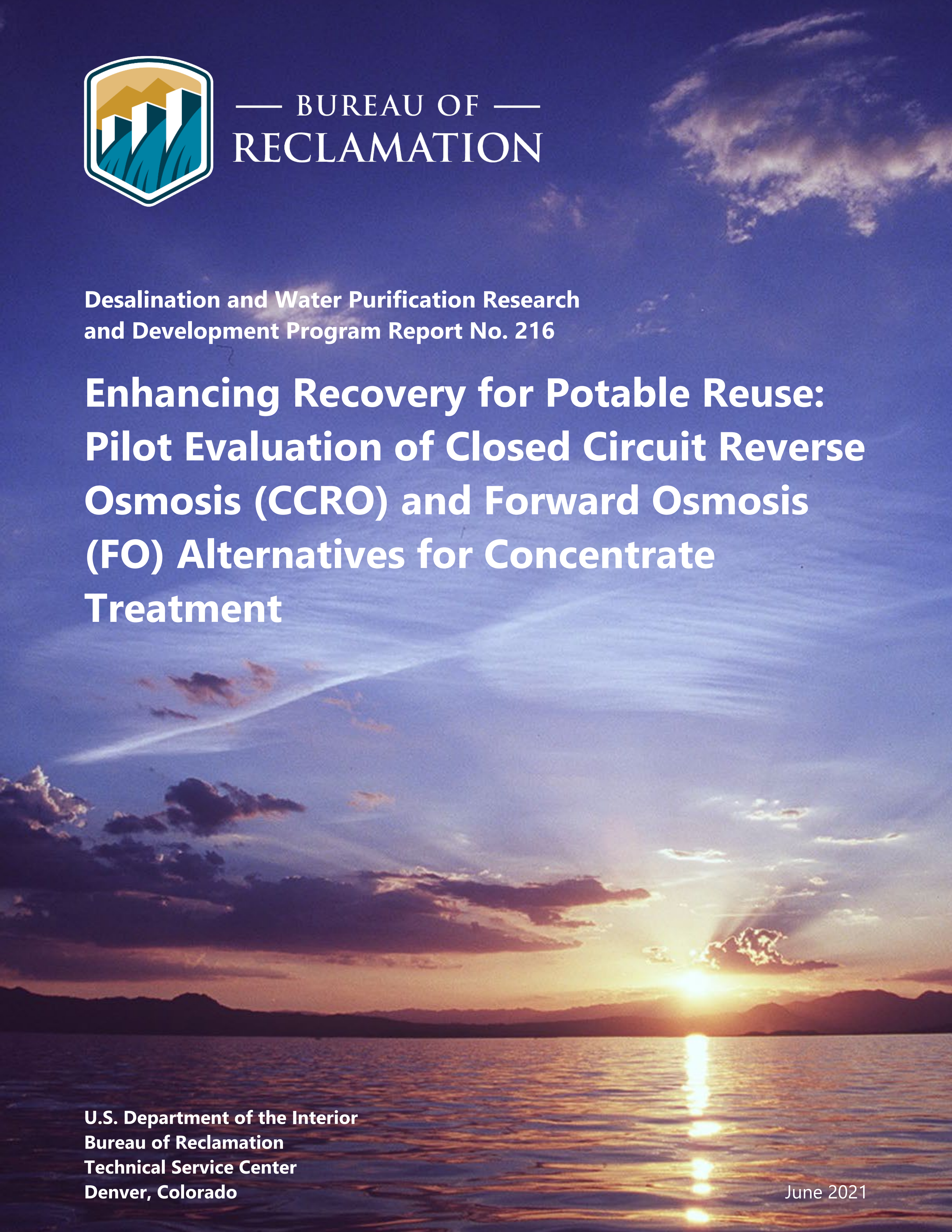

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Enhancing Recovery for Potable Reuse: Pilot Evaluation of Closed Circuit Reverse Osmosis (CCRO) and Forward Osmosis (FO) Alternatives for Concentrate Treatment

