research focusing on [issues related to] operations, maintenance, monitoring and process control." It then refers readers to a list of ongoing research projects.

The purpose of this chapter is to summarize the ongoing research on process control and monitoring for direct potable reuse projects while drawing on the results from testing of monitoring surrogates for this study.

5.1 Monitoring is About Risk Mitigation

The initial research projects on treatment process control for DPR focused on transferring risk mitigation approaches from other industries that require failsafe operation. Salveson et al. (2014) made a broader assessment of risk mitigation for DPR systems, borrowing their approach from aerospace, bridge building, and nuclear industries. One major conclusion from the study was that proper ***monitoring is critical to controlling risk.***

5.1.1 The Critical Control Point Approach

The Hazard Analysis and Critical Control Point (HACCP) approach is a rigorous system that can develop risk mitigation programs across a wide range of applications. It is the industry standard for controlling risk from microbial hazards in the food industry. In "translating" this approach for DPR, Halliwell et al. (2014) noted that harmful pathogens and chemicals in the water are the main hazards in a DPR scenario. Thus, regulatory bodies such as the TCEQ have completed much of the "Hazard Analysis" part of the process by developing water quality and treatment standards that protect public health.

With the hazard analysis complete, the next step is to define critical control points (CCPs). Walker et al. (2016), whose work builds on that of Halliwell and others, defined CCPs as "points in the treatment process that are specifically designed to reduce, prevent, or eliminate a human health hazard and for which controls exist to ensure the proper performance of that process." Thus, the CCP identification process must be tailored to individual projects.

Walker et al. (2016) developed a five-question metric providing a structured process for identifying CCPs, framing hazards specifically in terms of pathogen log-removal credits and water quality targets. This framing aligns the CCP approach directly with the parameters regulated in DPR projects. Figure 5.1 provides a copy of this metric.

