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Building-Scale Treatment for Direct Potable Water Reuse and Intelligent Control for Real Time Performance Monitoring Project (PureWaterSF)

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Prepared for the Bureau of Reclamation Under Agreement No. R17AC00002

by

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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PureWaterSF represents the combined efforts of the San Francisco Public Utilities Commission (SFPUC), the Desalination and Water Purification Research and Development Program, Bureau of Reclamation, the Water Research Foundation (WRF), Woodard & Curran (WC), and Carollo Engineers, Inc. (Carollo). Extensive assistance was provided by the SFPUC's engineering, operations, and maintenance staff. Their contributions are greatly appreciated.

Acronyms and Abbreviations

Acronym or Abbreviation	Definition
AOP	Advanced oxidation process
AWTF	Advanced water treatment facility
AWTO	Advanced water treatment operator
BAC	Biologically active carbon
BAT	Best available technology
BW	Backwash
Carollo	Carollo Engineers, Inc.
CCP	Critical control point
CIP	Clean-in-place
CRMWD	Colorado River Municipal Water District
CWRF	Cabezon Water Reclamation Facility
DBP	Disinfection byproduct
DDW	Division of Drinking Water
DOC	Dissolved organic carbon
DIT	Direct integrity testing
DPR	Direct potable reuse
EC	Electrical conductivity
ESCP	Enhanced source control program
FAT	Full advanced treatment
GMF	Granular media filtration
GWRS	Groundwater replenishment system
HACCP	Hazard analysis critical control point
IPR	Indirect potable reuse
LASAN	Los Angeles Sanitation
LESA	Lightweight expanded shale aggregate
LM	Living Machine
log	Logarithm
LRV	Log removal value
MC	Maintenance cleaning
MF	Membrane filtration
MFGM	Membrane Filtration Guidance Manual
MIT	Membrane integrity test

NA	Not available
NL	Notification level
NMED	New Mexico Environment Department
O&M	Operations and maintenance
OCP	Operational control point
OCWD	Orange County Water District
ORP	Oxidation-reduction potential
PDT	Pressure decay test
PVDF	Polyvinylidene fluoride
Q	Flow
QMRA	Quantitative microbiological risk assessment
Reclamation	Bureau of Reclamation
RO	Reverse osmosis
RP	Regional priority
RWPF	Raw water production facility
SB	Senate Bill
SBS	Sodium bisulfite solution
SFPUC	San Francisco Public Utilities Commission
SWTP	Surface water treatment plant
TI AWPF	Terminal Island Advanced Water Purification Facilities
TMP	Transmembrane pressure
TOC	Total organic carbon
UF	Microfiltration
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
UVI	UV intensity
UVT	Ultraviolet transmittance
WE	Water efficiency
WRF	Water Research Foundation

Measurements

Unit or Abbreviation	Measurement
%	Percent
°C	Degrees Celsius
°F	Degrees Fahrenheit
µm	Micrometer/micron
µS/cm	Microsiemens per centimeter
ft^2	Square feet
gfd	Gallons per day per square foot
gpm	Gallons per minute
mg/L	Milligrams per liter
mgd	Million gallons per day
NTU	Nephelometric Turbidity Units
ppm-hr	Parts per million per hour
psid	Pounds per square inch differential
psi/min	Pounds per square inch per minute
W/m^2	Watt per square meter

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Executive Summary

Potable water reuse systems, whether centralized or decentralized, need to provide consistent high-quality water produced from a multiple barrier treatment system. In the United States, potable reuse projects have successfully produced high-quality water from a range of treatment systems from about 1 million gallons per day (mgd) to more than 100 mgd. This project adds to the body of knowledge for demonstrated project successes as it addresses the challenges of operating and maintaining small and decentralized purification systems.

The San Francisco Public Utilities Commission (SFPUC) is a leader in the innovative and sustainable use of water in an urban setting. Currently, SFPUC uses a constructed wetland system to treat the wastewater generated in its headquarters building for non-potable reuse. PureWaterSF added to the existing system a demonstration direct potable reuse (DPR) building-scale treatment process that included ultrafiltration, reverse osmosis, and an ultraviolet advanced oxidation process (UF/RO/UV AOP) to purify the tertiary recycled water effluent from the wetland system. The treatment train, which treats approximately 80 percent of the water from the wetland system, was designed to have a small footprint and produce high-quality water that is able to meet drinking water standards. The treated water is redirected to the non-potable reuse system for toilet flushing in the SFPUC headquarter building.

Over 9 months, PureWaterSF continually monitored the process using real-time monitoring tools. This project examined the precision, accuracy, and overall reliability of these tools to document the performance of the advanced water purification facility. The results from the PureWaterSF project build on a body of knowledge for potable reuse systems and provide valuable information about the reliability of advanced water treatment systems and ability to monitor for target parameters.

1. Potable Water Reuse

There are different types of potable water reuse applications, both in the U.S. and globally, including:

1. Unplanned Potable Water Reuse: Unplanned potable reuse, often identified as de facto potable reuse, occurs when downstream surface waters subject to upstream wastewater discharges are used as a source of drinking water. As defined by NWRI (2015), "unplanned potable reuse is a common occurrence in many drinking water supplies derived from surface water supplies, principally rivers, and has been understood for at least 100 years, although the practice is not recognized officially."
2. Groundwater Augmentation: These applications send purified water to a groundwater basin (through surface spreading or injection) which is later extracted from the ground, further treated, and sent to the public for consumption.
3. Reservoir Water Augmentation: These applications send water to a surface water reservoir; the water is later treated by a surface water treatment plant (SWTP) and then sent to the public for consumption.
4. Raw Water Augmentation: These applications send purified water directly to an SWTP to be further treated and sent to the public for consumption.
5. Treated Drinking Water Augmentation: These applications send purified water directly to the distribution system for distribution to the public for consumption.

The applications described in items 1 and 2 above both utilize an environmental buffer prior to subsequent capture, treatment, and use. This kind of potable reuse is often referred to as Indirect Potable Reuse (IPR). Potable reuse without an environmental buffer (items 3 and 4 above) is referred to as Direct Potable Reuse (DPR). With one exception, potable water reuse projects across the United States are IPR projects, utilizing either a groundwater basin or surface water body prior to use of the water by the public.

For all of these systems, the combination of different elements (e.g. treatment, monitoring, environmental buffer) is used to result in a comparable level of public health protection. There are different ways to purify water for potable water reuse. For the project described in this report, the project team focused on the use of membranes and advanced oxidation to purify wastewater treatment plant effluent (e.g., microfiltration or ultrafiltration (MF/UF), reverse osmosis (RO), and ultraviolet light with and advanced oxidation process (UV AOP)) and treating the water to U.S. Environmental Protection Agency (USEPA) drinking water standards, even though the water is only used for non-potable use.

Potable reuse projects using MF/UF, RO, and UV AOP, which are the processes used for the PureWaterSF project described in this report, have been successfully implemented in the United States and have been shown to be protective of public health. Example operating potable reuse projects, including projects with MF/UF, RO, and UV AOP (all centralized projects) are shown in Table 1.

Table 1. Example Operational Groundwater Augmentation Potable Reuse Projects.

Agency	Project Name	Facility Start-up	Potable Reuse Type[1]	Current Treatment (beyond secondary)[2]	Capacity (mgd)
Los Angeles County Sanitation Districts, Water Replenishment District, Los Angeles County Department of Public Works	Montebello Forebay Groundwater Recharge Project	1962	Groundwater Augmentation: Spreading	Tertiary (GMF, disinfection)	50
Orange County Water District	Groundwater Replenishment System	1975 (original), 2008 (current configuration)	Groundwater Augmentation: Spreading, Injection	Purification (MF, RO, UV AOP)	100
West Basin Municipal Water District	West Coast Basin Seawater Intrusion Barrier	1992	Groundwater Augmentation: Injection	Purification (MF, RO, UV/H_2O_2)	17.5
Inland Empire Utilities Agency	Chino Basin	2005	Groundwater Augmentation: Spreading	Tertiary (GMF, disinfection)	19
Water Replenishment District	Alamitos Barrier	2005	Groundwater Augmentation: Injection	Purification (MF, RO, UV/H_2O_2)	10
Los Angeles Bureau of Sanitation	Terminal Island/ Dominguez Gap Seawater Intrusion	2006	Groundwater Augmentation: Injection	Purification (MF, RO, UV AOP)	12

Agency	Project Name	Facility Start-up	Potable Reuse Type[1]	Current Treatment (beyond secondary)[2]	Capacity (mgd)
	Barrier				
Water Replenishment District	Albert Robles Center	2019	Groundwater Augmentation: Spreading Injection	Purification (UF,RO,UV AOP)	9
				TOTAL	217.5

[1] Spreading or surface spreading involves augmenting groundwater with tertiary treated recycled water via spreading basins, followed by soil aquifer treatment; injection refers to augmenting groundwater with purified water treated via full advanced treatment..

[2] GMF is granular media filtration; MF/UF is microfiltration/ultrafiltration; RO is reverse osmosis; UV AOP is ultraviolet disinfection advanced oxidation process; UV/H_2O_2 is ultraviolet/hydrogen peroxide.

1.1. Example Potable Reuse Projects

Examples of centralized potable reuse projects are briefly reviewed in the following subsections, including those that use the MF, RO, and UV AOP treatment train and those that use non-RO based treatment trains.

1.1.1. Orange County Water District

The Orange County Water District's (OCWD's) Groundwater Replenishment System (GWRS) is the world's largest potable water reuse project, with a daily production of 100 million gallons of purified water which is injected into the local groundwater basin. Since starting up in the late 1970s, this project has injected more than 188 billion gallons of purified water into the groundwater basin, later to be extracted for potable water use. OCWD is currently expanding the GWRS to a total production of 130 mgd; construction began in 2019.

1.1.2. Terminal Island Advanced Water Purification Facility

The Los Angeles Sanitation (LASAN) Terminal Island Advanced Water Purification Facilities (TI AWPF) provides highly purified water to recharge the Dominguez Gap Barrier. The facility has been recently expanded to 12 mgd, including the addition of the world's first UV AOP using sodium hypochlorite. The project's expansion allows TI AWPF to continue supplying water to the Dominguez Gap Barrier and to supply reclaimed water to Harbor Area industrial users and replenish the evaporation losses at Lake Machado.

1.1.3. VenturaWaterPure

The goal of the City of Ventura and Ventura Water's VenturaWaterPure demonstration facility was to document the high quality of purified reclaimed water through extensive water quality testing, and to understand the impact of blending this purified water with the conventional finished potable water, which is a type of direct potable reuse (DPR). Additionally, this demonstration facility provided an educational opportunity for the community, allowing the public to see the processes and taste the purified water.

The VenturaWaterPure system, now in the early phases of design, will have multiple barriers for both pathogens and trace pollutants in excess of the treatment required for groundwater augmentation (IPR) in anticipation of future DPR. With IPR in the near term, the 4 mgd future purification process will utilize ozone, biologically active carbon (BAC), UF, RO, and UV AOP for IPR. For DPR, engineered storage would be added along with advanced monitoring and a polishing water treatment plant (free chlorination and membranes) prior to public consumption.

1.1.4. Gwinnett County, Georgia

Gwinnett County, Georgia is an industry pioneer in non-RO based potable water reuse. Along Gwinnett County's northern border lies Lake Lanier, the County's sole source of drinking water. Gwinnett County owns and operates the F. Wayne Hill Water Resources Center, one of the world's largest membrane (low pressure, not RO) and ozone (O_3) facilities. Multiple advanced technologies treat wastewater to near drinking water standards, including O_3 and BAC. Gwinnett County returns this highly treated water to Lake Lanier and the Chattahoochee River, which is a source of drinking water for downstream users. More details on the Gwinnett County potable reuse program can be found at https://watereuse.org/educate/profiles-in-reuse/global-connections/.

1.1.5. Rio Rancho New Mexico

Rio Rancho Pure (Rio Rancho New Mexico) represents a critical first potable reuse project in New Mexico and the first O_3/BAC system nationally used for purification and groundwater recharge. The advanced water treatment facility (AWTF) project utilizes a membrane bioreactor (MBR) at the Cabezon Water Reclamation Facility (CWRF), followed by O_3/BAC purification and groundwater recharge. The AWTF is designed to produce 1 mgd for groundwater recharge. This system – MBR, O_3, BAC – provides for multiple barriers for pathogens and chemical pollutants and meets all New Mexico Environment Department (NMED) standards.

1.1.6. Altamonte Springs Florida

The City of Altamonte Springs is a leading utility in water conservation and innovation in Central Florida. Continuing the history of employing sustainable water supply programs, the City embarked on a journey to explore DPR in an effort to plan for future sources of safe drinking water. This effort led to the design and construction of a permanent demonstration pilot system (approximately 20 to 30 gpm), "pureALTA," that demonstrates the successful operation of a treatment train for DPR.

The pureALTA project focused on purification without reverse osmosis, relying on O_3, BAC, ultrafiltration, granular activated carbon, and high dose UV for purification. Extensive testing results documented the robust nature of the technologies and the ability to destroy and/or remove all regulated chemical and microbial pollutants, as well as many unregulated contaminants.

1.2. Centralized Versus Decentralized – Comparison and Challenges

1.2.1. Value of Decentralized Treatment

1.2.1.1. General Industry Perspective

Decentralized treatment for water reuse has long been recognized as having significant potential benefits, including:

- The ability to source and produce water locally from a sustainable supply, i.e., wastewater; and
- The ability to implement reuse without needing substantial infrastructure to move the water, reducing the cost and energy associated with distributing recycled water from a central location.

The challenges to broader decentralized reuse are primarily:

- Cost of treatment, as large treatment systems have an economy of scale whereas small systems can have relatively high treatment costs for the amount of water produced;
- Costs of operation, as even very small water reuse systems require highly skilled operations and maintenance staff; and
- Regulations, because the industry has, with a few notable exceptions (e.g., San Francisco Public Utilities Commission), typically encouraged large centralized facilities for water reuse.

An extensive summary of the costs, benefits, and challenges of decentralized water reuse can be found in Salveson et al. (2009).

1.2.1.2. Building-Scale Decentralized Treatment

Building-scale water reuse can have significant benefits for utilities, building owners, and communities. Many buildings with onsite water reuse systems generate environmental and community benefits by integrating elements that increase urban greening, such as rain gardens, wetlands, and green roofs. In some cases, these serve as essential components of an onsite treatment process. These amenities can help manage stormwater, improve liveability of the urban environment, create public open space, reduce heat island effects, and defer capital investments in aging centralized infrastructure. Incorporating innovative onsite reuse systems also provides an opportunity to gain points toward LEED certification and significantly reduce buildings' potable water consumption.

In the summer of 2012, the San Francisco Public Utilities Commission (SFPUC) completed construction of its new, 277,500 square-foot headquarters at 525 Golden Gate Avenue in San Francisco's Civic Center District. The LEED Platinum building, housing approximately 950 employees, contains two onsite water systems – a Living Machine® and a rainwater harvesting system. The Living Machine® treats all of the building's wastewater, generally 4,000 to 6,000 gallons per day, and then distributes the treated water for toilet flushing. The system provides an annual potable offset of approximately 1,500,000 gallons, using a series of engineered wetlands located in the sidewalks surrounding the headquarters and in the building lobby to treat the wastewater.

From the beginning of the planning stage for the building, the SFPUC's goal was to have a headquarters that would demonstrate the agency's ambitious sustainability goals and serve as an example for building smart, efficient, and sustainable buildings. Implementing the onsite water systems allowed the headquarters to obtain additional LEED points towards LEED Platinum certification. The project received an additional six Water Efficiency (WE) points and two Regional Priority (RP) points by implementing the systems.

1.2.2. Comparisons Between Centralized and Decentralized Treatment

Potable water reuse systems, whether centralized or decentralized, demand consistent high-quality water produced from a multiple barrier treatment system. These systems must be monitored using both continuous online measurements and periodic grab samples to ensure that the water quality is protective of public health. The Framework for Direct Potable Reuse (NWRI 2015) and the 2017 Potable Reuse Compendium (USEPA 2017) outline a number of important components for successful potable water reuse projects, including:

1. A raw wastewater Enhanced Source Control Program (ESCP) to monitor and control chemical discharges from industrial and other sources;
2. An equalized flow through the wastewater treatment plant to minimize the wear and tear on equipment as well as to better produce a consistent and high-quality effluent;

3. A moderate- to high-quality biological wastewater treatment process to minimize downstream challenges to the Advanced Water Purification Facility (AWTF);
4. A clear understanding of pathogen concentrations, the level of treatment required, and the subsequent risk to public health;
5. Robust multiple barrier treatment systems;
6. Accurate and precise monitoring of treatment performance, allowing for water quality confidence; and
7. A well-trained operations and maintenance staff.

As shown previously, industry success in potable water reuse is based on large municipal projects ranging from approximately 1 mgd to >100 mgd. Many of these larger AWTFs, such as Orange County Water District's GWRS, are viewed worldwide as exemplary projects. As focus turns toward smaller and decentralized potable water reuse, such as at the building or neighborhood scales, projects must consider the unique challenges that may exist at this scale. The project described in this report examines some important differences between centralized and decentralized reuse, highlighting that, for the most part, decentralized systems face more challenges than centralized systems (Table 2). The sister project funded by the Water Research Foundation (WRF) under Agreement No. 04691 (WRF 4691) was completed in parallel with this Reclamation grant-funded project, using the same equipment and staff and examining several other key issues.

Table 2. Technical Issues Confronting Centralized and Decentralized AWTFs.

Issue	Large Centralized AWTF	Small Decentralized AWTF	Systems Facing the Greatest Impact/Risk
Source Control for Chemical Discharges	Centralized AWTFs can have a wide range of industries discharging challenging and hazardous materials into the wastewater collection system.	Decentralized AWTFs in a building have only municipal waste with a small amount of cleaning chemicals, which can be tightly controlled. Neighborhood-sized AWTFs can also tightly monitor and control industrial discharges.	Centralized systems
Wastewater Flow	Centralized AWTFs typically have some lower baseline of flow even during the night, along with some form of equalization. Centralized AWTFs can often be run as constant production facilities.	Decentralized AWTFs have highly variable flow and equalization is necessary to maintain constant flow. Without equalization, the on/off cycles impact system operational efficiency and put excess wear on the equipment.	Decentralized systems
Raw Wastewater Quality	Centralized facilities pull wastewater from large sewer-sheds, which include municipal waste combined with groundwater infiltration, stormwater (in some cases), industrial flows, and substantial amounts of wash waters (showers, laundry, etc.). The result is a fairly dilute waste stream.	Decentralized facilities can have highly concentrated organic waste, in particular for building-level purification in which the majority of wastewater is from toilets and urinals used only on weekdays. Neighborhood-level facilities may be influenced by many of the same diluting factors as large centralized facilities, depending on local factors and the age of the surrounding infrastructure.	Decentralized systems, in particular at the building scale
Wastewater Pathogens	Illnesses can vary throughout the year within a large community, but available data suggest some level of consistent background pathogen levels in municipal wastewater (Salveson et al. 2018) without large spikes in pathogen concentrations. Essentially, the large collections tend to equalize pathogen numbers for centralized facilities.	Little is known about the variations in pathogens in small systems, in particular at the building scale. From a public health perspective, the main concern would be high pathogen concentrations during periods of high illness within a building. Large spikes of pathogens in wastewater could lead to an outbreak if potable reuse is implemented without sufficient treatment barriers to handle such pathogen spikes.	Decentralized systems, in particular at the building scale
Wastewater Treatment	Centralized wastewater treatment plants typically have long track records of performance and regulatory compliance. Biological treatment systems are typically robust and engineered with a degree of conservatism (related to both capacity and organic loading). Many centralized wastewater treatment plants include nutrient removal and can produce a high quality secondary effluent which is ideal for downstream advanced treatment and purification.	Decentralized treatment systems have several challenges related to wastewater treatment. First, they are typically space-limited, so technology choices may focus on footprint and compact design instead of Best Available Technology (BAT). Second, decentralized treatment at a small scale is much more costly (per gallon treated) than centralized systems (Salveson et al. 2010). The result is a drive to reduce the capital and O&M cost of treatment for such decentralized systems, which can result in less robust and less redundant treatment systems.	Decentralized systems
AWTF Treatment Systems	Centralized AWTFs have been demonstrated to provide consistent treatment from one facility to the next. The use of membrane based systems (MF/UF, RO, UV AOP) has in particular shown consistent high quality finished water. The engineering industry understands how to design and construct these larger AWTFs.	Decentralized AWTF systems, in particular at the building scale, do not have a record of performance. At the low end flow range, the membrane based systems are typically “off-the-shelf” and not custom engineered, resulting in systems that can be either undersized or oversized for a particular application. The resulting treatment, operations, and water quality impacts have yet to be documented.	Potentially decentralized systems
AWTF Monitoring	Online monitoring systems for each key treatment process are critical for water quality confidence and regulatory approval. These monitoring systems can be delicate and result in numerical drift and need for frequent calibration and care. Centralized AWTFs have substantial staff dedicated to monitoring system performance (instrumentation technicians), thereby maintaining online equipment at or near optimal level with a high level of staff effort.	Decentralized systems require the same monitoring systems and the same level of support as large centralized systems, noting that larger systems may need more of each monitor in some cases. The challenge for decentralized systems is the disproportionate level of overall effort (staff hours per gallon produced) to maintain monitoring systems.	Decentralized systems
Operator Skills and Training	Regardless of size, potable reuse projects require the highest level of trained operations staff for operation. These Advanced Water Treatment Operators (AWTOs) must understand wastewater treatment, water treatment, advanced treatment systems, and regulatory issues. The California/Nevada AWWA and the Water Research Foundation have worked to develop and establish both AWTO standards and certification tests (CA/NV AWWA 2017) and AWTO training materials (Walker et al. 2016). Large established treatment plants have a broad range of talented operations and maintenance staff and the budget to train these staff to AWTO status.	Decentralized systems require the same caliber of O&M staff for successful potable water reuse production, placing a higher relative cost burden on smaller systems versus larger systems.	Similar for both

1.3. Movement Toward Direct Potable Reuse

This project focuses on DPR (as opposed to IPR) at the building scale. For perspective, there are two centralized DPR facilities currently operated worldwide. The first is in Windhoek, Namibia, which is a treated water augmentation project where the purified water is fed directly into the potable water distribution system. The second is in Big Spring, Texas, which is a raw water augmentation project where the purified water is blended with other raw water supplies and fed to a surface water treatment plant (SWTP). These projects have site-specific permits and treatment requirements set forth by regional regulatory agencies.