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14. ABSTRACT
Two alternative concentrate treatment technologies – closed circuit reverse osmosis (CCRO) and forward osmosis (FO) – were evaluated at pilot scale to recover water from reverse osmosis (RO) concentrate generated at the Orange County Water District (OCWD) Advanced Water Purification Facility (AWPF). Successful recovery of purified water from RO concentrate at potable reuse facilities will reduce the volume of the concentrate waste stream while generating more usable water. In addition to pilot operational feasibility and recovery optimization, the study focused on performance with respect to water quality of the product water; virus log removal via challenge testing; suitability of product water for subsequent treatment by ultraviolet advanced oxidation process (UV-AOP); and cost/footprint analysis (for a conceptual 10 or 20 million gallon per day [mgd] system) as part of an overall assessment of feasibility of these technologies for potable reuse. Both technologies (Desalitech CCRO and Porifera FO-RO) produced water of a very high quality (inorganic, organic and microbiological) suitable for blending with a primary RO system's permeate to increase overall water production and receive subsequent UV-AOP treatment in a conventional full advanced treatment train. Virus challenge testing using MS-2 coliphage demonstrated an average of 5.2-log removal by CCRO and 6.0 log-removal or greater by FO-RO. Greater virus log removal for FO-RO is likely attributed to the double membrane barrier. Based on log removal of spiked *N*-nitrosodimethylamine (NDMA) and 1,4-dioxane (common indicators of UV-AOP performance), the UV-AOP pilot treating CCRO and FO-RO permeate yielded similar performance as the existing full scale OCWD UV-AOP system that treats a conventional RO permeate. With respect to full-scale costs, the unit cost of product water produced by the two technologies is expected to be in the range of $1,126 to $1,382 per AF, depending on the volume of RO concentrate that is treated and the technology used. Given the +50%/-30% accuracy of the Class 5 cost estimate, the estimated capital plus operations and maintenance costs of the two technologies are the same on a dollar per acre-foot basis (total unit costs).

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Enhancing Recovery for Potable Reuse: Pilot Evaluation of Closed Circuit Reverse Osmosis (CCRO) and Forward Osmosis (FO) Alternatives for Concentrate Treatment

Prepared for the Bureau of Reclamation Under Agreement Number R17AC00151

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Mission Statements

The Department of the Interior conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

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.

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Acronyms and Abbreviations

Acronym or Abbreviation	Definition
3D	Three-dimensional
AACE	Association for the Advancement of Cost Engineering
AWC	American Water Chemicals
AWPF	Advanced water purification facility
CASWRCB	California State Water Resources Control Board
CC	Closed-circuit
CCRO	Closed-circuit reverse osmosis
CEC	California Energy Commission
CECs	Chemicals of emerging concern
CIP	Clean-in-place
CIT-1	CCRO feed conductivity
CIT-2	CCRO concentrate recirculation loop conductivity
DBPs	Disinfection byproducts
DWPR	Desalination and Water Purification Research and Development Program
EC	Electrical conductivity
EDS	Energy dispersive spectroscopy
EED	Electrical energy dose
EEM	Excitation-emission matrix
ELAP	Environmental Laboratory Accreditation Program
EPA	U.S. Environmental Protection Agency
FIB	Fecal indicator bacteria
FO	Forward osmosis
FPW	Final product water
FTIR	Fourier transform infrared spectroscopy
GC/MS	Gas chromatography/mass spectrometry
GWRS	Groundwater replenishing system
LACSD	Los Angeles County Sanitation Districts
LOI	Loss of ignition

Acronym or Abbreviation	Definition
LRV	Log removal value
MF	Microfiltration
MF/UF	Microfiltration/ultrafiltration
MS	Male-specific coliphage
MSU	Michigan State University
NDs	Non-detect results
O&M	Operation and maintenance
OCSD	Orange County Sanitation District
OCWD	Orange County Water District
PFDs	Process flow diagrams
R&D	Research and development
Reclamation	Bureau of Reclamation
RO	Reverse osmosis
ROF	Reverse osmosis feed water
SC	Side conduit
SEI®	Superimposed elemental imaging
SEM	Scanning electron microscopy
SOM	Somatic coliphage
SVOCs	Soluble volatile organic compounds
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
TOC	Total organic carbon
UV	Ultraviolet
UV-AOP	Ultraviolet advanced oxidation process
UVF	Ultraviolet reactor feedwater
UVP	Ultraviolet reactor product water
VOCs	Volatile organic compounds