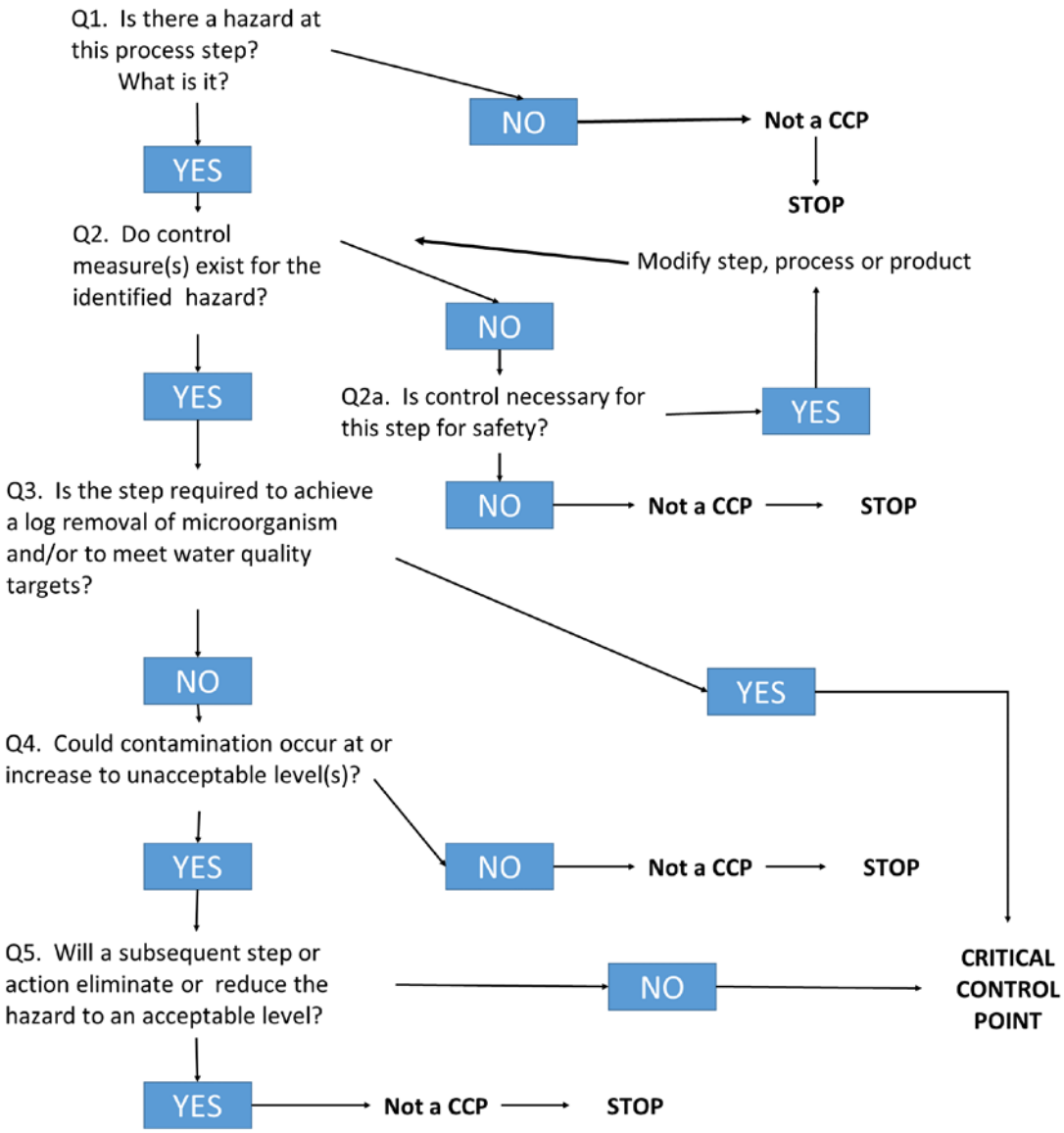


Figure 5.1 Five-question critical control point selection metric. (From Walker et al., 2016).

5.1.2 End-Of-Pipe Testing

Historically, advanced treatment facilities for potable reuse have relied on a large amount of end-of-pipe testing to confirm water quality, even for unregulated constituents. Today, the industry is using the more systematic and risk-based CCP approach.

Some amount of monitoring is needed to meet the requirements of existing regulations for drinking water treatment. Similarly, periodic confirmation monitoring for certain parameters is critical as a backstop for online monitoring methods.

However, as discussed in Section 4.4.1, in practice, monitoring directly for pathogens at relevant concentrations is impossible (see Table 2.1). For these constituents, advanced treatment

facilities, much like existing surface water treatment plants, must rely on proper operation and monitoring of individual processes, which is best accomplished through a CCP program.

In addition, in a DPR scenario, the response time to react to process failure is critical for protecting public health (Salveson et al., 2016). Water produced for DPR might be only a few hours away from being delivered into people's homes, meaning traditional laboratory methods do not provide information with sufficient response time to confirm finished water quality. Thus, online surrogates must be the primary line of defense against process failures.

Finally, too many individual chemicals are present in any water source and are nearly impossible to enumerate and quantify. Specific chemicals considered a higher risk to public health, for example those measured at concentrations within a factor of 10 or less of their drinking water standards should be frequently measured. Examples belonging to that category include nitrate, nitrite, disinfection byproducts, and any others that are identified during an initial screening of the effluent to be treated. For the remaining chemicals, robust treatment processes are sufficient if they (1) reduce the concentrations of chemicals of concern and (2) are evaluated systematically and monitored appropriately through a CCP approach.

5.1.3 Considering All Elements of the Urban Water Cycle

In the broadest sense, a CCP analysis could be conducted across all elements of the urban water cycle involved in a DPR project. For example, Walker et al. (2016) point out that a CCP could be located in the collection system if water quality hazards (metals or industrial organic chemicals, for example) need to be controlled in a DPR system's collection system. In fact, the DPR Resource Document, published by the Development Board (APAI, 2015), devotes a chapter to enhanced source control, an important part of any DPR project.