1.3.1. Colorado River Municipal Water District, Texas

The Colorado River Municipal Water District (CRMWD) is a regional water agency in Texas, serving the cities of Big Spring, Odessa, Snyder, and others, with a current combined population of about 500,000. Extreme drought in Texas led the CRMWD to construct the Raw Water Production Facility (RWPF) in Big Spring, Texas. The RWPF started operating in May 2013 with a steady production capacity of 2 mgd. The RWPF uses the same advanced treatment processes as OCWD's GWRS: MF, RO, and UV AOP. After purification, the water from the RWPF is fed into a raw water supply line which blends with other raw water (up to 50 percent) and is then subjected to treatment at a standard water treatment plant (media filtration and chlorine disinfection). The City of Big Spring's SWTP is the first downstream user to withdraw from the pipeline. The cities of Snyder, Odessa, Stanton, and Midland also operate SWTPs that take water downstream of that pipeline. A two-year evaluation of the CRMWD Big Spring facility, funded by the State of Texas and completed by Carollo Engineers, Inc. (Carollo), affirmed the water quality and performance of that facility (Steinle-Darling et al 2016).

1.3.2. DPR Regulatory Progress in the United States

No uniform regulations have been established within the State of California or nationally for DPR. However, substantial regulatory guidance for DPR has been completed on the national level (NWRI 2015) and on the state level in: New Mexico (NWRI 2016); Texas (TWDB 2015); Colorado (WRCO 2018); and Arizona (NWRI 2018). Florida's DPR regulations are currently under development. Recent legislation in California (AB 574) requires the State Water Resources Control Board to adopt uniform water recycling criteria for DPR through raw water augmentation by 2023. Efforts have been underway in California for a number of years to investigate the feasibility of DPR, and as a result, several documents have been completed which inform the direction of DPR regulations in California:

1. "A Proposed Framework for Regulating Direct Potable Reuse in California." The State Water Board Framework intends to primarily document and communicate the State Water Board Division of Drinking Water's (DDW) current thinking on regulating direct potable reuse in California. The Framework (SWRCB 2018) is not a regulatory document.
2. "Framework for Direct Potable Water Reuse." Funded by the WateReuse Association, American Water Works Association, and Water Environment Federation. This document provides an overview of DPR, identifies key issues that need to be addressed in the development of regulations, and provides step-by-step recommendations on how to safely implement DPR (NWRI, 2015).
3. "Investigation on the Feasibility of Developing Uniform Water Recycling Criteria for Direct Potable Reuse." Required by Senate Bill (SB) 918 in 2010, the California SWRCB is to investigate the feasibility of developing uniform water recycling criteria for direct potable reuse, convene an expert panel to study the technical and scientific issues, and provide a final report to the California State Legislature by December 31, 2016. SB 322 further required that SWRCB convene an advisory group comprised of utility stakeholders to advise SWRCB and its expert panel on the development of the feasibility report. SB 322 also amended the scope of the expert panel to include identification of research gaps that should be filled to support the development of uniform water recycling criteria for DPR. This section includes a summary of the findings from this report.

The key finding of the SWRCB Expert Panel described in item 3 above is as follows: "[It] is technically feasible to develop uniform water recycling criteria for DPR in California, and that those criteria could incorporate a level of public health protection as good as or better than what is currently provided by conventional drinking water supplies and IPR."

The Expert Panel identified several reliability features that should be incorporated into DPR and proposed research recommendations such that the findings from these parallel efforts can be used to inform the development of the criteria. These findings are summarized in Table 3; aspects that were addressed by PureWaterSF are highlighted in italics.

Table 3. SWRCB Expert Panel Reliability and Research Recommendations.

Type of Recommendation	Key Elements of Recommendation
A. Reliability features for incorporation into DPR projects	Objective: Address the absence of an environmental buffer and provide an equivalent level of health protection as IPR. Proposed Reliability Features: 1. *Providing multiple independent barriers and ensuring the barriers represent a diverse set of processes.* 2. Using parallel independent treatment trains. 3. *Incorporating frequent monitoring of surrogate parameters at each step to ensure treatment processes are performing properly.* 4. Providing a final treatment step to attenuate any remaining short-term chemical peaks. 5. Providing diversion of inadequately-treated water. 6. Developing and implementing rigorous response protocols, such as a formal Hazard Analysis Critical Control Point (HACCP) system.
B. Recommendations for non-treatment barriers adopted by SWRCB	**Operation and management:** 1. *Training and certification of operators for potable reuse treatment facilities.* 2. Ensuring that agencies implementing DPR projects have adequate technical, managerial, and financial capacity. **Process:** 1. Wastewater treatment plant optimization for DPR application. 2. Source control program enhancement to minimize discharges of toxic chemicals to sewer systems that feed into DPR treatment plants.
C. Research Recommendations	**Pathogens:** 1. *Generate better empirical dataset by monitoring pathogen concentration and variability in raw wastewater.* 2. Investigate feasibility of collecting raw wastewater pathogen concentration data associated with community outbreaks of disease and implement where possible. 3. Implement quantitative microbiological risk assessment (QMRA) to confirm necessary removal values for viruses, Cryptosporidium, and Giardia based on literature review and pathogen data. **Chemicals:** 1. Perform literature review to identify new compounds that are potential health risks from short-term exposures with a view to improve source control and final water quality monitoring. 2. Identify final treatment process options that can average out potential peaks of persistent chemicals. 3. Develop comprehensive analytical methods to identify unknown contaminants (e.g., low molecular weight compounds) that are currently hard to detect and/or remove.

1.4. Project Needs and Objectives

1.4.1. Needs

As noted above in Table 2, moving from centralized IPR to decentralized DPR presents a number of challenges. This project (Reclamation Grant No. R17AC00002) and its sister project (WRF 4691) look to better understand and address a number of these challenges as shown in Table 4. This Reclamation-funded project focuses on the reliability and value of online sensors and the challenges of decentralized DPR systems.

Table 4. Examples of Decentralized DPR Research Needs.

Issue	Research Needs	Issue Addressed in...
Wastewater Flow	Evaluate the impact of variable flow associated with Building Scale treatment on the short and long term operations of an AWTF.	Reclamation Grant No. R17AC00002[1]
Wastewater Pathogens	Document the concentration and variation of pathogens in raw wastewater at the building scale over a sufficient period of time. Understand the impact on public health risk associated with the pathogen concentrations.	WRF 4691[2]
Wastewater Treatment	Evaluate the impact of variable quality tertiary effluent at the building scale on AWTF.	Reclamation Grant No. R17AC00002
AWTF Treatment Systems	Document the impact of off-the-shelf purification systems compared to custom engineered systems in terms of operations and maintenance as well as water quality.	Reclamation Grant No. R17AC00002 (O&M) & WRF 4691 (Water Quality)
AWTF Monitoring	DPR systems require accurate and precise monitoring, even more so with decentralized systems; examine online monitoring systems to better understand reliability of performance.	Reclamation Grant No. R17AC00002

[1] Reclamation Grant No. R17AC00002USBR: Building-scale Treatment for Direct Potable Water Reuse & Intelligent Control for Real Time Performance Monitoring Project (PureWaterSF) US Bureau of Reclamation Agreement No. R17AC00002.

[2] WRF 4691: Building-Scale Treatment for Direct Potable Water Reuse & Intelligent Control for Real Time Performance Monitoring Project (PureWaterSF) Water Research Foundation Multi-Funded Research Agreement No. 04691.

1.4.2. Objectives

This research project evaluates the reliability of producing consistent purified water at a building scale with advanced water treatment technologies. The research objectives for this Reclamation-funded effort include:

- Demonstration of advanced water treatment and monitoring technologies to reliably convert building-sourced wastewaters into a high quality alternative future drinking water source.
- Use of monitoring tools to provide continuous and real-time treatment system performance data.
- Contribution of data to the growing body of potable water reuse research at a building-scale in California.

1.5. Project Overview

1.5.1. Overall Approach and Concepts

The PureWaterSF system's advanced water treatment train is a proven treatment process that provides multiple treatment barriers for pathogen and pollutant removal. The treatment train is operated to treat 0.9 gallons per minute (gpm) of tertiary effluent from the existing Living Machine® (LM) System, which is approximately 80 percent of the total production capacity of the LM System. The system operates 5 days per week and 24 hours per day. The LM is a full-scale system that treats 100 percent of SFPUC's wastewater from their headquarters building. The water from the LM is used for toilet and urinal flushing in the building.

The AWTF includes UF, RO, and UV AOP (using sodium hypochlorite as the oxidant). Chemical pretreatment includes the addition of ammonium sulfate to form chloramines (added ahead of UF) and antiscalant (added ahead of RO) for scaling prevention. The finished purified water is not consumed. Instead, it is combined with the RO concentrate and sent back to the reuse tank for non-potable reuse (toilet and urinal flushing). The treatment train, including monitoring systems, is presented in Figure 1.

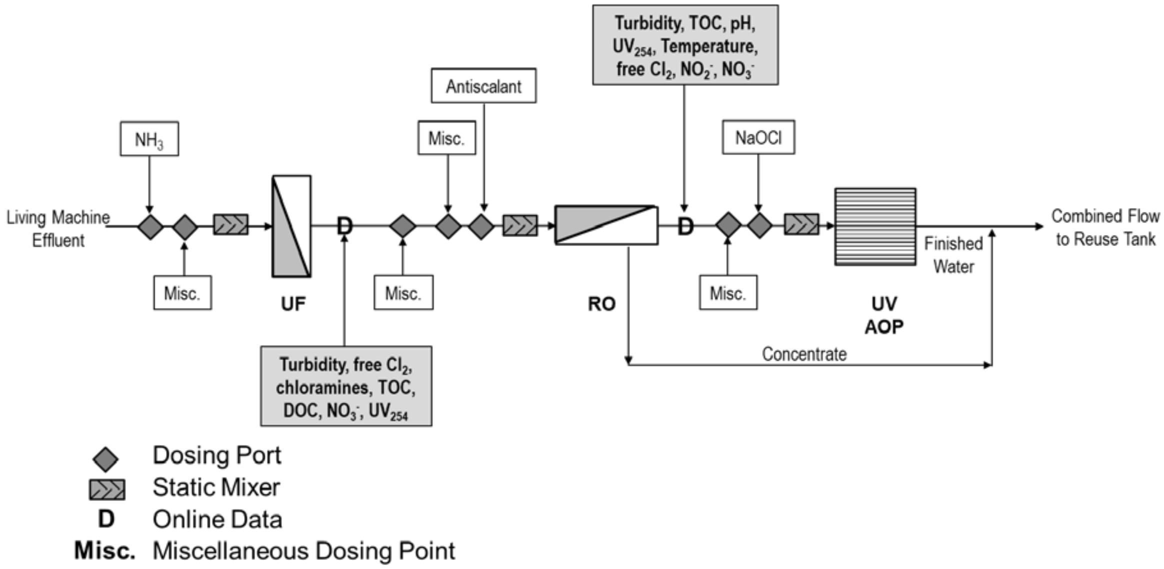

Figure 1. Advanced water treatment train. Sampling ports are included implicitly as part of the treatment processes. Online data are measured with online monitoring.

This project did not produce water for potable consumption and thus did not seek any regulatory credits for pathogen removal or destruction/removal of chemical constituents. With that said, the treatment processes were expected to provide robust treatment, as shown in Table 5.

Table 5. Target Log Removal Values through the AWTF.

Parameter	UF	RO	UV/AOP[1]	Total
Virus	0[2]	1.5[3]	6	7.5+
Protozoa (Giardia & Cryptosporidium)	4	1.5[3]	6	11.5+
NDMA[4]	--	~40% rejection	Typically >90% reduction	--
1,4-Dioxane	--		>0.5-log destruction[5]	--
Trace Pollutants	--	<MRL[6]	<MRL	--

[1] UV/AOP is the combination of a high dose UV system (e.g., 800+ mJ/cm^2) for 6-log pathogen destruction and NDMA photolysis and an oxidant (e.g., hydrogen peroxide or sodium hypochlorite) which results in hydroxyl radical formation when exposed to UV light.

[2] UF is proven to remove virus. Virus rejection ability of the UF in some locations is approved at 1 log credit (NWRI 2015). Various research reports have shown 3+ log reduction of seeded virus by UF (CWS 2014); however, most regulatory authorities will not credit UF with virus removal because of the lack of a daily or real time performance surrogate.

[3] 1.5 log reduction credit based on using electrical conductivity online monitoring. May receive up to 2 log reduction credit using TOC online monitoring. Various research reports have shown 3+ log reduction of seeded virus by RO (Ventura Water 2018; SCVWD 2016).

[4] NDMA is N-Nitrosodimethylamine.

[5] Reduction of 1,4 dioxane by AOP is used as a surrogate for destruction of a broad range of organic pollutants. 0.5 log reduction specified for some types of potable water reuse in California (DDW 2018).

[6] MRL is method reporting limit.

1.5.2. Critical Control Points and Operational Control Points Process Monitoring

Potable reuse trains, such as the long-standing treatment process at the Orange County Water District and others (CWS 2014; Trussell 2013), have repeatedly demonstrated the ability to meet USEPA drinking water and California Division of Drinking Water (DDW) Title 22 standards. For each key treatment process, the project evaluated the performance (and conservatism) of monitoring systems using a critical control point (CCP) philosophy. A CCP is a point in the treatment process where: (1) a human health hazard is reduced, prevented, or eliminated; (2) control can be applied to reduce, prevent, or eliminate process failure; and (3) monitors are used to confirm proper functioning.

For this work, the CCPs are the individual treatment processes – UF, RO, and UV AOP – which provide control for pathogens (including the provision of log reduction credits) and chemical constituents. For each CCP, one or more performance surrogates is used to verify that the process is functioning correctly in terms of controlling public health hazards. Through a combination of treatment system monitoring, CCP control, and overall water quality monitoring, PureWaterSF can have confidence in the quality of the purified water produced from the PureWaterSF demonstration facility. CCPs are supplemented with operational control points (OCP), which are locations within a treatment process that have monitoring and control related to system operational performance and efficiency, but not focused upon public health. Table 6 summarizes the CCPs, their performance surrogates used during this project, and the expected value or removal for each surrogate.

The purification system uses two s::can micro::stations (s::can) to perform advanced water quality monitoring. s::can instruments are spectrometers in the shape of a probe. More information about the s::can can be found in section 2.2.2.

Table 6. PureWaterSF Critical Control Points.

CCP Location	Performance Surrogate	Expected Value	Frequency and Value
UF	• Daily Pressure Decay Test (PDT) • Effluent Turbidity	<0.3 psi/min <0.1 NTU	• Daily correlates with protozoa rejection. • Continuous high turbidity values represent membrane failure.
RO	• TOC removal • EC removal • Nitrate (as Nitrogen) removal	95-99% 95-99% 65 – 85%	• Continuous TOC removal provides confidence in organic chemical removal and RO membrane integrity. • Three times per week EC removal provides confidence in salt rejection and RO membrane integrity. • Continuous nitrate removal provides confidence in RO performance.
UV AOP (NaOCl)	• UVT (UVA) • UV Intensity	>97%[1]	• Continuous UVT data provides information on RO membrane integrity and the impact of chlorine concentrations on water equality, which impact UV dose. • UVI (and flow (Q)), pulled from the UV HMI during times when the system was operational, is used to track dose delivery.

[1] UV Intensity (UVI) values are measured and tracked long-term, and provide for a clear understanding of UV dose maintenance through the use of a simple dose term for this demonstration, UVI/Q.

2. Technical Approach and Methods

2.1. PureWaterSF Components and Relevant Literature

This section summarizes each of the treatment systems used as part of the PureWaterSF demonstration project. It should be noted that the UF, RO, and UV AOP systems used for PureWaterSF were used for demonstration purposes only.

2.2. Design Criteria

2.2.1. Living Machine

The LM system treats the building's wastewater and distributes the treated water back to the building for toilet and urinal flushing. The wastewater is treated through an engineered wetland system located in the building's sidewalks and lobby and provides an average of 5,000 gallons of recycled water per day (3.5 gpm). The process consists of the six steps described below:

1. Primary Tank: The first treatment step occurs in a two-compartment primary tank (trash tank and settling tank) which receives raw sewage. The trash tank removes all coarse materials. The solids are pumped every three months to the adjacent sewer main. The settling tank allows finer solids to settle to the bottom.
2. Equalization & Recirculation Tanks: The primary tank effluent flows to the equalization tank which acts like a buffer tank until the recirculation tank pumps are ready to dose the wetlands.
3. Tidal Flow Wetlands: The wastewater is pumped from the recirculation tank to the tidal flow wetlands, filling the wetlands from the bottom and then draining by gravity back to the recirculation tank. The wetlands are filled with gravel media, called Lightweight Expanded Shale Aggregate (LESA). This media increases the available surface area for biofilm growth. This treatment process consisting of 12 cycles of filling and draining per day.
4. Polishing Vertical Flow Wetlands: After each cycle through the tidal flow wetland, the effluent is pumped from the recirculation tank and distributed to the vertical flow wetlands via perforated pipes near the surface of the LESA, allowing the water to trickle down through the LESA. The vertical flow wetlands remove remaining organic material and nitrogenous compounds.

5. Disinfection: The disinfection process consists of a 50 micron filter, 5 micron filter, ultraviolet system, and chlorination tablet feeder. The filters remove remaining suspended solids and reduce turbidity below 2 nephelometric turbidity units (NTU). The ultraviolet system destroys bacteria and viruses and the chlorination tablet feeder adds a small amount of chlorine residual to the water. Chlorine residual is controlled by an oxidation-reduction potential (ORP) probe inside the recycled water tank.
6. Recycled Water Tank: The treated water is stored until needed for toilet or urinal flushing.

Upgrades to the LM are scheduled to improve the disinfection step (chlorine dosing and UV system), but these improvements will not occur until after the completion of this project.

2.2.1.1. Living Machine Water Quality

A reliable, high-quality feed water ahead of purification is an important component of a successful potable water reuse system (NWRI 2015). The LM information below indicates water quality that is consistent with non-potable recycled water standards, but clearly documents a challenging water for purification due to periodic elevated effluent turbidity and free chlorine.

2.2.1.1.1. Living Machine Effluent Turbidity

Figure 2 shows the maximum daily turbidity of the LM effluent collected between June 2018 and February 2019. The daily maximum turbidity was consistently well below the maximum allowed value of 10 NTU and was generally less than 5 NTU. Turbidity values were reported at levels that did not impact permit compliance but do impact the fouling (and thus cleaning) rate of the UF system**.** The 75th and 90th percentile effluent turbidity values were 2.79 and 3.69 NTU, respectively.

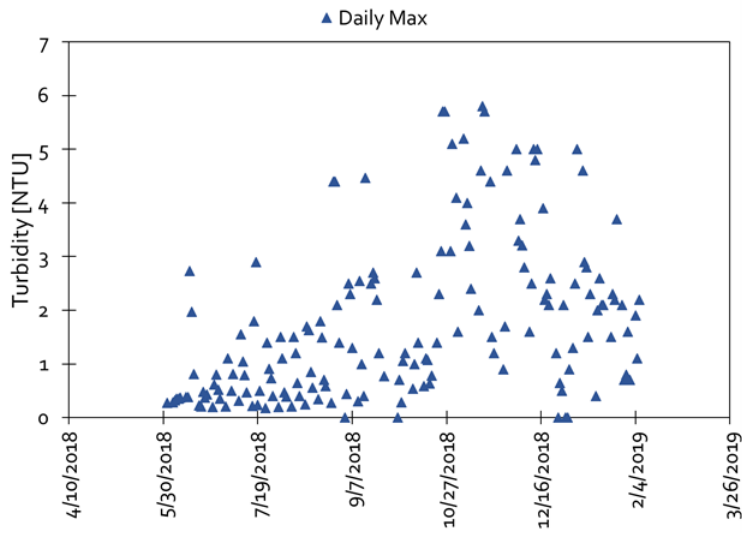

Figure 2. Living Machine Effluent Turbidity.

2.2.1.1.2. Living Machine Effluent Chlorine

The average daily minimum free chlorine residual concentration in the tertiary effluent from June 2018 to February 2019 was 0.82 mg/L, with a daily maximum free chlorine 90th percentile of 4.2 mg/L. Figure 3 shows the free chlorine concentration during the duration of the demonstration project. Spikes in the free chlorine concentration of the LM effluent represented significant challenges to the operation of the PureWaterSF system. Relatively low impact was expected on the UF membrane since the polyvinylidene fluoride (PVDF) membranes are relatively resistant to free chlorine concentrations. However, RO membranes are highly sensitive to the free chlorine concentrations above 0.01 mg/L and, following exposure to free chlorine, will lose their ability to remove salt and other chemical pollutants.

Ammonium sulfate was added ahead of the UF to form chloramines. Ammonium sulfate was dosed at a C:N ratio of 4:1 assuming a concentration of 5.5 mg/L of free chlorine. This was an effort to address unexpected spikes in the free chlorine concentration and avoid RO membrane damage.