Measurements

Unit	Measurement
%	percent
µg	microgram
µg/L	microgram per liter
µm	micrometer
0C	degree Celsius
AF	acre-feet
AFY	acre-feet per year
cm	centimeter
cm3	centimeter cube
d	day
ft	feet
ft2	feet square
gal	gallon
gfd	flux (gallons per day per foot-squared)
gfd/psi	specific flux (flux per pressure unit)
gpm	gallons per minute
hr	hour
in or ”	inch
kWh/kgal	kilowatt per hour per kilogallon
L	liter
LMH	liter per meter-squared per hour
log	log removal
M-1cm-1	molar absorption coefficient (one per molar per
M-1s-1	rate constant (one per molar per second)
m2	meter square
m3/day	cubic meter per day
mg/L	milligram per liter
mgd	million gallons per day
mJ/cm2	millijoules per square centimeter

Unit	Measurement
mL/min	milliliters per minute
MPN/100mL	most probable number per hundred of milliliter
mS/cm	milliSiemens per centimeter
ng/L	nanogram per liter
nm	nanometer
PFU/mL	particles forming unit per milliliter
ppm	parts per million
ppt	parts per trillion
psi	pound per square inch

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Executive Summary

Two alternative concentrate treatment technologies – closed circuit reverse osmosis (CCRO) and forward osmosis (FO) – were evaluated at pilot scale to recover water from reverse osmosis (RO) concentrate generated at the Orange County Water District (OCWD) Advanced Water Purification Facility (AWPF). The AWPF is a central component of OCWD's Groundwater Replenishment System (GWRS), which includes recharge facilities for potable reuse. Successful recovery of purified water from RO concentrate will reduce the volume of the concentrate waste stream while generating more usable water.

In addition to pilot operational feasibility and recovery optimization, the study focused on performance with respect to: water quality (chemical and microbial constituents, as well as virus log removal via challenge testing); suitability of product water for subsequent treatment by ultraviolet advanced oxidation process (UV-AOP); and cost/footprint analysis (for a conceptual 10 or 20 million gallon per day [mgd] system). This study was part of an overall assessment of feasibility of these technologies for potable reuse that was funded by the Bureau of Reclamation (Reclamation).

Both pilots received concentrate directly from the GWRS primary RO system. The Desalitech CCRO pilot unit was a 5.5 gallons per minute (gpm) ReFlex Max RO system that included a separate "side conduit" to displace concentrate without breaking unit feed pressure. After 18 months of near continuous piloting at OCWD, CCRO treatment of RO concentrate was shown to be technically feasible. The CCRO unit was able to achieve 59 to 61 percent (up to 66 percent) recovery, accounting for the GWRS primary RO system "loss" of RO feed due to the side conduit operation. This corresponds to approximately 91 percent (up to 92.8 percent) overall recovery based on GWRS RO and CCRO recoveries of 85 percent and 61 percent (up to 66 percent), respectively.

The Porifera FO-RO pilot unit was a 1 gpm system that uses a sodium chloride draw solution whereby the FO unit treats the incoming feed water (in this case, GWRS RO concentrate) and RO separates the FO permeate from the salt solution (regenerating the draw solution). Hence, during FO-RO, the treated water sees a double membrane barrier. During 18 months of non-continuous testing, the FO-RO pilot achieved a recovery of 30 to 45 percent, corresponding to approximately 89 to 91 percent overall theoretical recovery at full-scale.

Both technologies produced water of a very high quality (inorganic, organic, and microbiological), suitable for blending with a primary RO system's permeate to increase overall water production and receive subsequent UV-AOP treatment in a conventional full advanced treatment train. Virus challenge testing using MS-2 coliphage demonstrated an average of 5.2-log removal by CCRO and 6.0-log removal or greater by FO-RO. Greater virus log removal for FO-RO is likely attributed to the double membrane barrier. The UV-AOP suitability study consisted of pilot-scale UV/H_2O_2 treatment of CCRO product water and, separately, FO-RO product water. Based on log removal of spiked N-nitrosodimethylamine (NDMA) and 1,4-dioxane (common indicators of UV-AOP performance), the UV-AOP pilot treating CCRO and

FO-RO permeate yielded similar performance as the existing full scale OCWD UV-AOP system that treats a conventional RO permeate.