5.2 Monitoring Requirements at the Raw Water Production Facility

Figure 5.2 shows the current required monitoring program for the RWPF. This figure was obtained from the TCEQ (Wanielista Berg, 2016).

While not presented as a CCP approach, the monitoring requirements and shut-down conditions provide a functionally equivalent result. These monitoring requirements were "translated" into a CCP approach, shown in Table 5.1. The table lists the CCPs and the hazard the CCP addresses, the critical monitoring parameters, the frequency of measuring the parameters, and the corrective actions to take if a critical parameter is outside of its critical limits.

Table 5.1 A Critical Control Point Analysis of the Raw Water Production Facility

CCP	Hazard	Parameters	Frequency	Critical Limit	Corrective Action
Plant Influent	Increased pathogen load from incomplete treatment at WWTP	Turbidity	online[1]	< 10 NTU	Water routed to discharge
Microfilter Skids	Protozoa breakthrough from membrane failure	Integrity tests	daily and post-cleaning	must pass	Skid taken offline and repaired
		Individual filter effluent (IFE) turbidity	online[1]	< 0.15 NTU	Additional integrity test triggered
Reverse Osmosis Skids	Pathogen and chemical breakthrough due to membrane failure	Permeate electrical conductivity (EC)[2]	online[1]	< 20% or <40 uS over previous reading	Skid taken offline and repaired
Ultraviolet (UV) Light Reactors	Incomplete pathogen inactivation[3]	D_{val} (UV dose)	online[1]	> 100 mJ/cm^2	Product water diverted to discharge
		Flow	online[1]	< 7.39 mgd	
		UV transmittance	every 3 hours	> 40.3%	
		Lamp Status	online[1]	≤ 2 lamps off	
Product Water	Chemicals exceed MCLs	nitrate	daily	< 10 mg/L	Product water diverted to discharge, investigate, & remediate causes
		nitrite	each work day	< 1.0 mg/L	
	Pathogens present	*E. coli*	weekly	non-detect	

Notes:
1. Online readings are recorded and evaluated every five minutes.
2. Figure 6.1 shows electrical conductivity as "TDS."
3. All pathogens (*Giardia*, *Cryptosporidium*, and Virus) are inactivated during this treatment process. Incomplete pathogen inactivation could be caused by an upstream failure, which affects the UV reactors' ability to deliver the required dose, or by a UV equipment failure.