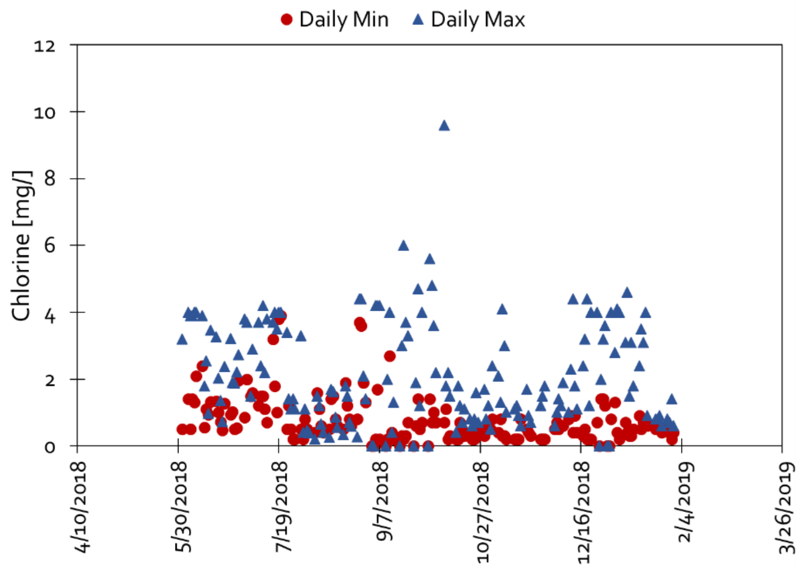

Figure 3. Living Machine Effluent Free Chlorine Concentration.

2.2.2. Online Monitoring

AWTFs typically rely on three instruments to evaluate the water quality in real time for three parameters: turbidity; electrical conductivity (EC); and total organic carbon (TOC). There are probes that can be used to monitor for a broader range of chemical pollutants and surrogates in real time, one of which is from s::can. The s::can instruments are spectrometers in the shape of a probe. In the measuring section, which is positioned between emitting and receiving units, the emitted light passes through the medium to be analyzed. Substances present in the medium located between the measuring windows of the probe absorb visible and UV light. Internally, a second light beam is guided across a comparison pathway (Figure 4). This two beam setup makes it possible to compensate, with each single measurement, the instrumental effects that could influence the quality of the measurement (e.g. aging of the light source). Appendix A includes the operations and maintenance (O&M) manual for the s::can.

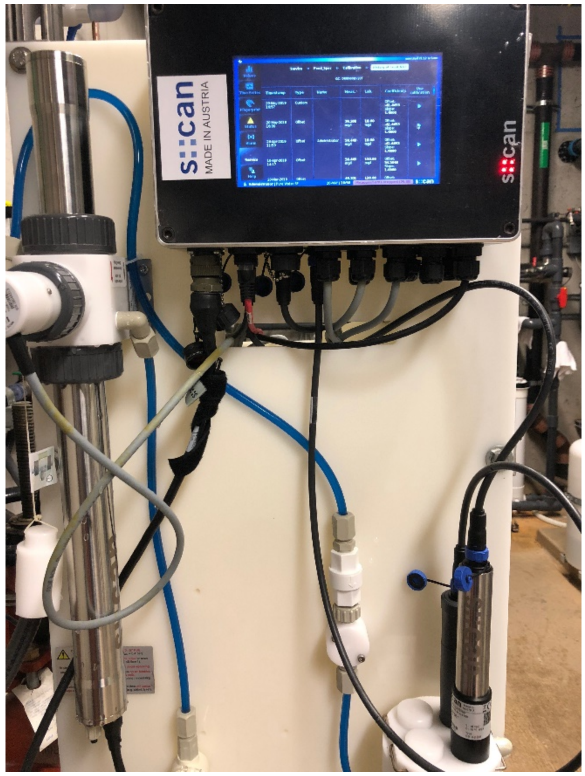

Figure 4. s::can System at PureWaterSF.

The s::can included Spectrolyzer, Chlorilyzer, and pH-meter probes to measure 10 constituents in both the RO feed and permeate water of the Pure Water system.

Table 7 below summarizes the parameters that were measured at the RO feed and permeate, noting that several of the s::can parameters are part of the CCP monitoring discussed above. The calibration of the s::can allowed an accurate assignment of sensor measurements to results of reference analytics. RO feed and permeate samples were taken and sent to Eurofins Scientific for analysis. During the sampling, sensor readings were also collected. A linear relationship was used to relate the laboratory results and the sensors readings (straight line defined by its offset and its slope).

Table 7. Constituents Measured by Each Probe.

Probe Type and Location / Parameter	CCP	OCP	RO Feed Spectrolyzer	RO Permeate Spectrolyzer	RO Feed Chlorilyzer	RO Permeate Chlorilyzer	RO Permeate pH-Temperature
Chloramine		✓	✓				
DOC		✓	✓				
Free Chlorine		✓			✓	✓	
Nitrate	✓		✓	✓			
Nitrite	✓			✓			
pH		✓					✓
Temperature		✓					✓
TOC	✓		✓	✓			
Turbidity		✓	✓	✓			
UV254	✓		✓	✓			

2.2.2.1. Data Collection and Access

The s::can sensors are connected to a micro::station and use monitoring software called moni::tool. The s::can collected data continuously and discrete data values were recorded approximately every 2 minutes (i.e. "measured" data). The s::can's proprietary software, vali::tool, was used to detect and mark untrustworthy data by detecting outliers and noise and checking for discontinuous data by selectively deleting these data points. Vali::tool also provided indications on sensor maintenance requirements as well as automatic detection of malfunctions. The vali::tool software provided both "clean data" and "measured data." Both data sets were analyzed to determine the performance of the advanced treatment system.

2.2.3. Low Pressure Membrane

The UF process is a low-pressure membrane filtration step that removes particulates and suspended solids and provides a barrier to pathogens. In particular, UF has been proven to reliably remove protozoa (*Giardia* and *Cryptosporidium*) and virus. In accordance with USEPA's Long Term 2 Enhanced Surface Water Treatment Rule for drinking water supplies, continuous 4-log protozoa removal credit is demonstrated by periodic direct integrity tests and continuous indirect integrity monitoring.

The UF system was manufactured by WesTech (Figure 5). The pilot system has one UF train with one membrane unit. The nominal pore size of this membrane, from Toray, is 0.01 micrometer/micron (μm). The Toray HFU-1010N membrane is constructed of PVDF polymer. The membrane utilizes outside-in hollow fibers, i.e., the flow of water is from the outside to the inside of the hollow fiber. The active membrane surface area of a module is 75 square feet (ft^2). The outer diameter of the membrane module is 4.5 inches and the length is 3.5 feet (ft). The Toray HFU-1010N membrane is chlorine tolerant (both free and combined) with a lifetime contact limit of 1,000,000 parts per million per hour (ppm-hr). The acid lifetime contact limit is 1,000 hrs. Appendix A includes the O&M manual for the UF system.

Figure 5. WesTech UF System at PureWaterSF.

The UF was operated primarily to produce feed water of appropriate quality and quantity for the downstream RO system as described below.

- RO Feed Water Quality: To reliably remove protozoa (*Giardia* and *Cryptosporidium*); Title 22 requires UF/MF filtrate turbidity to remain less than 0.2 NTU[1] when the system is operational. UFs are in widespread use in California in similar applications for their ability to reliably meet these water quality goals.
- RO Feed Water Quantity: To meet feed flow demands for the downstream RO systems (approximately 2 gpm); flux for the membrane system was approximately 51 gallons per day per square foot (gfd) (3 gpm/module) throughout the study, a rate substantially above conventional rates (e.g., 30

[1] Greater than 0.2 NTU no more than 5 percent of the time within a 24-hour period and no greater than 0.5 NTU at any time.

gfd). At these low production flows typical for building treatment, automated "off the shelf" membrane technology capacities are difficult to perfectly match process-to-process.

As shown in the results section, the UF for PureWaterSF was run at a flux much higher than a conventional system due to the need for a higher UF filtrate flow to run the RO system. Table 8 compares the operating conditions of the PureWaterSF system to another long running (and more conventional) system (Pismo Beach 2019).

Table 8. Ultrafiltration System Operating Parameters.

Parameter	Units	PureWaterSF	Pismo Beach Demonstration
Number of Trains in Operation	--	1	1
System Model	--	WesTech	Pall Microfiltration
Membrane Manufacturer	--	Toray	Pall
Model	--	HFU-1010N	UNA-620A
Membrane pore size	µm	0.01	0.1
Membrane Material	--	PVDF	PVDF
Installed Modules per Train	--	1	4
Membrane Area per Module	ft^2	75	538
Installed Membrane Area per System	ft^2	75	2,152
Filtration Transmembrane Pressure (TMP) Limit	psid	<29.0	43
Normalized Flux	gfd	41 – 51	33

Because the high UF flux was dictated by the downstream RO system demand, the UF pilot study focused on developing chemical cleaning strategies to minimize UF membrane system downtime. It should be noted that the UF system was used for demonstration purposes and does not mimic the conventional hydraulics of a full-scale system.

2.2.3.1. Ultrafiltration Backwash, Maintenance Cleaning, and Clean-in-Place

Backwash (BW) was performed every 30 minutes with filtered water (from the filtrate tank) to remove solids accumulated during filtration on the membrane's outside surface. Maintenance cleaning (MC) was used periodically to remove foulants from the membrane. For this project, the MC used a 250 to 300 mg/L sodium hypochlorite solution at ambient temperature. A portion of the 30 minute (total) MC duration was dedicated to recirculating and 20 minutes of soaking the membranes in the cleaning solution. The remaining time was dedicated to rack preparation, rinsing, and flushing steps. For this project, MCs were conducted every 12 or 24 hours. A more rigorous Clean-in-place (CIP) procedure was used approximately every month. The CIP consisted of two parts: (i) recirculation of sodium hypochlorite (10 percent), and (ii) citric acid (H_3Cit) (50 percent). The CIP solution was heated to a temperature between 90ºF and 100ºF. The total duration of the process is four hours, two hours for each of the chemicals. The UF system was backwashed three times after each chemical cleaning. For perspective on a conventional system, the cleaning procedures for PureWaterSF (run at the higher flux) are compared to another project (Pismo Beach 2019) in Table 9.

Table 9. Ultrafiltration Backwash and CIP Comparison.

Parameter	Units	PureWaterSF	Pismo Beach Demonstration
Backwash Frequency	minutes	30	32.1
MC Frequency	--	Daily and Twice/day	Daily
MC Soaking Time	minutes	10 / 20	30
MC Chemical	--	NaOCl	NaOCl
MC Chemical Concentration	mg/L	250 / 300	500
MC Temperature	°F	Ambient	90 -100
CIP Frequency	days	25	32
CIP Duration	hours	4	3
CIP Chemical	--	NaOCl & H_3Cit	NaOCl / NaOH & H_3Cit
CIP NaOCl Concentration	mg/L	600	500
CIP H3Cit	percent	50	50
CIP Temperature	°F	90 -100	90 -100

2.2.3.2. Ultrafiltration Chemicals

The pretreatment and cleaning chemicals used to reverse the fouling of the UF membrane are as follows:

- Pretreatment Chemicals – ammonium sulfate, dosed at a C:N ratio of 4:1.
- Cleaning Chemicals – MC sodium hypochlorite (10 percent) (250 – 300 mg/L); and CIP citric acid (50 percent).

2.2.4. Reverse Osmosis

RO removes dissolved salts and compounds that are not typically attenuated by MF. RO membranes provide high removal rates for trace pollutants (Salveson et al. 2010; Snyder et al. 2012). Extensive research has been completed on the type of contaminants removed by RO and expected removal rates based on compound charge and size. RO membranes are efficient at removing trace level pollutants at higher molecular weights, with low-molecular weight organic acids and neutral compounds being removed only partially, including NDMA, 1,4-dioxane, and certain other DBPs (Steinle-Darling et al. 2007; Bellona et al. 2008).

DDW has granted a 2-log reduction credit for all pathogens for RO (WRD 2013) based on a requirement to continuously monitor TOC and EC reduction across RO. The Orange County Water District currently attains 2-log pathogen credit through their online TOC meters. Alternative technologies, such as online fluorescent dye monitoring, have been shown to have higher sensitivity and resolution to monitor and demonstrate pathogen removal efficiency (Kitis et al. 2003; Henderson et al. 2009; Pype et al. 2013).

A single pass RO system includes a high-pressure feed pump, 2.5-inch fiberglass end entry pressure vessels, and 2.5-inch thin film composite RO membranes (Figure 6). This RO system does not mimic the hydraulics of a full-scale skid and would not accurately simulate full-scale water quality and operating data. However, an approximation of performance can be demonstrated. Appendix A includes the O&M manual for the RO system.

Figure 6. Evoqua Reverse Osmosis System at PureWaterSF.

Table 10 compares the RO system operational parameters and membrane specifications for PureWaterSF with the Pismo Beach demonstration project (Pismo Beach 2019). One of the main differences between the two projects is the low recovery of RO for PureWaterSF. The primary reason for this is the design of the RO system (single stage), though the RO feed water quality (silica and calcium concentrations) is believed to have had an impact.

Table 10. RO System Operating Parameters.

Parameter	Units	PureWaterSF	Pismo Beach Demonstration
Target Recovery	%	47.7	70 – 80
Number of Stages	--	1	2
Permeate Flow Rate	gpm	0.85 – 1	1st Stage: 6.3 – 13.5 2nd Stage: 10.7 – 11.0
Feed Flow Rate	gpm	2	34.3 – 44.0
Concentrate Recirculation Flow Rate[1]	gpm	1.4 – 1.5	--
Membrane Manufacturer	--	Dow Chemical	Dow Chemical

Parameter	Units	PureWaterSF	Pismo Beach Demonstration
Membrane Model	--	Filmtec™ LP-2540	1st Stage: ECO PRO-400 2nd Stage: BW30XFRLE 4040
Surface Area per Element	ft^2	28	1st Stage: 78 2nd Stage: 400
Total Number of Elements	--	4	1st Stage: 7 2nd Stage: 14
Element Diameter	in	2.5	1st Stage: 8 2nd Stage: 4
Element Length	in	40	40

[1] Concentrate recirculation is required to maintain the minimum flow leaving the last element in the system. Without the recirculation, the low flow can result in salts accumulating on the membrane and associated fouling.

The RO system operated 5 days per week and 24 hours per day. The system did not operate on weekends as there is little to no wastewater produced on the weekends at the SFPUC headquarters. Such operational times are appropriate to understand building scale DPR challenges for an office building but may be less appropriate for housing, which would operate more continuously.

At the end of every week, an automated flush on the concentrate side of the membrane was performed with feed water. For longer downtimes, the system was flushed with permeate and preserved with a 1 percent sodium bisulfite solution (SBS). The RO operated with chloramines and antiscalant addition for biofouling control and scaling prevention, respectively. Table 11 summarizes the RO feed water quality. The RO feed water silica concentration ranged from 25.1 to 65.0 mg/L, which limited the recovery for the system. Lower silica concentrations were recorded when potable water was added to the recycled water tank during LM operation and maintenance. An additional concern was the high concentration of calcium in the feed water. High calcium concentrations can interfere with many standard scale inhibitors that are supposed to target silica. The ansticalant manufacturer recommended the type and dose for this application.

Table 11. RO Feed Water Quality Data

Parameter	Units	Concentration[1]
Aluminum	mg/L	<0.005
Barium	mg/L	0.005
Bicarbonate	mg/L as $CaCO_3$	23.6
Bromide	mg/L as $CaCO_3$	0.160
Calcium	mg/L	102

Parameter	Units	Concentration[1]
Chloride	mg/L	193.6
Conductivity	μS/cm	1,741
Copper	mg/L	0.060
Fluoride	mg/L	0.49
Iron	mg/L	0.013
Magnesium	mg/L as $CaCO_3$	108
Manganese	mg/L	0.013
Nitrate as N	mg/L	70.56
pH	Unitless	6.33
Phosphate	mg/L	12.28
Potassium	mg/L	70.31
Silica	mg/L	60.8[2]
Sodium	mg/L	105.9
Strontium	mg/L	0.26
Sulfate	mg/L	137.5
Total Hardness	mg/L as $CaCO_3$	363
Total Organic Carbon	mg/L	8.48
Turbidity	NTU	0.15
Zinc	mg/L	0.036

[1] Sample collected 04/26/2018 during commissioning of the RO system.

[2] Average concentration based on 42 samples.

2.2.4.1. RO Chemicals

Chemical pre-treatment included antiscalant dosing to minimize mineral scaling. The pretreatment chemical used was an antiscalant (Vitec 1400) at a concentration of 2.2 mg/L.

2.2.5. UV Reactor

The UV reactor installed at PureWaterSF was provided by WEDECO. The WEDECO Spektron 5e is a 1-3 gpm reactor with one low pressure, high efficiency UV lamp with high UVC output and WEDECO-Ecoray® technology. The single UV lamp is protected by a quartz sleeve. Figure 7 shows the reactor and control cabinet. Appendix A includes the O&M manual for the reactor. Table 12 summarizes the UV design parameters for the system used at PureWaterSF.

Figure 7. WEDECO UV system at the PureWaterSF Demonstration.

Table 12. UV System Design Parameters.

Parameter	Units	Value
Reactor Model	--	Spektron 5e
Manufacturer	--	WEDECO
Design Flow	gpm	1-3
UV Dose	mJ/cm^2	1,000
UV Transmittance (UVT) Range	%	70 – 98
Operating Pressure	psi	16
UV Lamp	--	VRL 5
Lamp Power	W	80
Number of Lamps	--	1
Lamp Life	hour	Up to 12,000 hours
Lamp Sleeve Material	--	Pure Quartz
UV Sensor Type	--	SO 20101

2.2.5.1. Advanced Oxidation Process

High-dose UV photolysis provides an additional barrier for pathogens and chemicals, including NDMA. High UV doses on the order of 900 mJ/cm^2 can provide 90% reduction of NDMA (Sharpless and Linden 2003). Adding sodium hypochlorite (NaOCl) before high dose UV (typically in the range of 3 to 5 mg/L), results in the generation of hydroxyl radicals, which are the prerequisite for an advanced oxidation process. Hydroxyl radicals are nonselective oxidants that oxidize or break down most chemicals with which they come in contact, destroying a range of trace level pollutants. In particular, DDW requires that UV AOP provide at least 0.5 log reduction of 1,4-dioxane (DDW 2018), a conservative surrogate for destruction of trace pollutants by UV AOP.

3. Results and Discussion

PureWaterSF operated between late June 2018 and March 2019. Operational data are presented here for each of the advanced treatment units. These data can be used to evaluate the effectiveness of both the treatment and monitoring systems.

3.1. s::can Online Monitoring System

The sections below present a brief review of the application of the different meters used in the monitoring system, followed by a summary of the accuracy and precision of the meters.

3.1.1. Calibration

The s::can's calibration was scheduled every month for all the parameters unless the LM and/or PureWaterSF were not operational or were under maintenance. The only parameter that was calibrated weekly was the free chlorine for both the RO feed and permeate. Additionally, this parameter was calibrated every Monday or after a holiday when the s::can system was restarted or when the electrolyte gel was replaced as part of the probes maintenance protocol. Appendix B summarizes the grab samples collected for calibration of the s::can.

3.1.2. s::can Operational Challenges

The s::can was operated intermittently, on the same schedule as the treatment processes (5 days per week, 24 hours per day). Shutting down the s::can on the weekend particularly affected the start-up procedure of the chlorilyzer probe. This resulted in additional maintenance including weekly free chlorine calibrations and probe electrolyte gel replacement. Another operational challenge that impacted the performance of the s::can was the variability in the source water quality. During procurement of the probes, an expected water quality range was assumed that determined the concentration range of the probes. The most noticeable examples are the free chlorine concentration, chloramine, and TOC. A free chlorine concentration of less than 0.01 mg/L was expected in the RO feed and permeate; thus, a chlorilyzer with a measurement range of 0 to 2 mg/L was chosen for this application. However, concentrations greater than 4 mg/L were recorded. The same was true for the TOC concentration, where a concentration of less than 8 mg/L was expected based on verbal communication. Nevertheless, values of up to 15 mg/L were recorded. The s::can was able to measure values above the higher range, but the value would be recorded as "out-of-range" error.

3.1.3. Feed and Permeate Spectrolyzer

3.1.3.1. TOC and DOC

RO feed and permeate TOC data from the s::can were continuously recorded and used to monitor the RO system performance. The log reduction of TOC by RO can be used to conservatively estimate pathogen log reduction by RO. These results are included in Section 3.3.2.2.

Dissolved organic carbon (DOC) was not included in the analysis since it was expected that in the RO feed, essentially all TOC was DOC (UF removes all suspended solids ahead of RO, leaving only dissolved organic species). DOC data were not included for the analysis. For reference, the RO feed DOC concentration for the duration of the project can be found in Appendix C.

3.1.3.2. Turbidity

Turbidity data were used to monitor the UF system performance and the RO feed water quality. RO systems are sensitive to feed water quality data variation. Membrane manufacturers recommend an RO feed water turbidity of less than 1 NTU. Results for the turbidity are discussed in Section 3.2.2.2.

3.1.3.3. Nitrate and Nitrite as Nitrogen

The nitrate and nitrite concentrations as nitrogen were monitored as another means to evaluate the RO performance. Further, potable reuse projects need to meet primary drinking water maximum contaminant levels for nitrate and nitrite, which are 10 mg/L as N and 1 mg/L as N, respectively. The expected nitrate rejection by RO membranes can vary from 65 – 85 percent (Tchobanoglous et al.1991). These results are included in Section 3.3.2.3.

3.1.3.4. Chloramine

The chloramine concentration was monitored to control the exposure of the RO membranes to free and total chlorine. The maximum recommended chloramine concentration that RO membranes can be exposed is 2.5 mg/L, which was exceeded during some testing of PureWaterSF.