With respect to full-scale costs, CCRO is estimated to have a lower operations and maintenance (O&M) cost, while FO-RO is estimated to have a lower capital cost. Assuming that the capital cost is funded over a 30-year loan period at a fixed annual interest rate of 5 percent, the unit cost of product water produced by the two technologies is expected to be in the range of $1,126 to $1,382 per acre-foot, depending on the volume of RO concentrate that is treated and the technology used. Given the +50 percent/-30 percent accuracy of the Class 5 cost estimate, the estimated capital plus O&M costs of the two technologies are the same on a dollar per acre-foot basis (total unit costs).

1 Introduction

1.1 Project Background

Reverse osmosis (RO) is commonly used as the core treatment step to purify municipal wastewater for production of potable water as a new drinking water supply (recycled water) (Tchobanoglous et al. 2015). However, at a typical advanced treatment facility, the RO process can only achieve up to 85 percent recovery (i.e., for every 100 gallons of source wastewater, 85 gallons becomes potable water and 15 gallons becomes concentrate). The concentrate is a liquid waste stream containing all of the salts, organics, and microbes that were rejected by RO. It must be disposed of via ocean discharge, permitted inland surface discharges, evaporation ponds, or deep well injection (Pérez-González et al. 2012).

Alternatively, the RO concentrate could be treated further to recover more water. Doing so achieves two objectives: minimizing the waste stream volume that can be costly to dispose (particularly for inland facilities) and generating more product water. Water recovery from concentrate has the potential to increase the overall recovery of a potable reuse facility from 85 percent to greater than 95 percent. While not pursued in the past due to technological and cost limitations, water recovery from concentrate is becoming more economically favorable as the cost of membrane technology has dropped and the value of water has increased due to population growth and climate factors (Sethi et al. 2007; Li et al. 2018).

This study evaluated two alternative membrane-based treatment technologies at pilot scale at Orange County Water District's (OCWD) Advanced Water Purification Facility (AWPF). Together with recharge facilities, the AWPF is part of OCWD's Groundwater Replenishment System (GWRS) for groundwater recharge (potable reuse).

Conventional multi-stage RO configurations use long membrane arrays in series design to achieve high recovery by subjecting the lead elements to high-flux conditions and the tail elements to low crossflow conditions. This causes fouling to likely occur in the first stage and scaling likely to occur in the second or third stage. One of the non-conventional, alternative RO technologies recently gaining industry attention is Closed Circuit Reverse Osmosis (CCRO) developed by Desalitech (a wholly-owned subsidiary of DuPont).

Unlike the steady-state pass-through configuration of a conventional multi-stage RO system, CCRO recirculates the concentrate back to the feed as a semi-batch process using a single stage, short membrane array. Recirculation continues for minutes to a few hours until a given set-point is reached (e.g., reaching target recovery or avoiding exceedance of a permeate water quality threshold) and then the concentrated brine is purged from the system (Figure 1). CCRO alternates operation between closed circuit mode (100 percent recovery) and plug flow (or flushing) mode to mitigate membrane fouling and scaling, and to enhance recovery. Using standard RO components, recovery is achieved in time, crossflow is achieved using a circulation pump, and flux is controlled by the speed of a high pressure pump (Figure 1). Thus, unlike conventional RO where these three parameters are related (interdependent), in CCRO these parameters are uncoupled, allowing a new level of flexibility whereby these set-points can each be changed at the control panel.