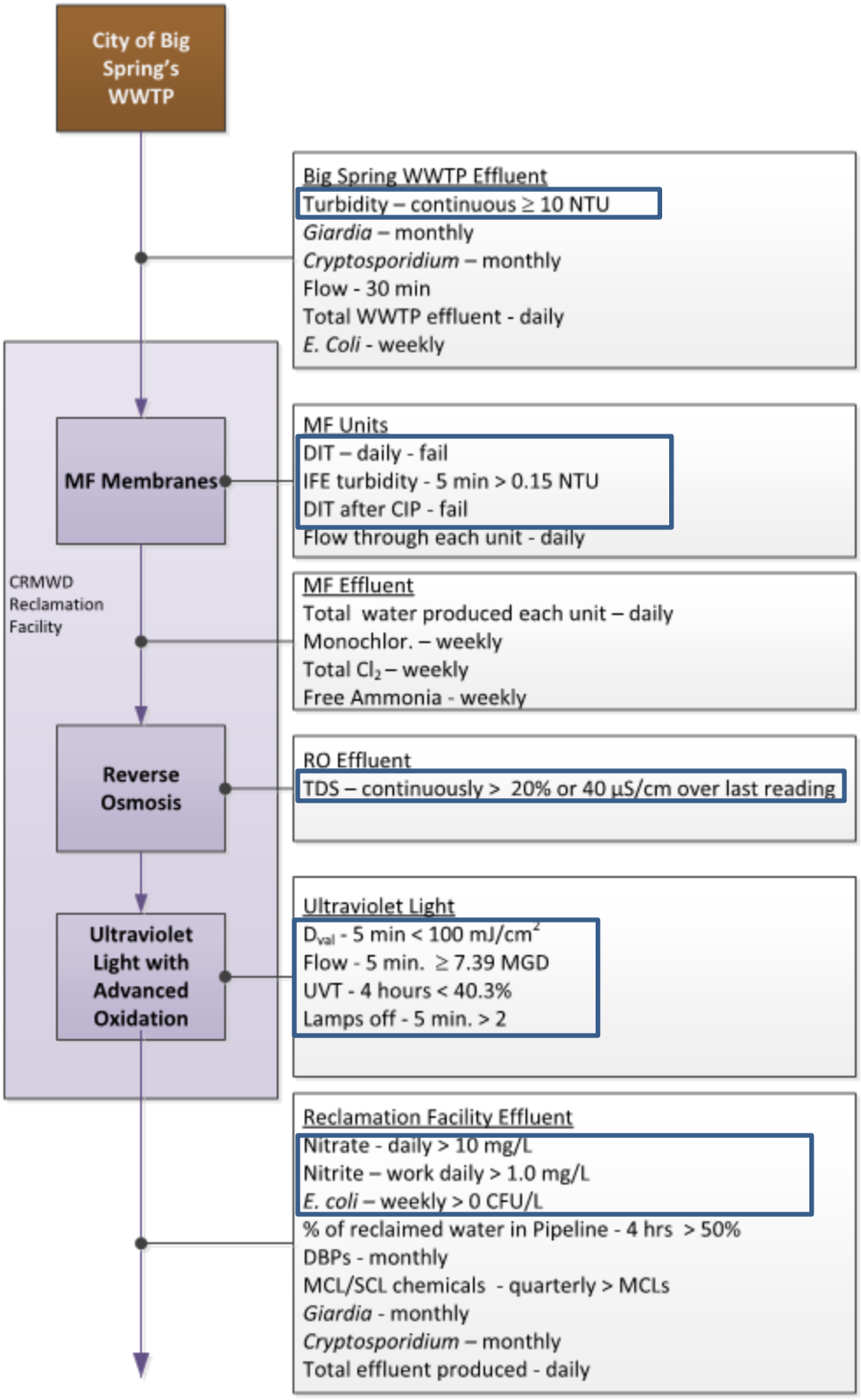


Figure 5.2 Required monitoring for raw water production facility. (Graphic as provided by TCEQ).

5.3 Recommended Standard and Additional Monitoring Methods

Table 5.2 summarizes the recommended monitoring methods for DPR projects. Standard methods are the methods in place at most advanced treatment facilities. The table's last column lists proposed and recommended monitoring methods that are not yet routinely included in potable reuse projects, and may be at varying stages of development or validation.

The RWPF's monitoring approach represents a solid, defensible approach to monitoring an advanced treatment facility, covering most of the recommended "standard" monitoring methods listed in Table 5.2. This study provided additional research and testing for some of the "additional" methods listed in Table 5.2. Further research and testing were done to advance the methods' application in future potable reuse projects. As described in Section 4.6, this application could increase confidence in the treatment processes for current and future projects and could reduce treatment redundancy and its associated cost.

Looking at the DPR system as a whole, Table 5.2 also lists some proposed monitoring concepts for processes upstream of the advanced treatment facility. These concepts include collection system monitoring for enhanced source control, and identifying CCPs at the WWTP for controllable parameters that affect downstream water quality related to potable reuse. Such parameters might include a minimum solids retention time (SRT) criterion, active status of tertiary filters (are they in use or being bypassed?), or a disinfectant residual range that balances an appropriate level of wastewater disinfection with the need to limit disinfection byproduct formation for downstream potable applications.

Finally, Table 5.2 also provides monitoring recommendations for other treatment processes that might be used in advanced treatment facilities, such as chlorine, ozone, and biologically active filtration (BAF).