3.1.3.5. UV254

UV254 is a measurement of how much light is absorbed by organic compounds present in water. This measurement can also be converted to UV transmittance (UVT), which describes the amount of light transmitted through water and is expressed as a percentage. A lower UVT value corresponds to the presence of more organics. UVT is not a commonly used surrogate for RO performance but it can provide important information on RO permeate quality. In particular, it provides information on the dissolved organic quality of RO permeate and information about the impact of chloramines and free chlorine in RO permeate on UV efficiency. Thus, it is included in the analysis of the RO and UV performance results. These results are included in Sections 3.3.2.4 and 3.4.

3.1.4. Feed and Permeate Chlorilyzer

This probe was used to measure the free chlorine concentration in the RO feed and permeate. This information was used to determine the exposure of RO membranes to free chlorine.

3.1.5. pH and Temperature probe

The RO feed pH and temperature were continuously monitored. The RO permeate pH is relevant to the performance of the UV AOP (NaOCl) since a pH between 5.5 to 8.3 is required for the optimal operation of the AOP using sodium hypochlorite (Chuang et al. 2017; Patton et al. 2016). The temperature is relevant because it impacts membrane flux and is used to normalize the permeate flow.

3.1.6. Data Collection Errors

For DPR systems in which we do not have an environmental buffer that results in large "response retention times" of months to years, we must rely more upon online meter accuracy for water quality confidence. As a result, when online meters drift significantly, or fault, we must assume that we have lost a treatment barrier. Accordingly, it is critical to understand the occurrence, duration, and type of status or error codes for each online parameter analyzed for this project. Additionally, the time that each probe was collecting data with no associated error should be known. The following analysis was used to compute the percent of time that each status occurred over the course of the project:

- All status and error codes that occurred during the operation of PureWaterSF were tabulated. Each discrete time stamp was associated with a particular status code. When two or more type of the same status code followed one another successively, the duration of time between the timestamps was computed.
- When the status changed from one status type to another, the total duration of the first status type was recorded as an "event" of that status type (i.e., regardless of the duration of the time).
- The total duration of all events was added for each status type.

Appendix D summarizes the performance of the probes by parameter, per status and error. Based on this analysis, it can be concluded that the probes operated under normal ("OK") status between 80 to 96 percent of the times during the operation of PureWaterSF. The parameters with the lowest performance percentage were chloramine and free chlorine (feed and permeate) with values of 80 and 82 percent, respectively. The most prevalent error recorded was "reading out of measuring range" (1 to 14 percent of the time) and "Reading Non-A-Number (NAN), Parameter error, wrong medium" (3 percent of the time).

3.1.6.1. Vali::tool Analysis

The vali::tool, an s::can product, provided "clean and measured" data and the status of each data point, including errors associated with the data point. In addition to the initial data sets, two additional data sets were produced during the data analysis: (i) data set containing only "measured values" with a status indicating normal operation, and (ii) another data set containing only "clean values" with errors removed. In summary, the following four data sets were analyzed:

- Measured Values – All Data – Raw data without any screening from the vali::tool.
- Measured Values – Errors Removed – Raw data where values with error codes associated with them were removed.
- Clean Values – All Data – Data screened using the vali::tool.
- Clean Values – Errors Removed – Data screened using the vali::tool, and where all values with associated error codes were removed.

All four data sets were plotted for each parameter to compare the values. Noting that vali::tool data was unavailable between August and November 2018, the four data sets of most parameters showed similar data trends when the probes operated within their operational range. In the case of the chlorilyzer, the difference between "clean" and "measured" was significant. The measured data set contains values up to 4 mg/L while the cleaned data showed values up to only around 2.5 mg/L. This was because the range of the probe is reliable to only 2 mg/L; measurements up to 4 mg/L are possible, though outside of calibration range. In reality, there may have been events when the free chlorine in the feed water was higher than 4 mg/L. For the purposes of this report, the measured values with the errors removed were used for the analysis of the treatment system performance. For reference, Appendix C shows the "Measured Values – All Data" data sets plotted against the "Clean Values – Errors Removed" data sets for all parameters (i.e., the data set with the most values compared against the data set with the least values).

3.1.7. s::can Key Findings

Future studies should examine a broader range of sensor technologies, looking at operational ranges (low to high values for the specific parameters), accuracy (relative to calibrated values), and precision (lack of variability). Testing sensors from multiple suppliers (e.g., s::can, Hach, etc) is recommended.

Table 13 provides a summary of the probes' performance based on their public health or operational impact for the duration of the project. All probes were operational without any errors over 80 percent of the time. Most of the errors were related to "out-of-range" errors due to the unanticipated source water quality. The following topics are noted relative to probe performance:

- The chlorilyzer required additional calibration and maintenance due to the operational schedule.
- Overall, the s::can was able to monitor the RO system and provide useful data to determine the performance variability.
- The overall monitoring reliability of the system could be improved through use of redundant (backup) probes.
- Future studies should examine a broader range of sensor technologies, looking at operational ranges (low to high values for the specific parameters), accuracy (relative to calibrated values), and precision (lack of variability). Testing sensors from multiple suppliers (e.g., s::can, Hach, etc) is recommended.

Table 13. s::can Performance Summary

Online Parameter	CCP	OCP	Reliable Operation (% of Time)[1]	Water Quality Impact (Pathogen or Chemical Pollutant)		Public Health Significance	Operational Significance
				Pathogen	Chemical Pollutant		
Chloramine		✓	80		✓	Increase formation potential of NDMA	RO membrane damage
DOC	✓		95	✓	✓	Increase the concentration of total carbon	NA
Free Chlorine		✓	83 / 82		✓	Values should be below the regulated value	RO membrane damage
Nitrate	✓		91 / 83		✓	Values should be below the regulated value	NA
Nitrite	✓		91		✓	Values should be below the regulated value	NA
pH		✓	96		✓	NA	pH between 5.5 – 8.3 is required for the optimal operation of the AOP using sodium hypochlorite
Temperature		✓	96		✓	NA	NA
TOC	✓		95 / 94	✓	✓	Values should be below the regulated value	RO membrane fouling
Turbidity		✓	93 / 92	✓		NA	RO membrane fouling
UV254	✓		95 / 95	✓	✓	NA	Impact UV performance

[1] Results based on “Measured Values - Errors Removed” and with “Out-of-Range” errors removed.

3.2. Ultrafiltration System Operational and Testing Objectives

3.2.1. UF Operational Challenges

Due to high variability of the UF feed water and the higher UF flux, more frequent maintenance cleaning (MC) using higher-than-normal chlorine concentrations and extended soaking was required to maintain UF system performance. Unlike RO membranes, PVDF membranes are more resistant to, but not immune from, free chlorine concentrations.

Other operational challenges were caused by the footprint of the system. Smaller feed and filtrate tanks required addition of water during CIPs or decreasing the number of BWs after the CIPs. Another challenge observed was related to the size of the compressor. Occasionally, the compressor was not able to provide enough air to open/close the air actuated valves, causing the system to shut down with an alarm (e.g., high TMP alarm or high pump temperature).

3.2.2. Evaluation Criteria for UF Performance

Membrane fouling is measured by the rise in transmembrane pressure or, inversely, the decrease in permeability. Clean membrane TMP ranged from 4.5-12.8 pounds per square inch (psi) and permeability was approximately 7.5 gfd/psi. The UF was operated until the transmembrane pressure reached its manufacturer specified maximum of 29.9 psi. At that point, the membrane was taken off line for a CIP. MC strategies were used much more frequently to maintain the system in operation to provide feed water to the RO system.

The main objectives of the UF are to provide robust pathogen removal from the LM effluent and provide continuous high-quality source water to the RO system. During the nine months of operation, ammonium sulfate was added to the UF feed to form chloramines. No coagulant was added to the system ahead of UF (and at all for the entire system). Table 14 summarizes the operational modifications made over the duration of the membrane pilot. The operational changes were primarily made to have continuous operation of the UF system and provide enough feed water for the RO system.

Table 14. Ultrafiltration Operational Modifications

Date	Flux [gfd]	MC	CIP	Action	Result of Modification
04/17/18	41	Daily	--	WesTech decommissioned the UF system. System operates for approximately one-hour per day.	NA
06/26/2018	41	Daily	--	All systems in operation. UF starts treating LM effluent at a recovery of 92.1 percent.	Average TMP =4.5 psid.
07/25/2018	44	Daily	--	Flow rate was increased from 2.5 to 2.7 gpm to supply the demand of the RO.	System operated at a TMP of approximately 4.6 psid.
08/13/2018	51	Daily	--	Flow rate was increased from 2.7 to 3.0 gpm to supply the demand of the RO. Recovery = 92.6 percent.	System operated at an average TMP of 5.89 psid.
08/29/2018	51	Daily	--	High TMP alarm. System shutdown at 29.9 psid. MC requested with 300 mg/L of NaOCl and extended soaking time = 20 min.	TMP recovered to 8.91 psid and continued operation.
10/26/2018	51	Daily	--	MC requested with 250 mg/L of NaOCl and soaking time of 10 min.	TMP recovered to 6.542 psid and continued operation.
10/30/2018	51	Daily	--	UF shutdown with high TMP alarm due to a compressor failure. Requested MC before restarting the UF.	Restart compressor and restart system.

Date	Flux [gfd]	MC	CIP	Action	Result of Modification
11/02/2018	51	Daily	--	UF down due to issues with air compressor	Contacted WesTech to get a new compressor.
11/16/2018	51	Daily	--	Air compressor stopped operating. Had to reset.	Lack of air prevented the system to operate in backwash mode.
11/19/2018	51	Daily	--	Fitting on the feed side of the UF feed pump cracked.	System stopped until repaired was completed.
11/28/2018	51	Daily	--	High turbidity in the LM resulted in a high TMP alarm. MC requested with 250 mg/L of NaOCl and soaking time = 10 min.	TMP recovered to 12.8 psid for a couple days but high turbidity caused a continued increase.
12/05/2018	51	Daily	--	MC requested with 250 mg/L of NaOCl and soaking time = 10 min.	TMP recovered (TMP = 9.9 psid) but increased after a couple of days of operation.
12/07/2018	51	Daily	--	MC requested with 250 mg/L of NaOCl and soaking time = 10 min	Controlled TMP but increased after a couple of days of operation.
12/11/2018	51	Daily	✓	NaOCl CIP. Cleaned the system before December shut down.	TMP before CIP 29.79 psid. CIP was left on stand-by during LM maintenance on December.
12/12/2018	51	Daily	✓	CIP was left on stand-by mode during LM maintenance on December.	NA
01/04/2019	51	Daily	--	Backwash pump VFD failed.	Prevented the UF system to complete backwash causing an increased in the TMP and a shutdown alarm. The

Date	Flux [gfd]	MC	CIP	Action	Result of Modification
					VFD was reset and the backwash pump was back in operation.
01/16/2019	51	Daily	✓	NaOCl and Citric Acid (H3Cit) CIP. Cleaned the system before December shut down.	TMP before CIP = 21.2 psid. TMP after CIP = 7.5 psid.
01/22/2019	51	Twice/day	✓	Per recommendation, WesTech performed another CIP (NaOCl + (H3Cit)) and increased MC to twice per day	TMP before CIP = 26.11 psid TMP after CIP = 6.1 psid.
02/15/2019	51	Twice/day		CIP NaOCl + H_3Cit	TMP before CIP = 27.35 psid TMP after CIP = 5.5 psid.
03/15/2019	51	Twice/day	✓	CIP NaOCl + H_3Cit	TMP before CIP = 28.03 psid TMP after CIP = 7.9 psid.

3.2.2.1. Membrane Hydraulic Performance

The UF system started treating LM effluent in late June 2018. For the first month of operation, the UF system operated at an average flux of 41 gfd. The flux was increased to 44 gfd and subsequently to 51 gfd to meet the demand of feed water to the RO system. These UF flux values are higher than conventionally used for potable water reuse projects (typically in the 30 gfd range). Descriptions of membrane performance, observed trends, and critical operating parameters are presented in this section. Figure 8 and Figure 9 show trends in membrane hydraulic performance and the normalized permeability at 20 degrees Celsius (°C) (68 °F). The red horizontal line shown in Figure 8 represents the maximum operational TMP. The frequency of CIP or extended MC is shown as black vertical lines.

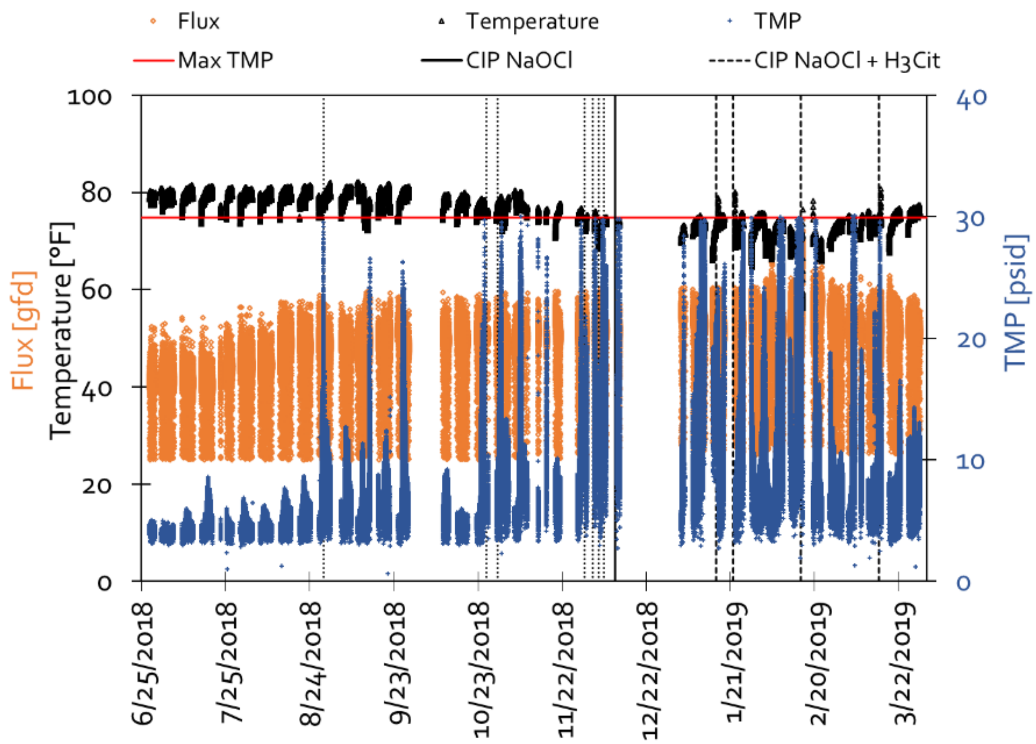

Figure 8. Hydraulic Performance for PureWaterSF.

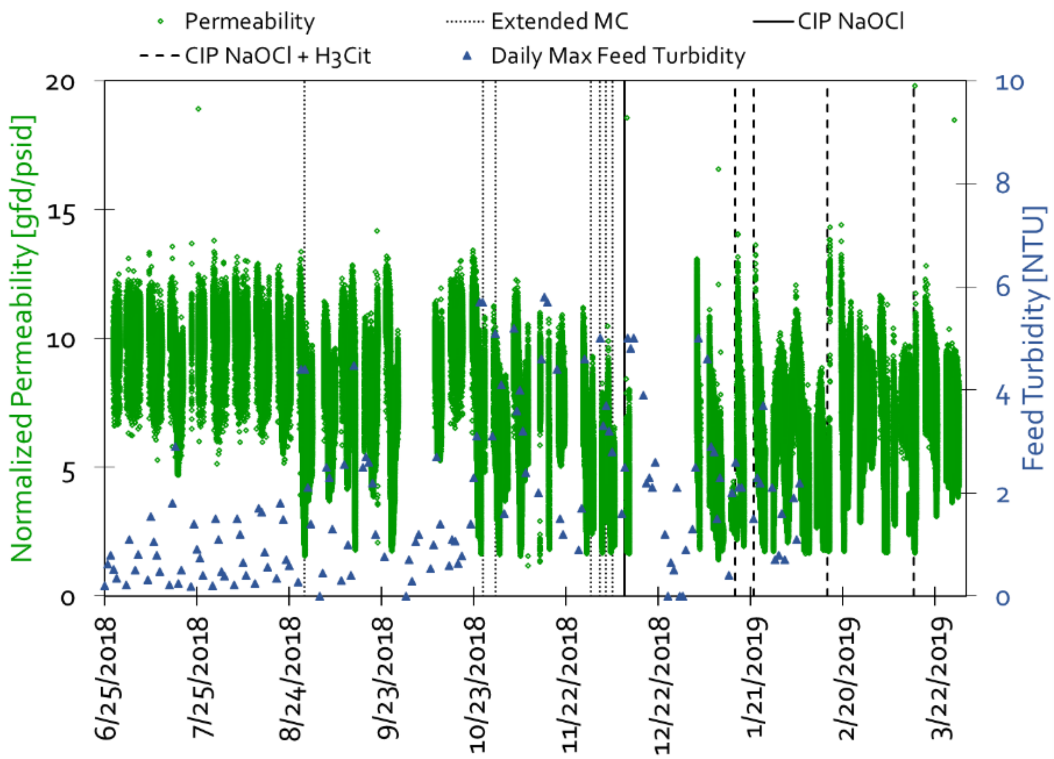

Figure 9. UF System Permeability (68 °F) and UF Feed Turbidity

3.2.2.2. Turbidity

The UF system was not equipped with a turbidity meter but relied on the s::can to record the UF filtrate (RO feed) turbidity. UF Filtrate s::can turbidity averaged at 0.34 NTU and was within the specifications for RO feed water. However, these values were above Title 22 standards and USEPA MFGM[2] (Membrane Filtration Guidance Manual) limits for indirect integrity testing. Table 15 summarizes the 50th, 75th, and 90th percentiles for the duration of the demonstration project for the s::can and grab samples. Grab sample values are approximately half of the value recorded

[2] Per the MFGM, if the turbidity control limit is exceeded, then a MIT is performed. If the test is passed, as was the case for all operation of the UF system for this project, the unit is allowed to be put back into production. Because turbidity does not meet MFGM sensitivity or resolution criteria, a direct integrity test is considered a far more meaningful result. If the turbidity exceeds the control limit (the default MFGM value is 0.15 NTU), then a test is completed. If the test passes, then all is considered well with the membrane system and the limitations of turbidity measurements are accepted.

by s::can, which may suggest more frequent calibration was required to have a more accurate measurement. Figure 10 shows the UF filtrate and the LM effluent turbidity.

Table 15. UF Feed and Filtrate Turbidity.

Sample	Feed Turbidity[1] [NTU]			Filtrate Turbidity[2] [NTU]		
	50th Percentile	75th Percentile	90th Percentile	50th Percentile	75th Percentile	90th Percentile
Online monitoring	1.79	2.79	3.69	0.34	0.57	0.77
Grab (n=6)	NA	NA	NA	0.18	0.37	0.39

[1] LM online monitoring turbidity meter.

[2] s::can

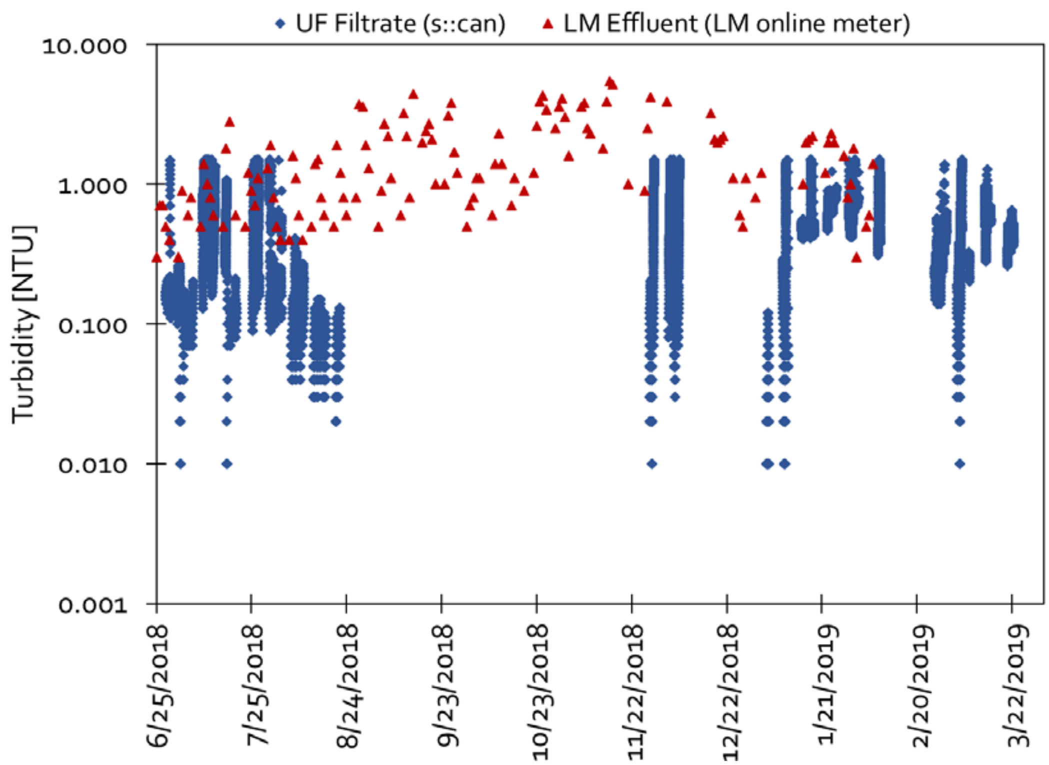

Figure 10. UF System Filtrate Turbidity.