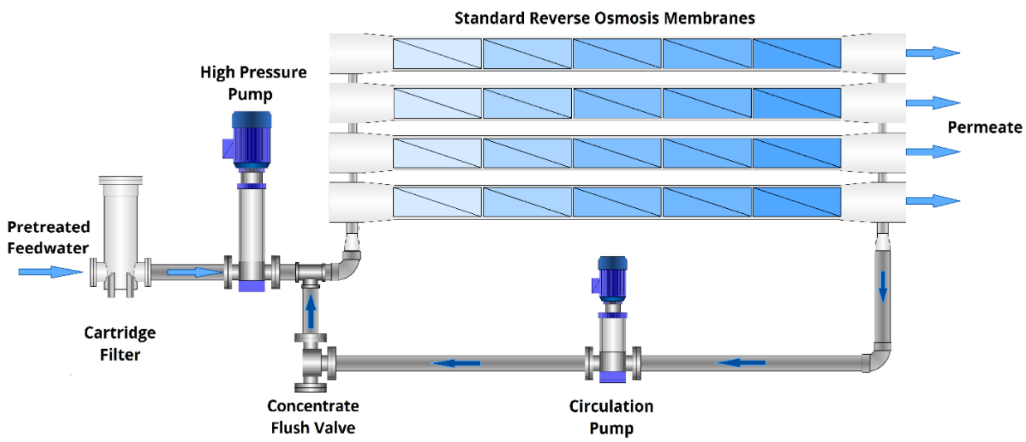

Figure 1. Schematic of Desalitech closed circuit reverse osmosis process

Another non-conventional membrane-based water treatment technology is forward osmosis (FO). FO is an osmotically-driven water purification process using a semipermeable membrane. FO is an emerging membrane technology with a range of possible water treatment applications. It has been studied for decades, but only recently obtained broader commercial adoption (Awad et al. 2019; Revanur et al. 2014; Tiraferri 2020).

A “draw” solution (an osmotic agent) of high concentration relative to the feed water induces flow of water from the feed through the FO membrane and into the draw solution (diluting the draw). This process separates the feed water from its wastewater-derived constituents. In contrast, RO uses hydraulic pressure as the driving force for separation, which requires significantly more energy than FO. Permeate that has co-mingled with the draw solution must be separated from the draw compound.

In the case of Porifera’s FO technology that was tested in the present study, this is accomplished using RO. Thus, coming after the FO step, the RO experiences dramatically reduced fouling and energy (compared to the use of RO to directly treat the feed water) given the very high quality of the blended FO permeate and draw. The concentrated draw solution is thus regenerated and returned to the FO membranes (as the reject from RO) and the process is repeated. In the case of the Porifera FO-RO system, the recirculating draw solution consists of an osmotic agent (sodium chloride) to create the osmotic driving force and dye markers (i.e. rhodamine, fluorescein) to monitor the feed outlet and permeate.

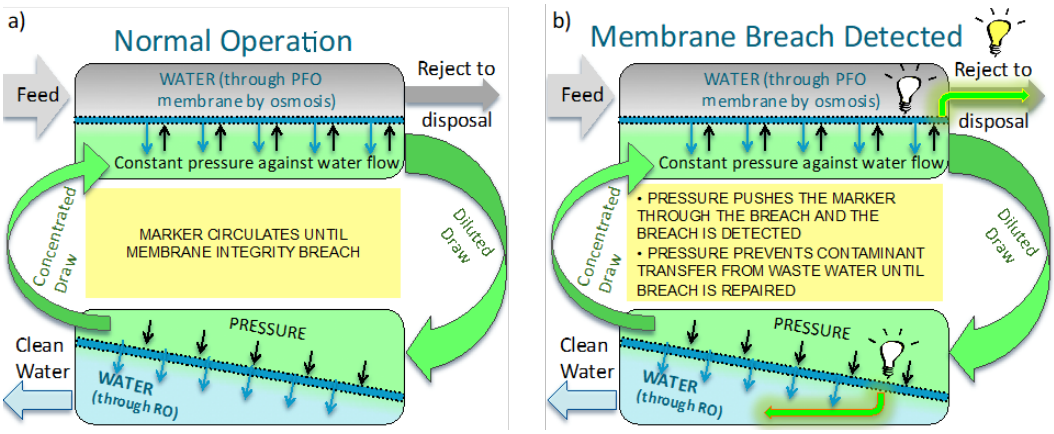

Figure 2. Simplified illustration of Breach-Activated Barrier™ which is automatically activated by a membrane barrier breach; (a) shows normal operation; (b) shows when breach is detected (Desormeaux 2019)

Porifera's patented dprShield technology, as demonstrated in a previous California Energy Commission (CEC) funded project (Desormeaux et al. 2019), is unique to forward osmosis technologies and enables extra protection for wastewater reuse. This system effectively removes trace contaminants through two "tight" membranes (the FO and RO membranes). In the event that one of the membrane barriers is breached, a third Breach-Activated Barrier™ is activated by the breach itself and the contaminants are pushed away from the clean water stream to promote a fail-safe operation (Figure 2).