Table 5.2 Monitoring Approaches for Advanced Treatment Processes

CCP	Monitoring Parameter	Standard Methods	Additional Methods
Upstream Processes (several CCPs possible)	• Goal: Influent meets assumptions used to develop treatment goals	• Currently none	• Collection system monitoring (metals, organics, flow) • WWTP disinfectant residual (if applicable) • WWTP filters operating (if applicable) • Online toxicity monitors
Influent	• Upstream water quality • Influent meeting assumptions used to develop treatment goals	• **Online turbidity** • **Flow**	• TOC for baseline monitoring • Online monitoring of *E.* coli
MF/UF	• Protozoa log removal (MF and UF) • Bacteria removal • Solids removal (turbidity)	• **Pressure Decay Test (PDT, online) determines membrane integrity** • **Online turbidity, recorded frequently**	• **Filtrate particle counts (bench top) and/or reduction of particles across MF membranes** • Trend PDT data to forecast membrane repair needs

Table 5.2 Monitoring Approaches for Advanced Treatment Processes (continued)

CCP	Monitoring Parameter	Standard Methods	Additional Methods
RO	• Pathogen log removals • Salinity • Bulk and trace organic constituents	• **Reduction of electrical conductivity (EC, online) across RO** • Reduction of total organic carbon (TOC, online) across RO	• UV absorbance (UVA, online) • **Online or periodic injection and monitoring of fluorescent dye, such as Trasar**.
UV	• Pathogen log removals • NDMA	• **UV dose, which is a function of online UV transmittance (UVT), flow, and UV lamp intensity (UVI)**	• **Periodic measurement of chloramine destruction** with the H_2O_2 off. This test would confirm a high UV dose delivery. • Chloramine destruction can be correlated to the UV dose control algorithm, improving online dose estimation accuracy.
UV/AOP	• Selected organic constituents (e.g., 1,4-dioxane)	• Electrical Energy per Order of Magnitude (EEO) method	• Oxidant weighted UV dose (online) • Oxidant dose (peroxide, e.g.) • UV dose monitoring (using chloramine destruction) to provide confidence in the AOP treatment.
ESB[2] with Chlorine	• Pathogen log removals, mainly virus	• Online Cl_2 residual, also pH, temperature, and flow (Ct concept)	
O_3	• Pathogen removal (virus, *Giardia*)[3] • Trace and bulk organic constituents	• Online O_3 residual (Ct concept)	Applied ozone-dose based: • O_3/TOC ratio • Ratio of O_3 to total initial ozone demand (e.g., TOC + nitrite)
BAF	• Pathogen removal, especially protozoa • DBPs	• No current industry standard for performance monitoring	Under investigation: • TOC reduction across BAF • UVT increase across BAF • ATP

Note:
1 Bolded methods are used at RWPF (Standard Methods) or were tested for this study (Additional Methods)
2. Engineered Storage Buffer (ESB)
3. Log removal credit is not anticipated for ozone if no residual is maintained. However, studied conducted as part of WE&RF 11-02 (Trussell et al, 2016) indicate that significant virus inactivation is achieved well before any measurable residual can be measured.

Additional information about monitoring, operations, and maintenance for DPR facilities can be found by contacting the Water Environment and Reuse Foundation, which has several research projects ongoing on these topics.

6 Conclusions

Samples collected in the study unequivocally showed that the RWPF produces water of very high quality. In fact, the water is more than sufficient to serve as a raw water source that is blended with other, conventional raw water sources before being retreated in conventional water treatment plants served by the CRMWD.

6.1 Summary of Testing Results

TCEQ-required compliance testing (Appendix C) already addresses parameters with regulatory limits. For this study, none of the parameters were exceeded. In fact, except for two analytes (TTHMs and nitrate), regulated constituents were either not detected or were present in the product water at concentrations at least a factor of 10 below their regulatory limits.

In addition, grab sampling for constituents of emerging concern (CECs) and disinfection byproducts (DBPs), shown in Appendix A, indicate that concentrations in the RWPF plant *influent* are below health-based benchmarks defined by a national panel of experts, except for TTHMs and HAA_5, which represent the two groups of regulated conventional disinfection byproducts. The RWPF reduces these concentrations such that product water concentrations are well below regulatory limits.