3.2.2.3. Membrane Integrity Tests

Membrane integrity tests (MITs) are used to detect broken membrane fibers, which could signal a loss of pathogen removal. The MIT results are particularly important due to the higher than anticipated UF filtrate turbidity values reviewed above. UF systems, with fibers intact, are well proven to remove protozoan pathogens (*Giardia* and *Cryptosporidium*). UF systems have been shown to remove virus with 3+ log reduction in some cases (CWS 2014), but it must be noted that with a few exceptions, UF systems are not credited with virus removal as there is no online or even reliable daily method to verify UF membrane integrity as it applies to virus removal. On the other hand, MIT tests are done daily to verify membrane integrity for protozoa removal. The pressure decay results from the MITs averaged 0.019 psi/min (99th percentile = 0.028 psi/min) and were used to calculate the system's log reduction values (LRVs) for *Giardia* and *Cryptosporidium* (calculation shown in Appendix E). As demonstrated in Figure 11, the UF consistently demonstrated LRVs greater than 4-log (red horizontal line) with an average LRV of 4.58 (10th percentile = 4.57 and 5th percentile 4.33). These data show that the UF produced water within the specifications despite the higher turbidity (than expected) values recorded by the s::can.

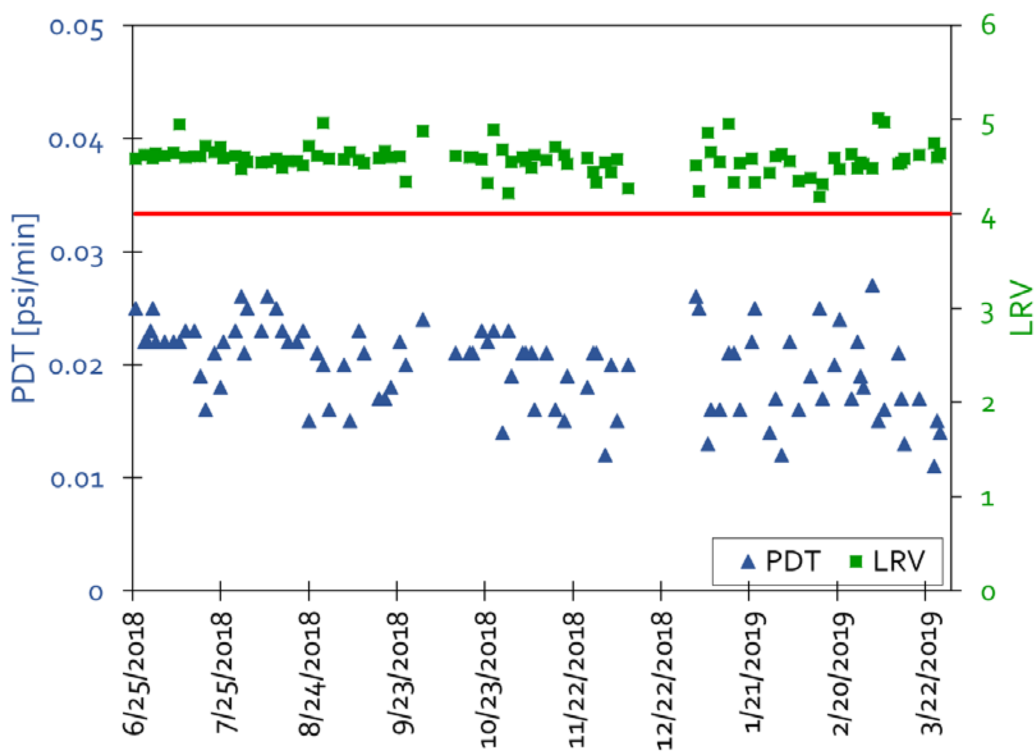

Figure 11. Pressure Decay Test Results and Log Removal Values.

3.2.3. UF Key findings

Key findings for the UF system are summarized below:

- Increasing the flux to meet the RO demand had an impact on the TMP and permeability, and thus on the cleaning regime for this UF system.
- The average TMP during the operation of PureWaterSF was 7.5 psid with a maximum TMP of 29.9 psi (system shutdown).
- The UF system demonstrated the ability to operate continuously with approximately 30 days between CIPs.
- During the rainy season (December to March), the UF system's performance was impacted by the LM water quality. It is suspected that sudden spikes in the total suspended solids (data not available) in the LM effluent accelerated membrane fouling reflected as an increase in the TMP.
- MC and CIP were able to reverse fouling.
- Average UF filtrate measured by the s::can was within specifications for RO feed water (<1 NTU) but higher than the grab samples values.
- The UF provided a consistent barrier to pathogens (protozoa) with 4-log to >4.5-log removal on the challenging water quality (turbidity spikes, high chlorine concentrations), as measured through the membrane integrity tests.

3.3. Reverse Osmosis

The primary goal of the RO analysis was to evaluate RO performance and understand if there were noticeable impacts due to UF filtrate water quality. RO performance was evaluated in terms of grab sample EC and online TOC.

3.3.1. RO Operational Challenges

Unlike other water reuse applications where chlorine and ammonium sulfate are dosed at set concentrations and can be controlled to form chloramines (and not have free chlorine) ahead of an RO system, this is a particular system in which the project team did not have control on the free chlorine concentrations in the LM effluent. Ammonium sulfate was dosed to form chloramines assuming a free chlorine concentration of 5.5 mg/L in the LM effluent. However, the free chlorine concentration varied from 0.21 to 9.6 mg/L as shown in Figure 3, resulting in free chlorine in the RO feed and thus a high potential for RO membrane oxidation. The s::can recorded 88 events where the RO feed free chlorine concentration was above 0.01 mg/L and 57 events where the chloramine concentration was above 2.5 mg/L (noting that chloramine concentrations below 2.5 mg/L are typical). However, only a fraction of these events were reported by the operators during working hours. When noticed during working hours, the RO system was shut down to prevent membrane damage. Additional exposure to free chlorine might have occurred since it was not possible to flush the pressure vessels with unchlorinated water at the time of the shutdown. It is well documented that oxidation of RO membranes and loss of salt rejection will occur after approximately 200 to 1,000 hours of exposure to 1 mg/l of free chlorine (200 to 1,000 ppm-h tolerance) (Dow 2019). This operational challenge appears to have compromised membrane integrity, thus reducing the rejection of dissolved salts and trace organic chemicals.

Due to the 5 days per week, 24 hours per day operational schedule, the RO system had to be stopped and started frequently. Such operation may have also impacted the performance of the RO system. Generally, RO systems show better performance with continuous operation.

3.3.2. RO Membrane Performance and Recovery

PureWaterSF operation started in late June 2018 and ended on March 31, 2019. The system operated at an average 47.7 percent recovery, well below potable reuse industry standards of 75 to 85 percent. This lower recovery was due to the configuration of the RO system and the challenging concentration (e.g., high silica and calcium) in the feed to the RO. Table 16 summarizes the RO operational changes during the demonstration study.

RO systems for indirect potable reuse are currently granted pathogen (protozoan and enteric virus) LRV credits in California based on the removal of surrogates such as EC or TOC. It should be noted that the use of parameters like EC and TOC for direct integrity testing (DIT) might be revised in the future by DDW because they do not meet the sensitivity and resolution required for DIT methods by the USEPA MFGM (USEPA, 2005). The information below for EC and TOC log reduction, based upon the literature, provides a conservative estimate of pathogen removal by RO.

Table 16. RO System Operational Changes.

Date	Action	Result of Modification
04/20/2018	Evoqua commissioned the system.	NA
09/07/2018	RO antiscalant pump failure.	Shut down system until antiscalant pump was primed.
10/28/12018 - 11/04/2018	RO PSI fault alarm.	Low feed pressure. Manipulated RO feed by-pass valve to increase pressure.
11/26/2018-12/03/2018	Shut down RO system during holiday.	Preserved RO membranes with SBS.

Date	Action	Result of Modification
03/13/2019 - 03/14//2019	RO PSI fault alarm.	Low feed pressure. Manipulated RO feed by-pass valve to increase pressure.
12/11/2018 - 01/03/2019	Shut down RO system during LM maintenance and holiday.	Preserved RO membranes with SBS.

RO performance data were analyzed using the membrane supplier Hydranautics RODATA normalization excel file. RODATA uses the ASTM D4516 method to calculate the normalized flow, differential pressure, and the salt passage. Figure 12 and Figure 13 show the normalized permeate flow, differential pressure, and the normalized salt passage. The RO performance parameters were normalized to the initial operating conditions.

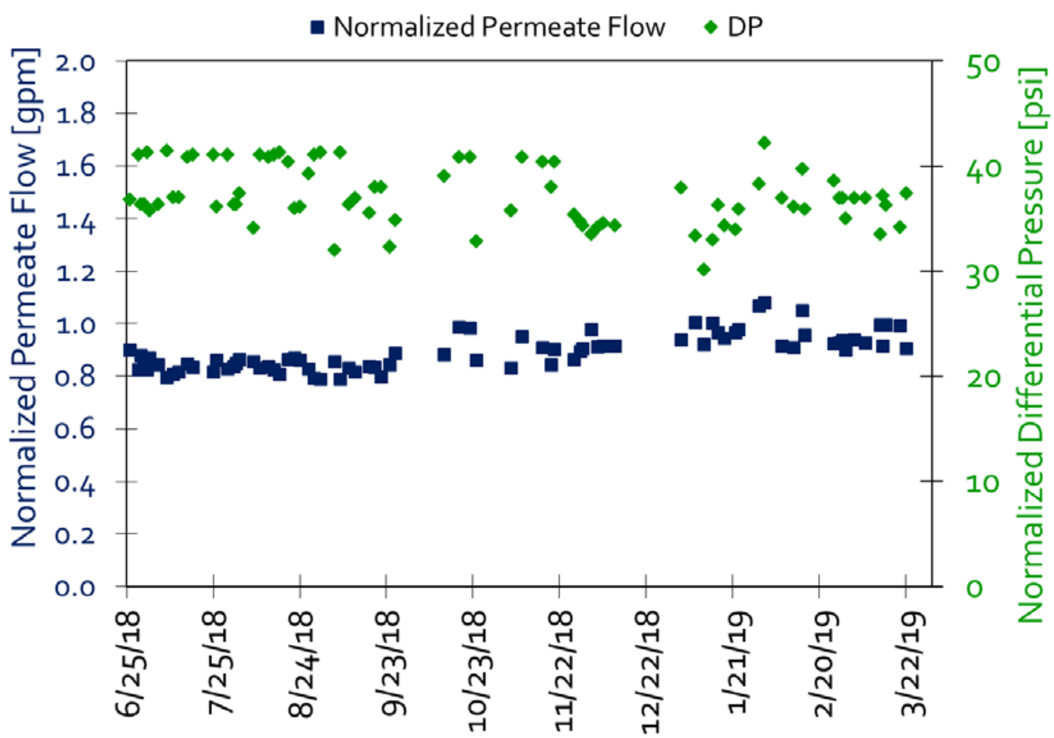

Figure 12. RO Normalized Permeate Flow and Differential Pressure.

A stable operation was observed during the first 5 months of operation. The average normalized permeate flow was 0.86 gpm. An increase of 14 percent in the normalized permeate flow (0.83 to 0.95 gpm) was observed after the membranes were preserved with a solution of 1 percent SBS for a week in late November and then for three weeks on December while the LM underwent maintenance. The variability in the normalized differential pressure data can be attributed to noise due to pressure and/or flow instruments variation and operator reading variations. In this case, the normalized salt passage provides a clearer view on the changes in the membrane performance and water quality with an increase from approximately 5 to

10 percent. This increase in salt passage is likely the result of free chlorine oxidation of the RO membrane.

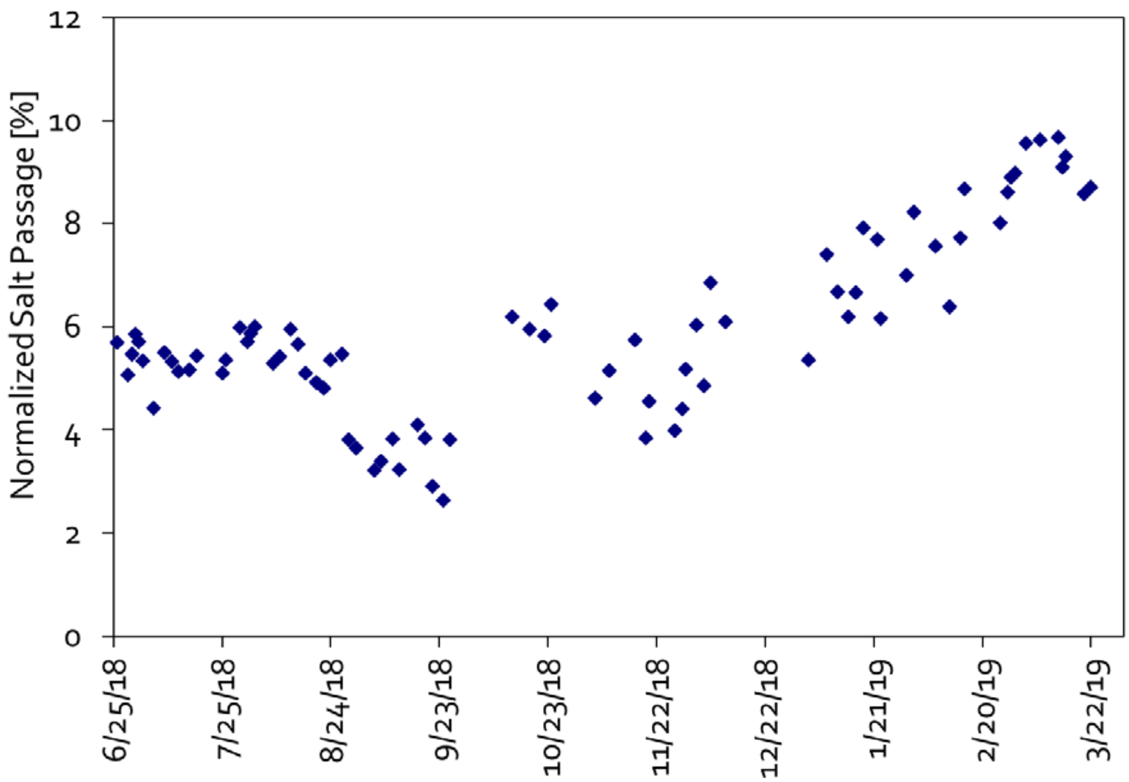

Figure 13. RO Normalized Salt Passage.

3.3.2.1. Electrical Conductivity

The RO system was equipped with an online EC probe (not continuous recording). Observations based on the data shown in Figure 14 are summarized below.

- Influent EC averaged a value of 1,496 microsiemens per centimeter (µS/cm). The permeate EC averaged 116 µS/cm. Higher conductvity values were observed at the end of the pilot plant operation. As mentioned above, this is likely the result of free chlorine oxidation of the RO membranes.
- The average log reduction of EC across the system was 1.13, with a 10^{th} percentile log reduction value of 0.98.
- The LRV trend during the demonstration project is shown in Figure 15. These values are lower than the values observed at the Pismo Beach demonstration and Ventura demonstration of 1.4 and 1.6, respectively (Ventura Water 2018; Pismo Beach 2019).

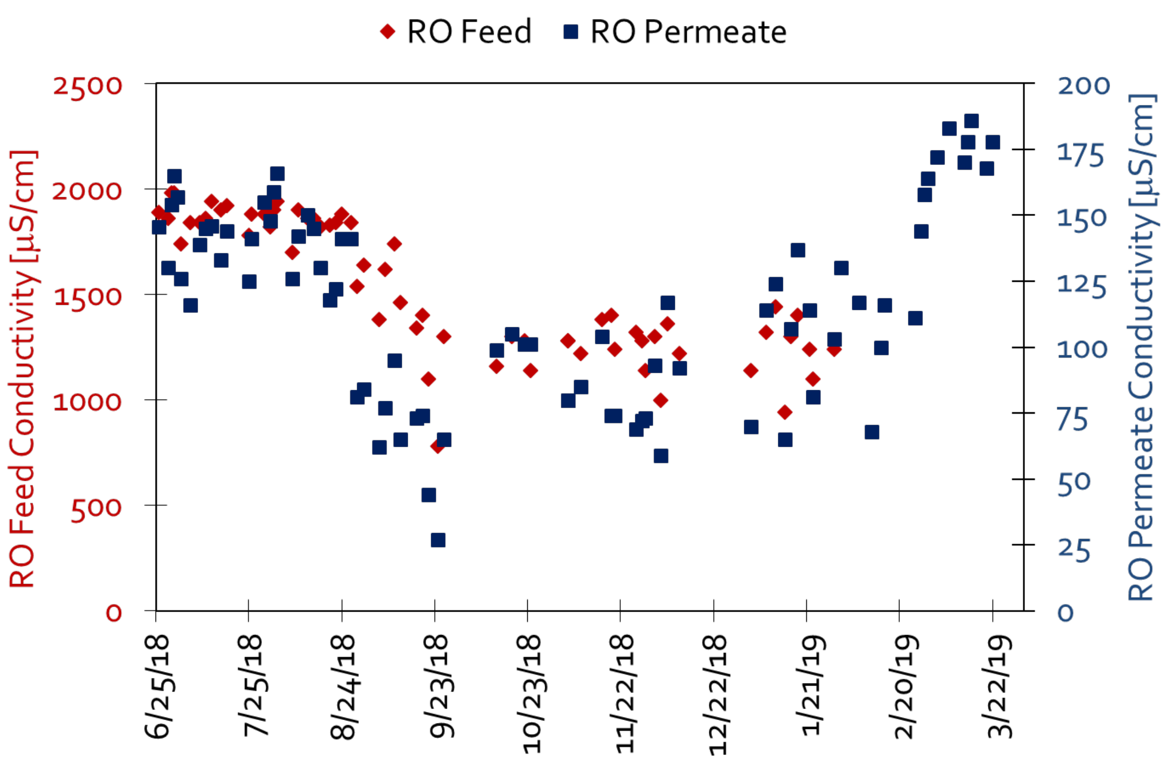

Figure 14. RO Feed and Permeate Electrical Conductivity.

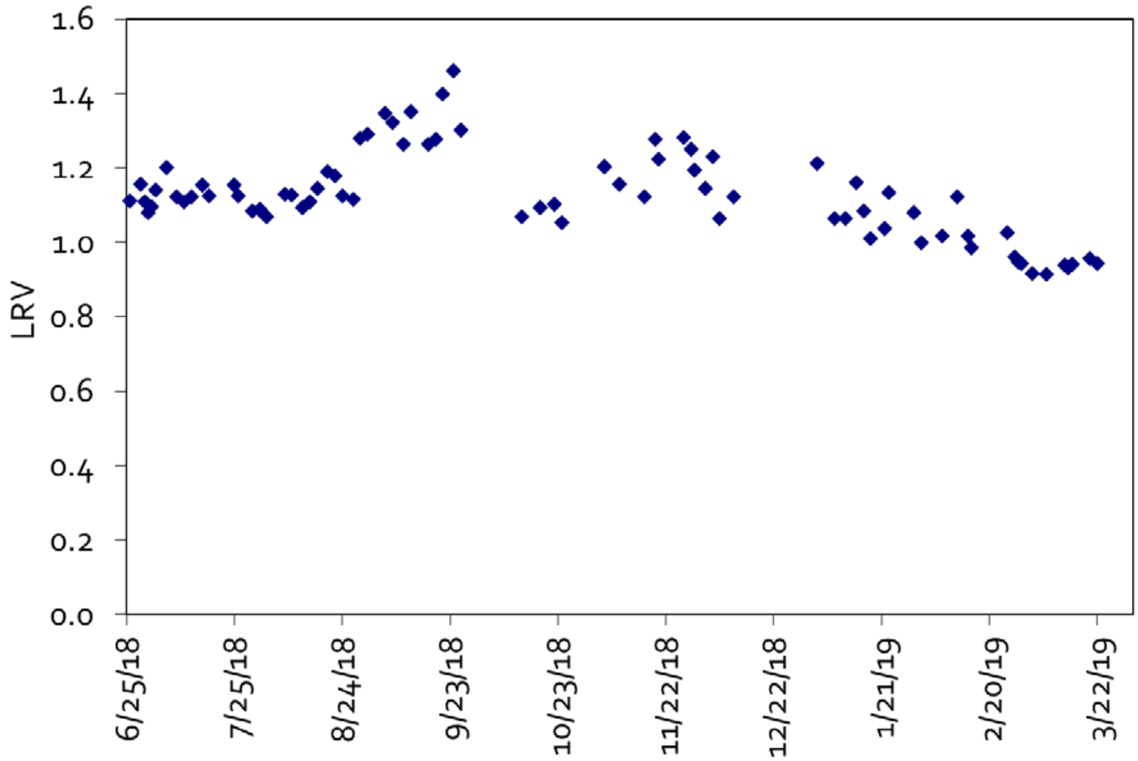

Figure 15. RO LRV Based on Electrical Conductivity Reduction.

3.3.2.2. Total Organic Carbon

The RO system used the s::can to measure TOC at the RO feed and permeate; the data are summarized below in Figure 16. The TOC concentration in the RO permeate increased over the course of the demonstration project. This matches the EC data trends and can be attributed to the oxidation of the RO membranes by free chlorine. During the nine-month operation, the s::can recorded 32 events (3 percent of the time of operation) where the TOC concentration in the RO permeate was above the DDW-required maximum concentration of 0.5 mg/L (DDW 2018). Most of these events occurred during the last 3 months of operation. The spike in TOC observed during early November was recorded during intermittent operation of the RO system due to a low-pressure alarm that caused the system to shut down.

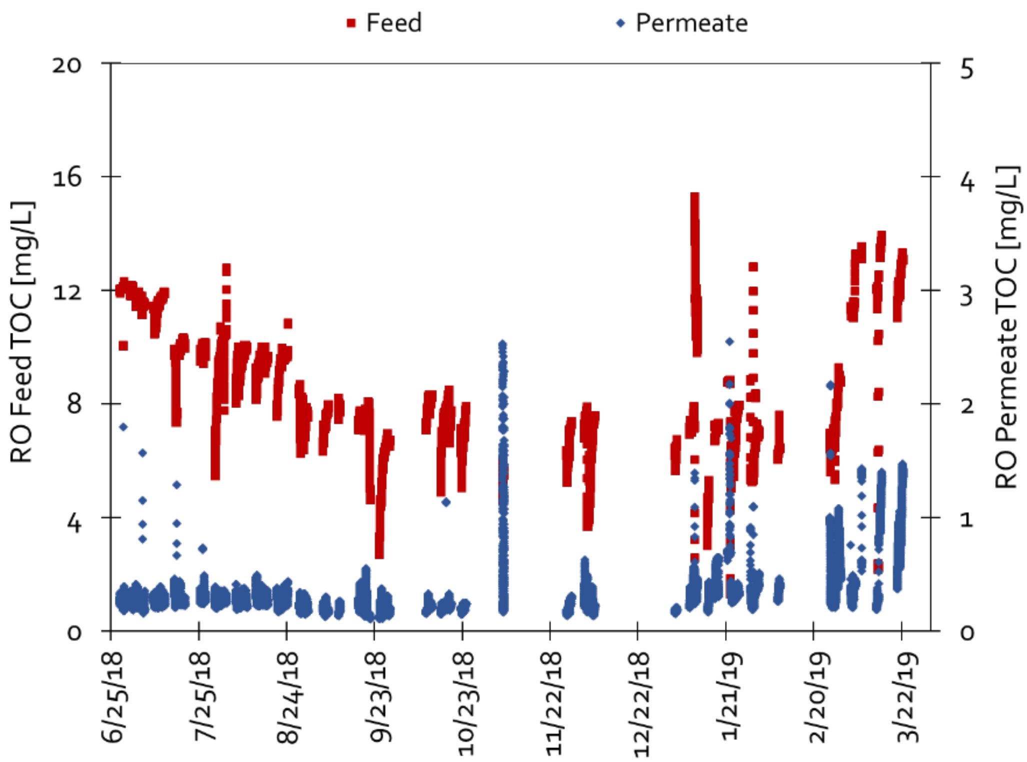

Figure 16. RO Feed and Permeate TOC Concentration.

Table 17 summarizes the RO feed and permeate TOC concentration measured by the s::can, noting both substantial variation of the permeate TOC data (average 0.36 mg/L) and the high values (0.63 mg/L). Comparable TOC concentrations were observed from the grab samples for the RO feed and permeate. The TOC grab concentrations averaged 10.98 and 0.33 for the RO feed and permeate, respectively. The log removal value (LRV) for TOC averaged 1.41 (10^{th} percentile = 1.17; n= 36,960). As it was observed in the EC LRV trend, the TOC LRV decreases towards the end of the demonstration period (Figure 17), suggesting RO membrane damage due to free chlorine exposure.

Table 17. TOC s::can Online Monitoring vs. Grab Samples Summary.

Location	Average		10th Percentile		90th Percentile	
	s::can	Grab	s::can	Grab	s::can	Grab
Feed	8.9	10.98	2.3	9.57	11.81	12.38
Permeate	0.36	0.33	0.07	0.28	0.58	0.38

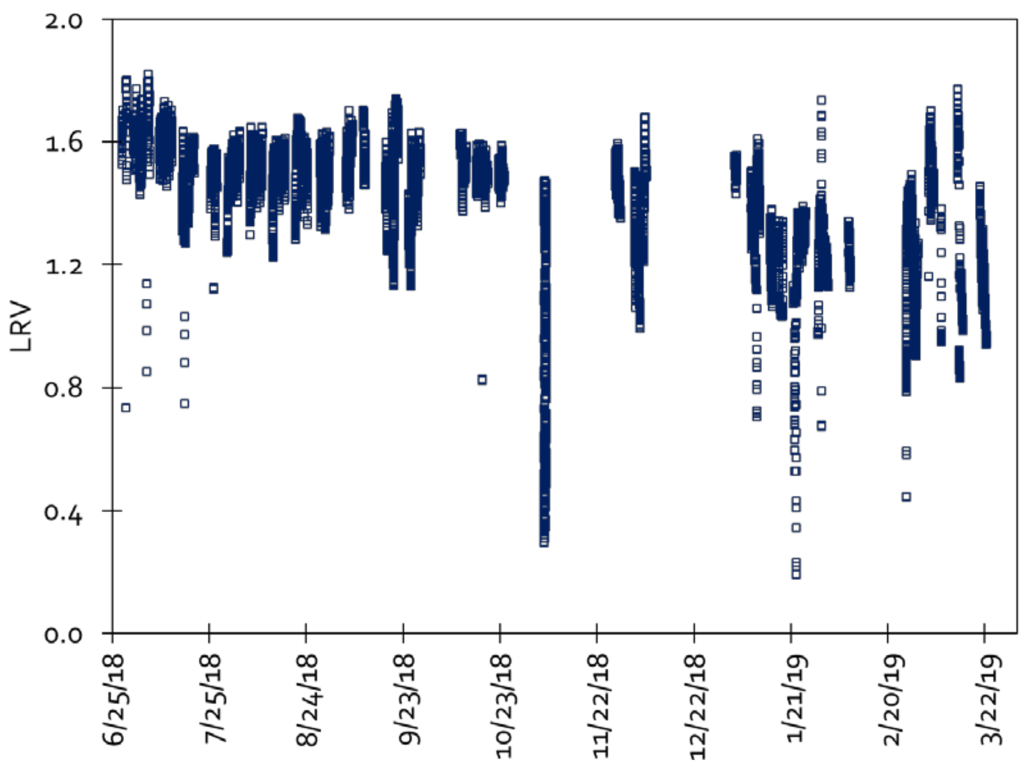

Figure 17. RO TOC Log Removal Value.

The TOC reduction in other research typically has shown values greater than 1.5. For example, WateReuse Research Foundation Project 11-02 (Gerringer et al. 2014) showed TOC reduced from 5 mg/L to 0.1 mg/L (ASTM 5310C), a log reduction of 1.7. Care should be taken in examining TOC removal by RO systems, as much greater log removal of TOC has been shown for projects with online TOC meters (which have a low-level detection limit), as shown in Table 18.

As referenced earlier, the State of California does credit virus and protozoa removal for RO based upon the log reduction of TOC (or EC), which has been shown in the literature to be a conservative assumption.

Table 18. Comparison of TOC and EC LRVs for Various California Potable Reuse Facilities.

Location/Type	TOC LRV	EC LRV	Notes
Oxnard/Full Scale	>1.5 (grab)	1.3 to 1.4	EC online TOC Grab samples, MDL 0.5 mg/L

Location/Type	TOC LRV	EC LRV	Notes
SCVWD/Full Scale	>1.4 (grab)	1.7	EC online TOC Grab samples, MDL 0.5 mg/L
Terminal Island/Full Scale	>2.2 (online) >1.2 (grab)	1.6 to 1.7	EC online TOC Grab samples, MDL 0.5 mg/L TOC online down to 0.01 mg/L
Pismo/Demo	>1.6 (grab)	~1.6	TOC Grab samples, MDL 0.5 mg/L EC online
Ventura/Demo	>1.4 (grab)	1.3 to 1.8	EC online TOC Grab samples, MDL 0.5 mg/L
San Diego/Demo	2 to 2.3 (online)	1.7 to 1.9	EC online /TOC Online

3.3.2.3. Nitrate and Nitrite

The nitrate and nitrite in the RO feed and permeate were continuously monitored during the operation of PureWaterSF using the s::can (Figure 18). Average nitrate concentrations in the feed and permeate were 35.39 mg/L and 7.07 mg/L, respectively. Higher concentrations were observed at the beginning of testing as the s::can was being calibrated. The nitrate average concentration in the RO permeate is below the regulatory limit of 10 mg/L. The nitrite average concentration of 0.48 mg/L in the permeate was below the regulatory limit of 1 mg/L. As observed with the TOC concentration, the nitrate and nitrite concentration in the RO permeate increased as the demonstration project progressed.

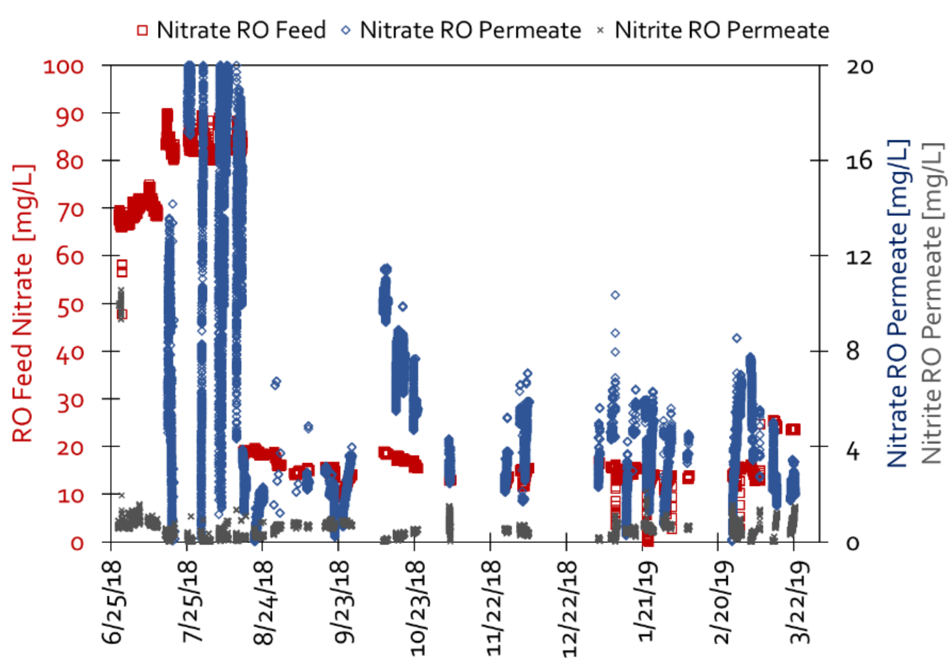

Figure 18. RO Feed and Permeate Nitrate and Nitrite Concentration.

Table 19. Nitrate and Nitrite Summary Results.

Parameter	Feed				Permeate			
	5th	Average	75th	90th	5th	Average	75th	90th
Nitrate as N [mg/L]	13.53	35.39	55.46	73.51	5.18	7.07	12.1	16.63
Nitrite as N [mg/L]	NA	NA	NA	NA	0.2	0.48	0.76	1.01

3.3.2.4. UV254

The s::can collected continuous data for UV254 for the RO feed and permeate. For the purpose of this analysis, Figure 19 shows the calculated UVT from the UV254 values for the RO feed and permeate. As expected, the UVT values increase after the RO system due to the removal of organic compounds by RO. The RO feed chloramine concentration and the RO permeate (UV AOP feed) UVT and free chlorine concentration are shown in Figure 20 and Figure 21. There is not a noticeable impact on the UVT with variation in the RO feed chloramine nor the RO permeate free chlorine concentration.

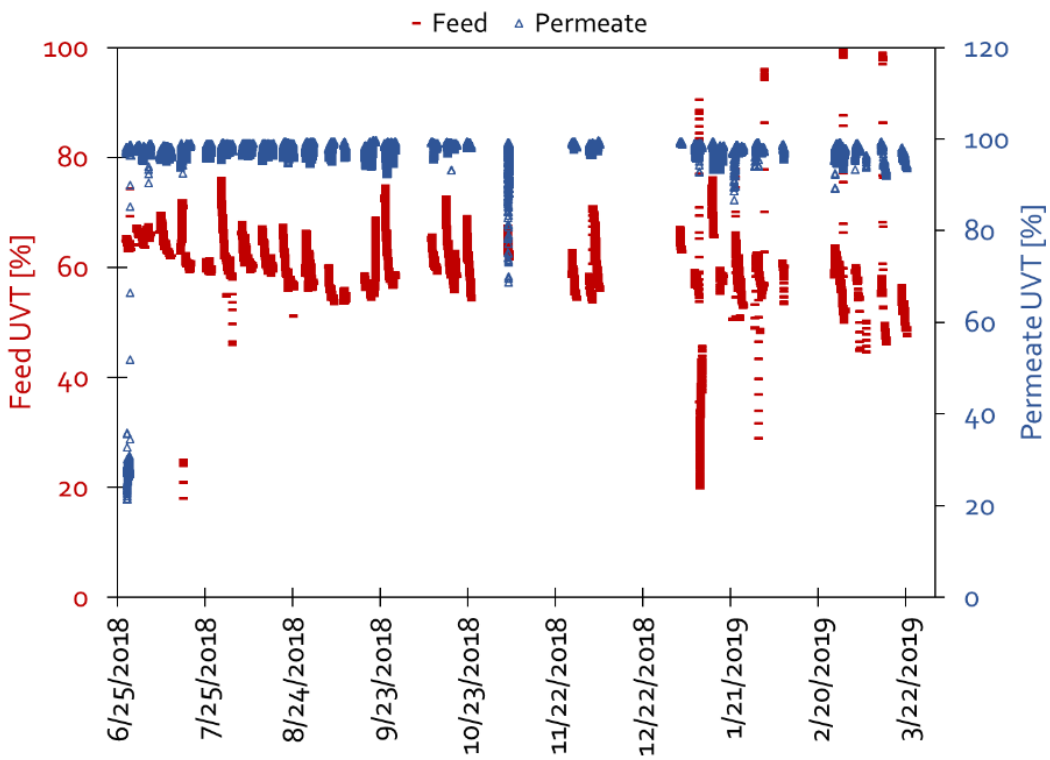

Figure 19. RO Feed and Permeate UVT.

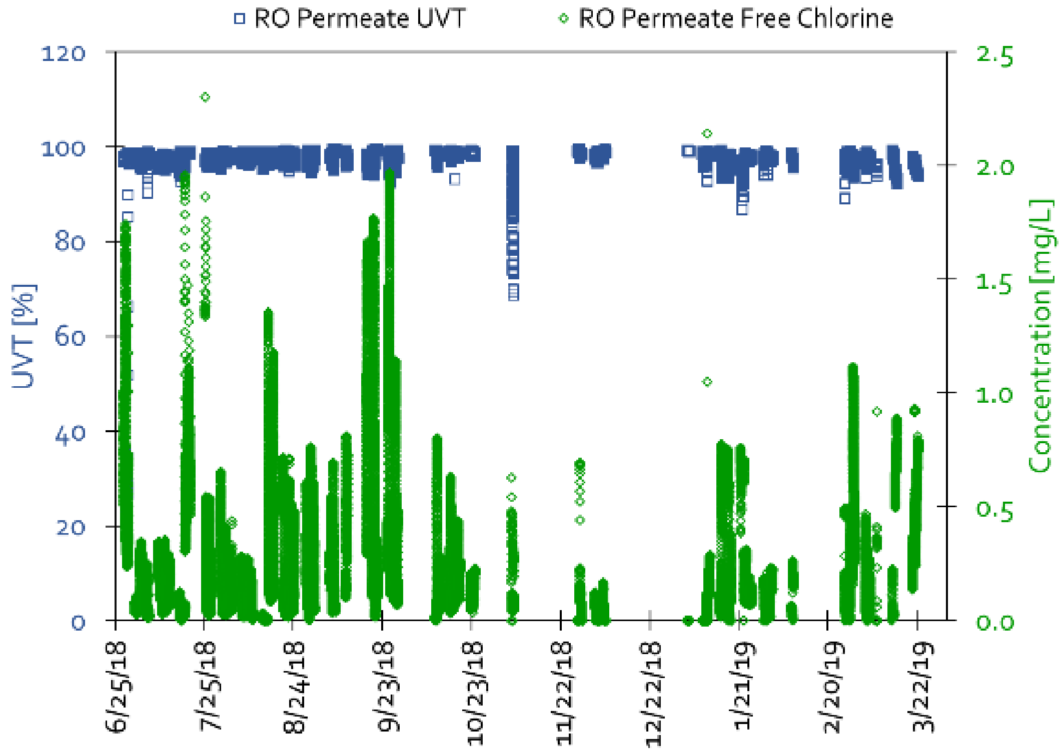

Figure 20. RO Permeate UVT and Free Chlorine.

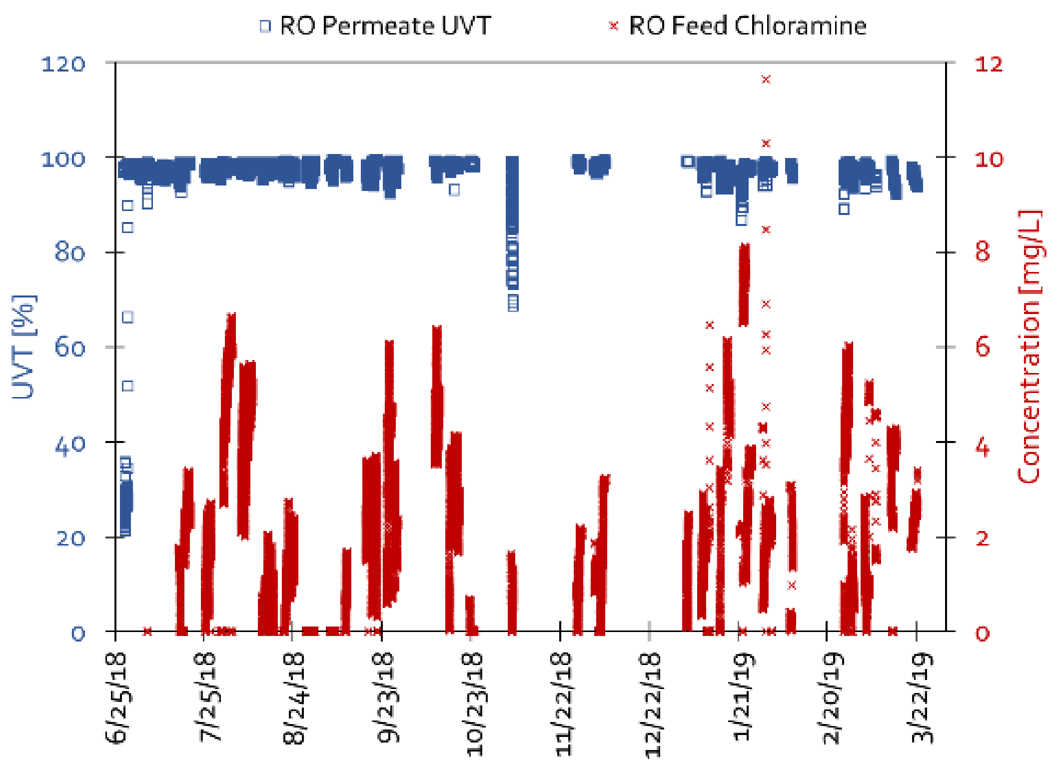

Figure 21. RO Feed Chloramine and RO Permeate UVT.

3.3.3. RO Key Findings

Key findings for the RO system are summarized below:

- High free chlorine concentration in the RO feed water likely oxidized the membrane and damaged the membrane integrity. As a result, an increase in the EC, TOC, nitrate, and nitrite concentrations occurred as the project progressed.
- Lower average LRVs for EC and TOC were observed during the operation of PureWaterSF compared to other demonstration projects like Ventura and Pismo Beach. These lower values may be attributed to damage to the RO membranes due to high free chlorine concentration (>0.01 mg/L) exposure.
- No noticeable impact from the feed chloramine and permeate free chlorine concentration was observed on the UVT in the feed to the UV AOP system.

Note that the impact of free chlorine on RO performance is a concern to the industry but was especially challenging for this demonstration facility due to the Living Machine effluent disinfection system. The issue was primarily a result of the fact that the Living Machine was not designed to feed an advanced water treatment system. The chlorination system as designed is effective at maintaining a chlorine residual for the non-potable water feeding the building's toilets. This free chlorine challenge is not an inherent problem for building-scale reuse and can easily be eliminated by designing a treatment train appropriate for the envisioned end uses.

3.4. Ultraviolet Advanced Oxidation Process

The UV AOP system was only put into operation during tours and during sampling events. UV system operational criteria are well-determined through work at other locations.

For potable reuse applications, the UV system provides three important benefits:

- UV inactivates virus, protozoa, and bacteria. No measurable concentrations of these pathogens are typically found in RO permeate, but the added disinfection is needed to further reduce viable pathogen concentrations.
- The UV system destroys NDMA, a pollutant with a CA DDW (2018a) notification level (NL) of 10 ng/L (parts per trillion). UV is proven to destroy NDMA through photolysis, with approximately 90 percent removal based upon a UV dose of ~900 mJ/cm^2 (Sharpless and Linden 2003). For a potable reuse system, the UV system must meet the NDMA NL of 10 ng/L, and a robust design can result in an NDMA level of 5 ng/L on average (or lower).

- The UV process, when combined with an oxidant (H_2O_2 or NaOCl), generates hydroxyl radicals which destroy a wide range of trace level pollutants. As part of a potable reuse treatment train, DDW (2018a) requires AOP that provides a minimum of 0.5 log reduction of 1,4-dioxane. The UV dose that, when combined with an oxidant, is necessary to provide 0.5 log reduction of 1,4-dioxane is site-specific and based on a number of water quality parameters, including the concentration and type of hydroxyl radical scavengers in the water.

Figure 22 shows the UV AOP influent (RO permeate) UVT data, continuously recorded by s::can, and UVI measured by the UV system's sensor for the duration of PureWaterSF. Permeate UVT values were lower by the end of the demonstration project consistent with the trend observed in the EC and TOC concentrations. UVI values also decreased, likely impacted by the UVT values.