While product water from the plant contained several measureable concentrations in the ng/L range, with insignificant exceptions, CECs were lower than background concentrations of the same CECs measured in the conventional surface water, as sampled at Moss Creek Lake.

Pathogen testing yielded equally clear results: Protozoa (*Giardia* and *Cryptosporidium*) and bacteria (*E. coli*) were not detected past the first treatment process (microfiltration). Not a single sample collected at the RWPF tested positive for enteric virus.

In fact, in conjunction with the (minimum) 4-log virus inactivation provided by the UV reactors, sampling of the RO permeate confirmed that the water meets finished drinking water standards for virus. A similar argument can be made for *Cryptosporidium* and *Giardia*, since none were detected (< 0.1 (oo)cyst per L) after the microfilters and an additional 6-log of inactivation is credited to the UV system.

Surrogate testing provided more insight into ways to improve confidence in the treatment process. Monitoring influent turbidity cannot account for every spike in pathogen concentrations. However, it does provides a useful tool for evaluating upstream WWTP treatment.

For the MF process, effluent turbidity monitoring and particle size distribution testing increased confidence in the integrity of the membranes. To measure direct integrity, these tests should be done more frequently than pressure decay tests.

For the RO membranes, 3D TRASAR® is a promising off-the-shelf technology for monitoring membrane integrity and could be applied at the RWPF or other DPR facilities to demonstrate pathogen LRV. In Texas and in other states, Nalco is pursuing additional demonstration work so regulators can approve the technology as an integrity monitor.

For UV/AOP, chloramines removal correlated excellently with UV dose (in the absence of H_2O_2 addition) based on this study and previous studies. Because the relationship between UV dose and pathogen inactivation is well established, chloramines removal can be a good surrogate to

confirm ongoing UV inactivation of pathogens and the UV dose needed for effective UV AOP operation.

Conversely, no correlation was established at the RWPF between UV dose and NDMA destruction. This lack of correlation was because of the low NDMA concentrations in the feed to the UV system. Although not ideal for a system monitoring analysis, the low NDMA levels are a positive result for water quality.

6.2 Looking Ahead to Future Direct Potable Reuse Facilities

Based on the results of this and several concurrent pilot investigations, including the one recently completed by El Paso Water Utilities (Russell, 2016), DPR projects that employ the "standard" advanced treatment processes used at the RWPF (MF, RO, and UV/AOP), the constituents closest to exceeding regulatory limits in drinking water are inorganic nitrogen species (nitrate and potentially nitrite) and DBPs. A similar result was found from a desktop risk assessment described in the DPR Resource Document (APAI, 2015).

Thus, along with providing an adequate level of pathogen inactivation, nitrogen species and DBPs should be highlighted while evaluating treatment and monitoring processes for any DPR project. Treatment for both of these chemical constituent groups is most effectively addressed not during advanced treatment, but by carefully considering the upstream wastewater treatment processes. Nitrate and nitrite can be removed very effectively during secondary or tertiary treatment if that process is designed and operated appropriately. DBP formation could be mitigated by selecting alternative disinfectants or by bifurcating the process train between wastewater disinfection for disposal and advanced treatment for potable reuse before the final chlorination step.

More generally, when considering existing and future DPR facilities, it is important to consider upstream effects on the advanced treatment system. Important measures to consider include enhanced source control with potential collection system monitoring, design integration with water reclamation facilities, and careful consideration of the operational standards and philosophies at these upstream facilities as they transition from waste management facilities to the first steps in a system that produces drinking water.

Beyond treatment process considerations, monitoring approaches for DPR projects should be considered during the design of the advanced treatment facilities. In addition to end-of-pipe testing to confirm water quality, a monitoring program should include measures that will alert operators to any issues in real time. Both the approaches to monitoring as well as the technology and tools available to perform this type of monitoring are evolving rapidly, and future DPR projects should therefore include a review of current advanced monitoring approaches.

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