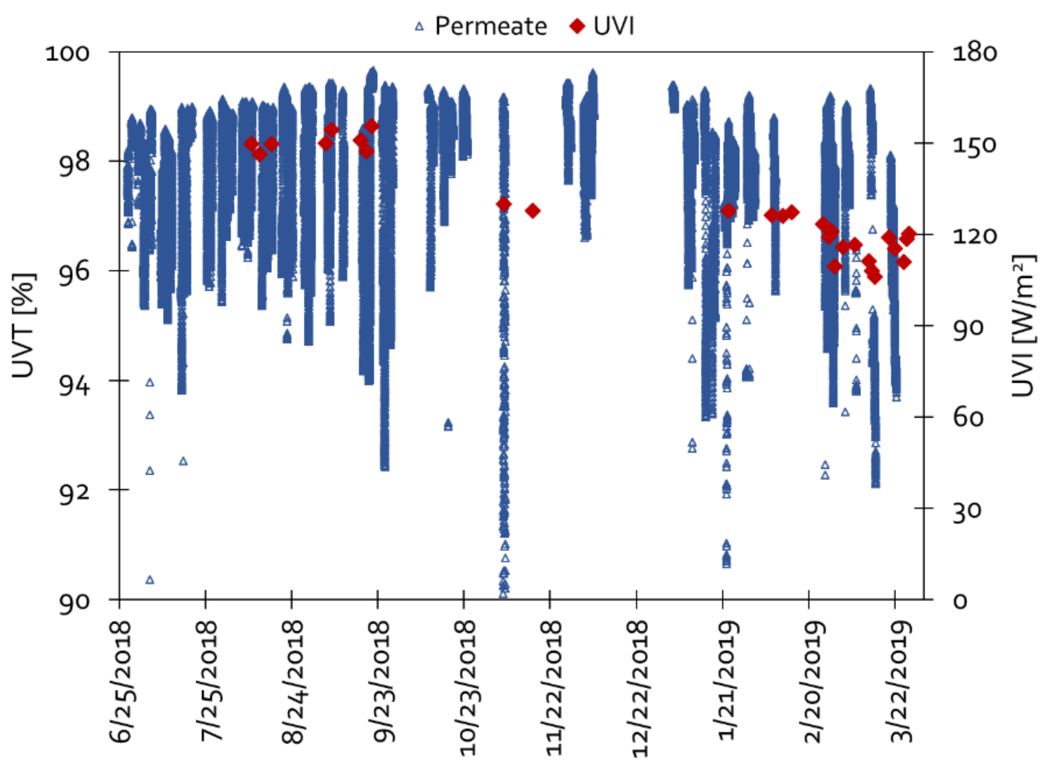

Figure 22. UV AOP Influent UVT and UV Intensity.

Table 20 summarizes the data collected during the operation of the UV system. The average effluent UVT was 99.08 percent. It should be noted that no NaOCl was dosed ahead of UV during the operation of the UV when this data was collected, but both free chlorine and chloramines were in the RO permeate as discussed previously. All UVI measurements were recorded with the UV lamp operating at a 100 percent set point.

Table 20. UV Summary Results.

Parameter	5^{th} Percentile	Average	75^{th} Percentile	90^{th} Percentile
UVI [W/m^2]	101.98	127.96	138.62	148.21
UVT Influent [%]	94.24	97.16	98.36	99.44
UVT Effluent [%]	98.42	99.08	99.35	99.59

Additional testing will be performed during the second part of this project (funded by the WRF 4691 grant) to demonstrate the performance of the UV system, including pathogen surrogate seeding and dose/response. PureWaterSF will also monitor for pathogen removal by collecting grab samples for pathogens and surrogates at various points in advanced water treatment train (raw wastewater, RO feed and permeate, and UV AOP effluent (finished water).

4. Conclusions and Next Steps

4.1. Conclusions

Based on the operational results presented in this report, conclusions about the operation of PureWaterSF are summarized below for different elements of the system.

For the s::can element:

- Overall, the s::can was able to monitor the RO system and provide useful data to determine the performance variability.
- The overall reliability of the probe varied by parameter, and a higher degree of reliability is necessary for operational potable water reuse systems.
- Additional maintenance and calibration were required to keep the chlorilyzer probe operational.

Table 21 summarizes the performance of the s::can by CCP and OCP.

Table 21. s::can Performance Summary.

Process	Parameter	CCP Surrogate	OCP	Location	Reliability of Online Probe (percent)	Significant Challenges
UF	PDT	✓		UF system	NA	None
	Turbidity		✓	s::can (RO feed and permeate)	93 / 92	Lower range values might need to increase calibration frequency
RO	EC	✓		RO system	NA	None
	Temperature		✓	s::can (RO permeate) and RO system	96	None
	pH		✓	s::can (RO permeate)	96	None
	TOC	✓		s::can (RO feed and permeate)	95 / 94	Feed water quality variation – out-of-range operation
	Nitrate	✓		s::can (RO	91 / 83	Reading out-

Process	Parameter	CCP Surrogate	OCP	Location	Reliability of Online Probe (percent)	Significant Challenges
				feed and permeate)		of-range
	Nitrite	✓		s::can (RO permeate)	91	Reading out-of-range
	Free Chlorine		✓	s::can (RO feed and permeate)	83 / 82	Feed water quality variation – out-of-range operation. Weekly operation and maintenance (electrolyte gel replacement and calibration)
	Chloramine		✓	s::can (RO feed)	80	Feed water quality variation Out-of-range operation
UV	UVI	✓		UV system	NA	None
	UV254	✓		s::can (RO permeate = UV influent)	96 / 94	None
	Free Chlorine		✓	s::can (RO permeate = UV influent)	82	Feed water quality variation – out-of-range operation
	Chloramine		✓	s::can (RO feed)	80	Feed water quality variation – out-of-range operation

For the UF system:

- UF was a suitable pretreatment for RO feed water. The UF filtrate was within specificatons for RO feed water.
- MC and CIPs were able to reverse fouling and recover permeability.
- Even though the UF filtrate turbidity values were above Title 22 and USEPA MFGM, the PDT and calculated LRVs were between 4-log to >4.5-log removal, as measured through the membrane integrity tests.

For the RO system:

- High free chlorine concentration in the RO feed water likely oxidized the membrane and damaged the membrane integrity. As a result, an increase in the EC, TOC, nitrate, and nitrite concentrations occurred as the project progressed.
- Lower average LRVs measured via EC and TOC rejection were observed as compared to values observed in other demonstration projects.

For the UV AOP system:

- Additional testing will be performed in the next phase of this project to determine the performance of the UV AOP system.

This project represents an important evaluation of decentralized DPR at the building scale. Regarding the critical components to successfully implement DPR (NWRI 2015), Table 22 summarizes the challenges encountered during operation of PureWaterSF and future potential solutions proposed to reduce or manage the implications.

Table 22. Challenges Encountered during PureWaterSF Operation and Future Potential Solutions.

Issue	Challenges encountered for This Building Scale AWTF	Specific Factors Affected by Challenge	Potential Solutions/Conclusions from This Work
Source Control for Chemical Discharges	• No outstanding challenge. Only municipal waste with a small volume of cleaning chemicals.	No challenges.	(Not Studied for this work) • Use biodegradable cleaning chemicals. • Educate the users on good disposal practices (avoid disposal of pharmaceuticals and personal care products).
Wastewater Flow and Quality	• Highly variable wastewater flow results in cycling of the treatment systems and variable effluent quality after treatment. • Highly concentrated organic waste. o Majority of wastewater is from toilets and urinals. o Only occurs during weekdays.	Challenge to any type and size of building scale treatment system.	• Equalization needed to maintain constant flow. Without equalization, the on/off cycles impact system operational efficiency and put excess wear on the equipment. • Design biological systems for a more concentrated waste in some locations.
Wastewater Pathogens	• Lack of information on small systems pathogen variations, in particular at the Building Scale. o Concern focuses upon periods of high illness within a building.	Greater potential challenge and risk for smaller systems.	(Studied as part of WRF 4691) • Examine wastewater pathogen concentrations and variability from a small population. • Increase treatment barriers to compensate for potentially higher pathogen levels during a local outbreak.
Wastewater Treatment	• Limited space. Technology may be based on footprint and compact design instead of BAT. • Cost. Substantially higher cost per gallon treated for decentralized system.	Challenge to any type and size of building scale treatment system.	• Do not let footprint dictate process or process components. • Recirculating systems, engineered due to variable flow, should be minimized or avoided, reducing or eliminating the water quality challenges (turbidity/solids and free chlorine) witnessed as part of this project.
AWTF Performance	• Lack of a performance record for regulatory and public confidence.	Challenges can apply to many types of	• Related to the Living Machine, equalized flow and unchlorinated feed water would improve system

Issue	Challenges encountered for This Building Scale AWTF	Specific Factors Affected by Challenge	Potential Solutions/Conclusions from This Work
	• Impact of variable feed water quality on AWTF performance, membrane integrity, and membrane O&M.	biological systems but was keenly impacted by the Living Machine.	performance. • Extensive evaluation of pathogen and chemical rejection by decentralized systems (as is being done by WRF 4691) would improve confidence in public health protection. • Use of accurate and precise online monitoring systems is needed to better track, trend, and repair AWTF performance.
AWTF Monitoring	• Decentralized DPR systems require equal or greater monitoring (in the breadth and type of monitoring systems) compared to centralized systems.	Challenge to any type and size of building scale treatment system.	• Surrogates can be used for each key process to provide confidence in treatment performance. • Progress in real time or near real time pathogen monitoring will provide greater operational confidence.
	• Accuracy and precision of monitoring systems remain a challenge and must be better understood (and addressed) prior to implementation of decentralized DPR systems.	Challenge to any type and size of building scale treatment system	• Increase calibration frequency of sensitive parameters (e.g., free chlorine and turbidity). • Develop sensor technologies with a greater operational range, precision, and accuracy. • Include additional probes for redundancy.
	• Substantial O&M time is needed for the current online metering systems.	Challenge particular to the Living Machine effluent, but also challenging to any size project.	• More research is needed to define effective combinations of sensor networks to provide greater reliability.

4.2. Recommended Next Steps

4.2.1. Technical Recommendations

An extensive amount of information on the PureWaterSF building-scale AWTF was captured in the nine-month duration of the study. A few key areas for optimization were identified that could not be included in this study due to budget constraints and/or time limits. Several research concepts are presented below that can be explored to optimize the performance of PureWaterSF.

For the s::can element:

- Increase the calibration frequency to capture the water quality variability.
- Install different online monitoring systems to compare results' reliability and accuracy. Particularly for chlorine, turbidity, and TOC.

For the UF system:

- Test different coagulant types and concentrations to help with TSS spikes in the UF feed water.
- Determine DBPs (THMs and HAA5) formation pre-chloramination of the membrane.

For the RO system:

- Operate the RO after the LM's disinfection step improvements are completed to optimize the chlorine dose ahead of PureWaterSF.
- Implement better control of chlorine dose to allow operation of the RO system without exceeding the recommended concentration of 0.01 mg/L of free chlorine, thus preventing oxidation of the RO membranes and improving the rejection of dissolved salts and trace organics.
- Conduct RO Membrane autopsy to determine the type and concentration of material fouling/scaling the membrane.

For the UV AOP system (UV challenge test included in WRF 4691):

- Microbial Challenge – Validate the high dose delivered using microbiological challenge study, i.e., Aspergillus brasiliensis (A. brasiliensis), a fungal spore with a high resistance to UV. The test organism allows an estimation of dose, which can then be correlated to a specific log reduction of a broad range of pathogens, including virus. This organism has been successfully tested at the Direct Potable Reuse Demonstration Pilot in Altamonte Springs and at the Pismo Beach Demonstration Project (City of Altamonte Springs 2018; Pismo Beach 2019).

- Chemical Challenge – Perform destruction of 1,4-dioxane across the UV AOP system. Of particular interest is to determine the impact of chloramines as hydroxyl radical scavengers. Chloramines react quickly with hydroxyl radicals and thus prevent them from reacting with the contaminants they are intended to destroy (Johnson et al. 2002; Chuang et al. 2017; Patton et al. 2016).

WRF 4691 Additional Work:

- Conventional Parameters
    - These parameters will be measured at the UF, RO, and UV AOP effluent.
    - Regulated parameters for potable water in California (as defined by Primary Maximum Contaminant Levels (MCLs) and Secondary MCLs.
- Trace Level Chemical Constituents: Regulated chemicals and unregulated trace level chemical constituents will be monitored across the advanced water treatment train.
    - Pharmaceuticals and Personal care Products (PPCPs), Perfluorinated Compounds (PFCs)
    - N-nitrosomorpholine (NMOR) and N-Nitrosodimethylamine (NDMA)
    - NDMA Simulated Distribution System (SDS)
    - Trihalomethanes (THM) and Haloacetic Acids (HAAs) SDS
    - Perfluorooctanesulfonic acid (PFAS)
    - Fluorescence excitation-emission matrices (EEMs)
    - Non-Target Analysis NTA using gas chromatography (GC-NTA) and liquid chromatography (LC-NTA).
- Advanced Analytics
    - Estrogen-like chemicals using human estrogen receptor (alpha and alpha/beta) responsive cell bioassays.
    - Androgen-like chemicals using a human androgen receptor-responsive cell bioassay.
    - Glucocorticoid / -progesterone-like chemicals using a human glucocorticoid and progesterone receptor-responsive cell bioassay.
    - Dioxin-like chemicals using human or rodent Ah receptor-responsive cell bioassays.
    - Cytotoxic chemicals that produce toxicity in the mammalian cells.

4.2.2. Broader Considerations

The future of water reuse includes both centralized and decentralized systems. While the focus of this research is on the technologies and the processes, there is substantial information that can be applied to any decentralized purification system. A design and operational framework is needed for decentralized non-potable reuse facilities to consider how to properly convert to potable water reuse.

Such a conversion will require robust upgrades in treatment processes and process monitoring as well as operations and maintenance training and skill. The costs of these upgrades need to be balanced with the water supply benefit (e.g., building wide increase in water reuse for potable compared to non-potable applications such as toilet flushing and irrigation).

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Glossary

Terminology related to potable water reuse has evolved from the initial classification of indirect and direct potable water reuse defined in the report *Framework for Direct Potable Reuse* (WateReuse 2015) to more specific definitions established by California Assembly Bill 574, passed in October 2017. This bill finds that, by June 2018, the State Board should establish a framework for the regulation of potable reuse projects to encourage the development of potable reuse to mitigate the impact of long-term drought and climate change. The term "potable reuse" incorporates all types of water reuse that are safely incorporated into potable water supplies. For the purposes of this report, the term "potable reuse" refers to the practice of using purified water derived from wastewater effluent to supplement water supplies.

The definitions below were compiled from the *Framework for Direct Potable Reuse* and California Assembly Bill 574 to reflect the recent changes in the terminology and for the specific terminology applicable to PureWaterSF:

Disinfected Tertiary Recycled Water: Water that has been filtered and subsequently disinfected to "Title 22" standards for unrestricted non-potable reuse applications.

Purified Water: Water that has been treated at a wastewater treatment plant and a full advanced treatment plant (or advanced water purification facility) and has been verified through monitoring to be suitable for augmenting drinking water supplies.

Indirect Potable Reuse (IPR): The addition of recycled and/or purified water to augment groundwater or surface waters. Groundwater and surface waters are considered environmental buffers for providing public health protection benefits, such as contaminant attenuation dilution, and time to detect and respond to failures before final treatment and distribution. Indirect potable reuse can used with advanced treated water but can also be accomplished with tertiary effluent when applied by spreading (i.e., groundwater recharge) to take advantage of soil aquifer treatment (SAT).

IPR for Groundwater Recharge: Planned used of purified recycled water for replenishment of a groundwater basin or an aquifer that has been designated as a source of water supply for a public water system.

Reservoir Water Augmentation: Planned placement of purified recycled water into a raw surface water reservoir used as a source of domestic drinking water supply for a public water or into a constructed system conveying water to such a reservoir.

Direct Potable Reuse (DPR): Planned introduction of purified recycle water either directly into a public water system, or into a raw water supply immediately upstream of a water treatment plant. DPR includes (i) raw water augmentation and (ii) treated drinking water augmentation. Additional treatment, monitoring, and/or an engineered buffer(s) would be used in place of an environmental buffer to provide equivalent protection of public health and response time in the event that the purified water does not meet specifications.

Raw Water Augmentation: Planned placement of purified recycled water into a system of pipelines or aqueducts that deliver raw water to a drinking water treatment plant that provides water to a public water system.

Treated Drinking Water Augmentation: Planned placement of purified recycled water into the water distribution system of a public water system.

Appendix A. s::can Calibration Standards Grab Samples Summary

Parameter	Units	7/9/18		8/8/18		8/15/18		9/19/18		10/17/18		11/28/18		2/27/19		3/20/19		Average	
		Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate
Chloramine	mg/L	2.1	NA	1.1	NA	0.4	NA	0.75	NA	0.76	NA	0.19	NA	2.4	NA	2.1	NA	1.23	NA
DOC	mg/L	7.2	NA	8.3	NA	8.4	NA	12	NA	11	NA	11	NA	11	NA	13	NA	10.24	NA
Free Chlorine	mg/L	0.13	ND (0.1)	ND (0.1)	ND (0.1)	0.1	ND (0.05)	0.06	0.06	ND (0.05)	ND (0.05)	ND (0.01)	ND (0.1)	0.1	0.05	0.09	0.08	0.09	0.09
Nitrate as N	mg/L	84	11	67	9.7	70	NA	18	3.2	33	7.2	13	2.9	24	7.7	18	NA	40.87	6.95
Nitrite as N	mg/L	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)	NA	ND (0.05)
pH	--	NA	6.1	NA	5.9	NA	6	NA	6.3	NA	6.2	NA	6.2	NA	6.2	NA	6.4	NA	6.2
TOC	mg/L	9.8	0.3	10	ND (0.3)	10	0.34	12	ND (0.3)	11	0.33	11	0.34	11	0.3	13	0.42	10.98	0.33
Turbidity	NTU	NA	NA	0.0656	0.0269	0.1271	0.0633	0.1576	0.1204	0.1073	0.0655	0.3339	0.0721	0.1171	0.0872	0.4052	0.2773	0.1777	0.0971

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Appendix B. s::can Feed and Permeate Probes Performance Summary

Status Type	Definition	Chloramine		Turbidity		TOC		DOC		Nitrate		Nitrite		UV254t		Free Chlorine		pH		Temperature	
		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence	
		Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate
Blank	No status registered	4	NA	4	4	4	4	4	NA	4	4	NA	4	4	4	4	4	NA	4	4	NA
Ok 0x0000.0000.0000.0000	Operational	80	NA	93	92	95	94	95	NA	91	83	NA	91	95	94	83	82	NA	96	96	NA
Ok 0x0000.0000.8001.0000	Reading out of measuring range	0	NA	2	3	0	2	0	NA	4	10	NA	2	0	2	0	0	NA	0	0	NA
Error 0x0010.0000.0009.0000	Reading Non-A-Number (NAN), Parameter error, wrong medium	0	NA	1	2	1	0	1	NA	1	3	NA	3	1	0	0	0	NA	0	0	NA
Error 0x0011.0000.0000.0000	No communication between sensor and terminal.	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	0	NA	0	0	NA
Ok 0x0000.0000.8000.0000	Reading out of measuring range	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	3	0	NA	0	0	NA
Ok 0x0000.0000.8001.0000	Reading out of measuring range	14	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	0	NA	0	0	NA
Ok 0x0000.0000.8021.0000	Parameter not ready and out of measuring range	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	4	2	NA	0	0	NA
Error 0x0000.8000.0000.0000	Sensor maintenance required	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	8	NA	0	0	NA
Error 0x0000.8000.0021.0000	Sensor maintenance required: Parameter not ready	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	3	1	NA	0	0	NA
Error 0x0000.8000.8000.0000	Sensor maintenance required: Reading out of measuring range	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	2	3	NA	0	0	NA

Status Type	Definition	Chloramine		Turbidity		TOC		DOC		Nitrate		Nitrite		UV254t		Free Chlorine		pH		Temperature	
		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence		Percent Occurrence	
		Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate	Feed	Permeate
Error 0x0010.0000.0009.0000	[No system status error definition]: Parameter error, wrong medium.	2	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	0	NA	0	0	NA
Error 0x0000.8000.0000.0000	Sensor maintenance required	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	1	0	NA	0	0	NA
Error 0x0010.0000.8001.0000	[No system status error definition]: Reading out of measuring range.	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	0	NA	0	0	NA
Error 0x0010.8000.8021.0000	[No system status error definition]: Parameter not ready and out of measuring range.	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	0	NA	0	0	NA
Error 0x0011.0000.0000.0000	No communication between sensor and terminal.	0	NA	0	0	0	0	0	NA	0	0	NA	0	0	0	0	0	NA	0	0	NA
Total		100	--	100	100	100	100	100	--	100	100	--	100	100	100	100	100	--	100	100	--

Appendix C. Raw s::can Data

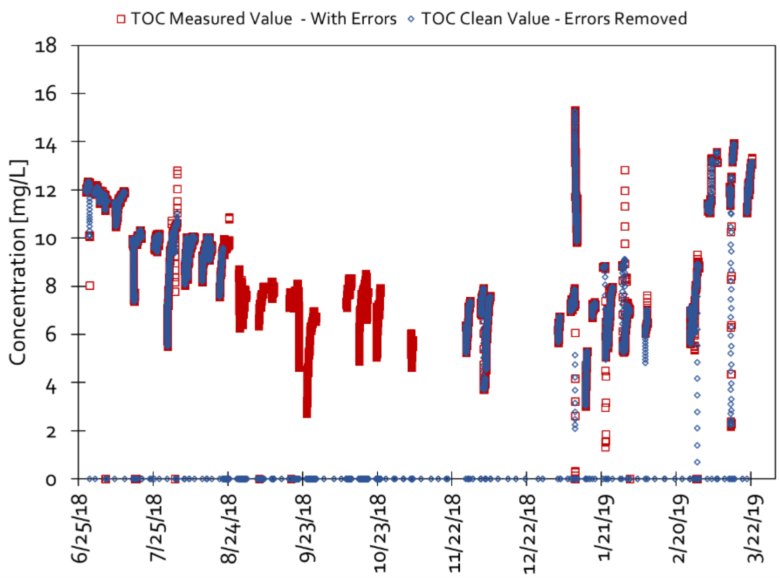

Figure C1. Feed TOC Measured vs Clean Value Comparison.

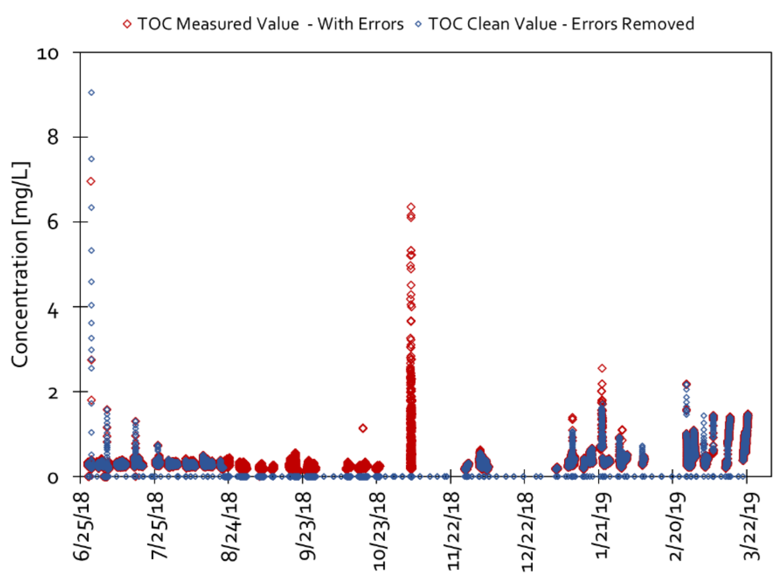

Figure C2. Permeate TOC Measured vs Clean Value Comparison.

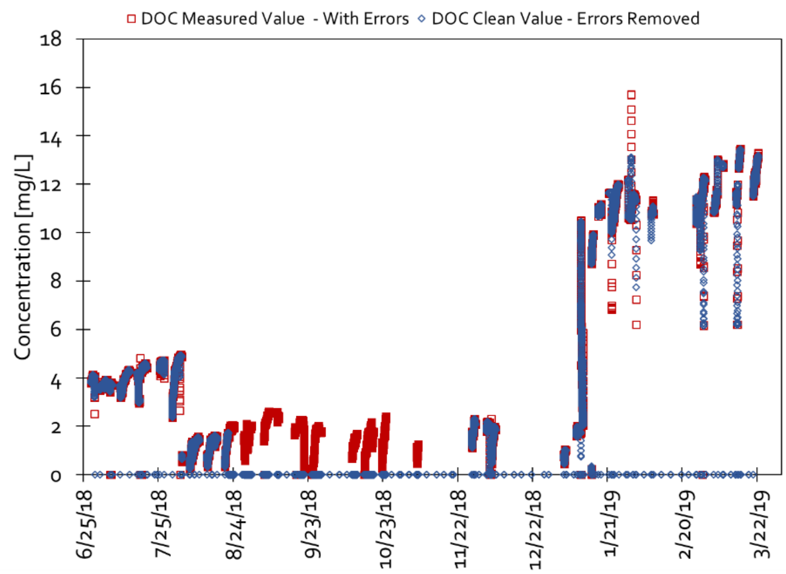

Figure C3. Feed DOC Measured vs Clean Value Comparison.

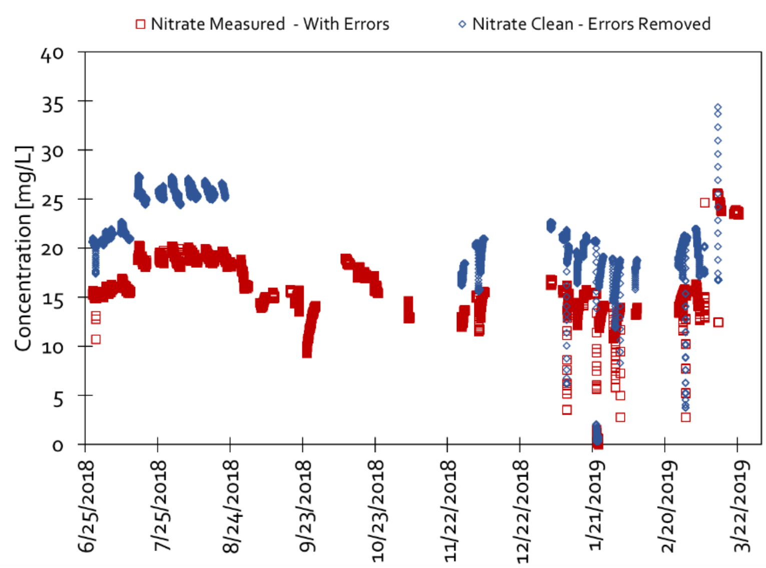

Figure C4. Feed Nitrate Measured vs Clean Value Comparison.

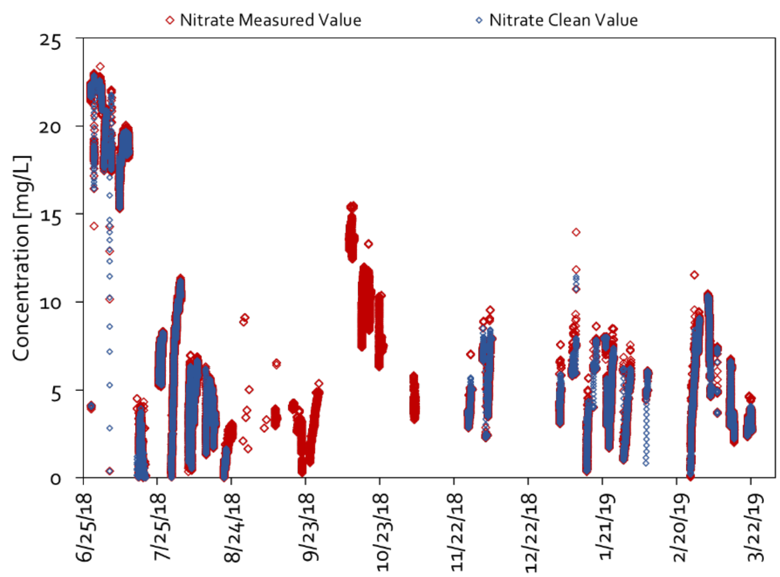

Figure C5. Permeate Nitrate Measured vs Clean Value Comparison.

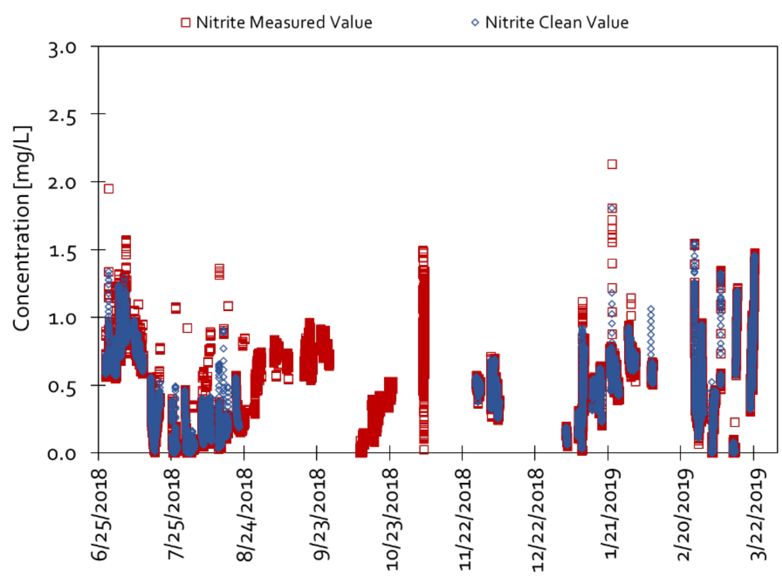

Figure C6. Permeate Nitrite Measured vs Clean Value Comparison.

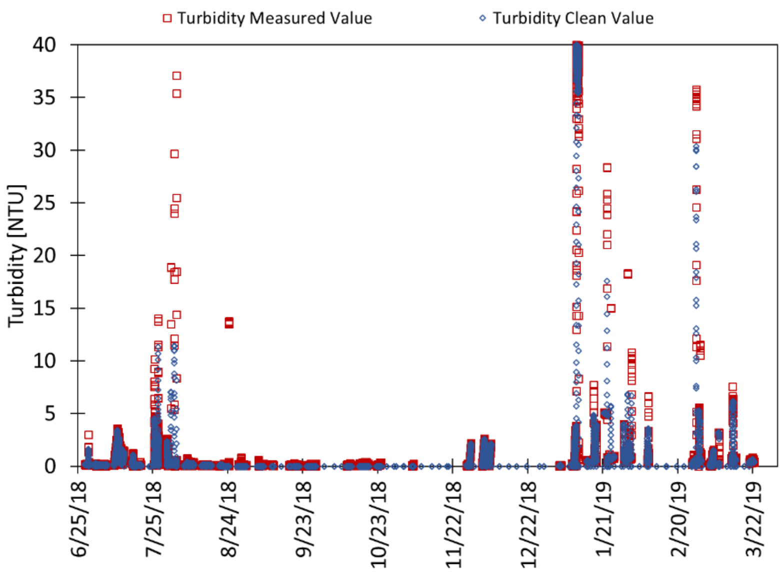

Figure C7. Feed Turbidity Measured vs Clean Value Comparison.

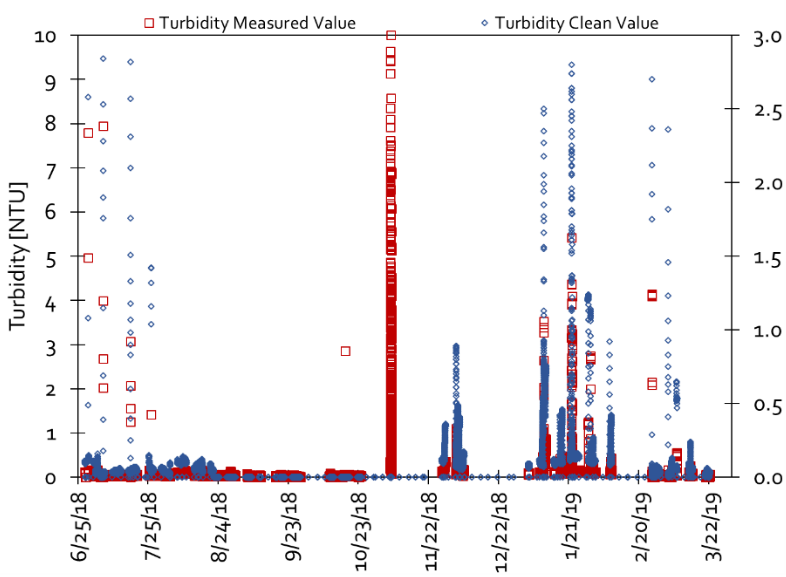

Figure C8. Permeate Turbidity Measured vs Clean Value Comparison.

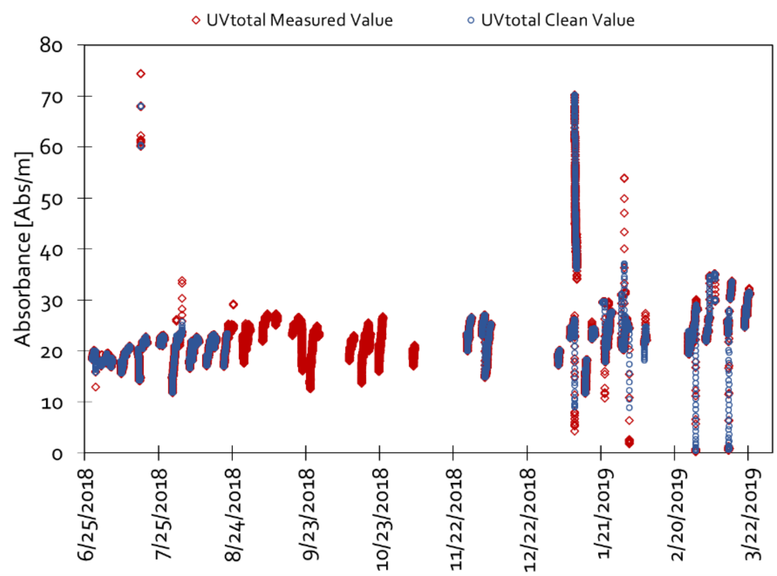

Figure C9. Feed UV_{total} Measured vs Clean Value Comparison.

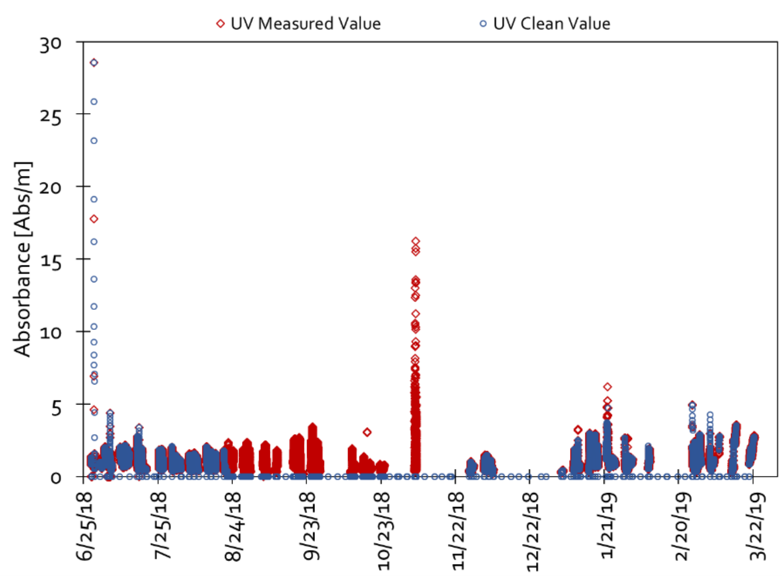

Figure C10. Permeate UV Measured vs Clean Value Comparison.

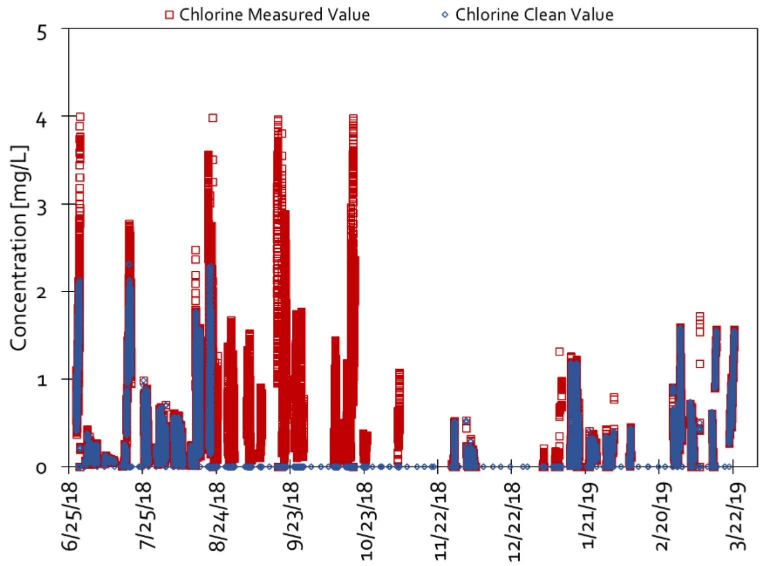

Figure C11. Feed Free Chlorine Measured vs Clean Value Comparison.

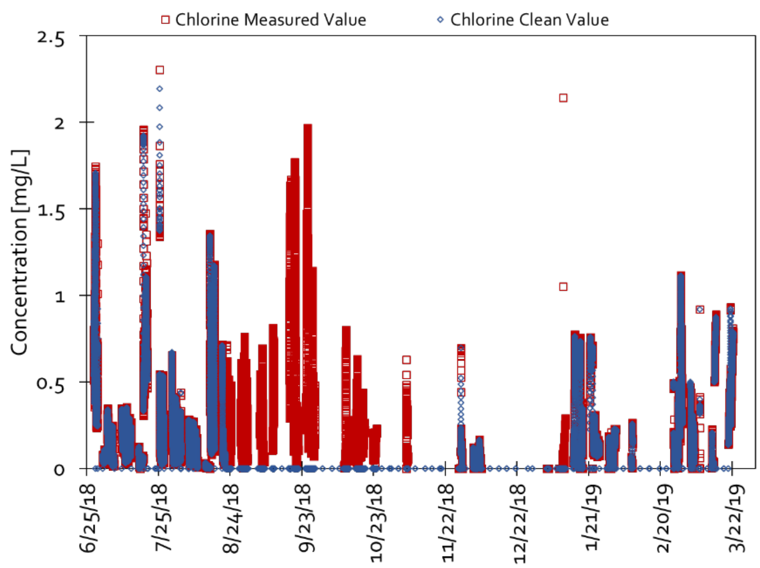

Figure C12. Permeate Free Chlorine Measured vs Clean Value Comparison.

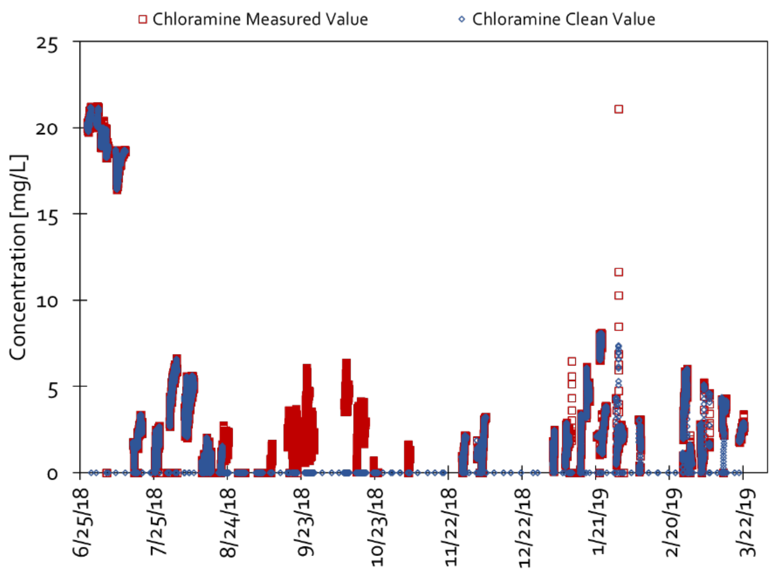

Figure C13. Feed Chloramine Measured vs Clean Value Comparison.

Appendix D – Log Removal Value Calculation

Membrane Integrity Test

The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) defines membrane filtration as follows:

"Membrane filtration is a pressure or vacuum driven separation process in which particulate matter larger than 1 micrometer is rejected by an engineered barrier, primarily through a size-exclusion mechanism, and which has a measurable removal efficiency of a target organism that can be verified through the application of a direct integrity test. This definition includes the common membrane technologies of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. [40 CFR 141.2]"

According to the LT2ESWTR, *Cryptosporidium* removal credit is given to a membrane filtration system if the process complies with the definition above, the removal efficiency is established through a product-specific challenge test, and the system undergoes periodic direct integrity test and continuous indirect integrity monitoring.

Direct Integrity Testing

A direct integrity test is defined as a physical test applied to a membrane unit in order to identify and isolate integrity breaches. Three criteria are required to be met for a direct integrity test:

i. Resolution - The direct integrity test must be applied such that a 3 micrometer (μm) breach contributes to the response from the test;

ii. Sensitivity - The direct integrity test must be capable of verifying log removal value (LRV) awarded to the membrane process;

iii. Frequency - The direct integrity test must be applied at a frequency of at least once per day.

Toray's UF membrane performs a pressure based direct integrity test (pressure decay test, or PDT) every 24 hours, which involves applying a pressure to one side of the membrane barrier and monitoring for pressure loss to establish whether an integrity breach is present. To achieve the 3 μm resolution, the net applied pressure during this test must be enough to overcome the capillary forces in a 3 μm hole, ensuring that any breach large enough to pass *Cryptosporidium oocysts* would also pass air during the test.

As part of the direct integrity test, a control limit (upper control limit, or UCL) needs to be established that represents a threshold response which, if exceeded, indicates a potential integrity problem and triggers subsequent corrective action. If the integrity test response is below the UCL, the membrane should achieve the LRV equal to or greater than the awarded log removal credit. The UCL is calculated by using system design parameters and can be calculated using the following formula.

$$UCL = \frac{Q_p \ x \ ALCR \ x \ P_{atm}}{10^{LRC} \ x \ V_{sys} \ x \ VCF}$$

Equation 4.17 (USEPA 2005), where:

- Q_p: membrane unit design capacity filtrate flow (gpm)
- ALCR: air-liquid conversion ratio (dimensionless)
- P_{atm}: atmospheric pressure (psia)
- LRC: log removal credit (dimensionless)
- V_{sys}: volume of pressurized air in the system during the test (gal)
- VCF: volumetric concentration factor (dimensionless)

The ALCR is a calculated value for every PDT, which provides an LRV as calculated by the formula below:

$$LRV = \log\left(\frac{Q_p \ x \ ALCR \ x \ P_{atm}}{\Delta P_{test} \ x \ V_{sys} \ x \ VCF}\right)$$

Equation 4.9 (USEPA 2005), where:

- ΔP_{test}: smallest rate of pressure decay that can be reliably measured and associated with a known integrity breach during the integrity test (psi/min)