This patent-pending technology represents a significant advancement in the field of potable reuse. The defining characteristic of the Breach-Activated Barrier™ technology is that the hydrostatic pressure is higher on the draw side of the FO membrane than on the feed side (overpressure); this is a new approach enabled by Porifera's unique design. If a membrane breach occurs in the FO membrane, the osmotic driving force is immediately dissipated and the hydrostatic "overpressure" pushes contaminants and the dye marker out of the draw loop and into the wastewater feed stream. The dye marker is detected with sensors that continuously monitor the feed outlet and permeate, triggering automatic warning signals and shutdown of the breached module. The Breach-Activated Barrier™ uses the hydrostatic "overpressure" to prevent contamination of the draw solution and final product water, and it uses a marker to confirm protection in real-time.

1.2 Problem Statement

At 75 to 85 percent recovery, conventional RO systems for potable reuse are somewhat inefficient. OCWD and the potable reuse industry seeks to identify a cost-effective treatment process that could be used to increase RO system recovery and to minimize the RO concentrate waste stream. As such, the new process would provide an environmental benefit with respect to water resources management (i.e., increasing the efficiency of water recycling) and generate a new water supply for the region. Both CCRO and FO-RO technologies appear promising for generation of more water from a primary RO system's concentrate; however, it is critical to determine feasibility and compare performance of the technologies in pilot-scale first in a water reuse application.

CCRO has been evaluated in other studies for treatment of municipal wastewater for potable reuse (i.e., as a replacement to conventional multi-stage RO); the novel aspect of the present study was the focus on treatment of RO concentrate (i.e., as a supplement to a primary RO process to serve as a quasi "fourth stage" membrane system). FO technology has not been piloted for treatment of municipal wastewater for potable reuse but has been studied when integrated with membrane distillation (MD) and electrodialysis (FO-ED) process in treatment of municipal wastewater (Korenak et al. 2017).

For this study, pilot-scale testing of RO concentrate treatment using CCRO and FO-RO as alternative technologies was conducted at OCWD. The main challenges were to overcome the typical limitations of membrane scaling and fouling problems, specifically regarding silica and organic fouling. The highest recovery and permeate flux the system can operate and the chemical cleaning interval were determined for both pilot systems.

Pilot operational feasibility and optimization tests were ongoing prior to the start of the current work and continued during this phase of the study. Since the product water from these two treatment technologies is proposed for potable reuse, water quality and technological integrity must meet current recycled water regulations and qualify for the necessary permits that satisfy local regulators with respect to public health. Thus, beyond operational performance, this project also evaluated the performance of the two treatment processes with respect to product water quality, assessed treatability of the product water by ultraviolet advanced oxidation process (UV-AOP), and performed full-scale predicted cost analysis. These metrics provided an overall evaluation of the feasibility and acceptability of the treatment processes for potable reuse. With respect to product water quality, a comprehensive water quality evaluation was conducted for this project, including both chemical and microbial constituents as well as determination of virus log removal.

1.3 Previous Research for the Project

1.3.1 CCRO Pilot Study Treating Primary RO Feed at OCWD

The CCRO process has been implemented at over 200 full-scale plants in multiple industrial market sectors including power generation, food and beverage, chemical manufacturing, mining, pharmaceutical, pulp and paper, car manufacturing, refining, agriculture, and oil and gas, including over a dozen industrial water reuse applications with the oldest installations operating for over ten years. In the municipal market, CCRO has been implemented at multiple full-scale systems (with a 10+ mgd plant currently under construction in the southeastern U.S.) and CCRO has been piloted at multiple reuse facilities in California with positive results. In January 2014, the first municipal reuse pilot using CCRO was successfully commissioned by the Sanitation Districts of Los Angeles County (LACSD) treating tertiary effluent providing a sustained RO system recovery of 93 percent (Mansell et al. 2015). The City of Los Angeles (Wang 2018) and Padre Dam Municipal Water District (Idica et al. 2017) subsequently commenced similar pilots in 2015 and 2016, respectively, and demonstrated that 95 percent recovery or more was sustainable by incorporating CCRO in treating tertiary effluent for potable reuse.

A recent pilot study in three distinct phases evaluated CCRO's ability to treat OCWD AWPF RO feed and RO concentrate, assessed operations and maintenance requirements, and explored optimum CCRO operating conditions that would result in sustained performance at maximum recovery. The results were prepared by Desalitech and Jacobs and is described in detail in a separate report (Hwang et al. 2020) and is summarized briefly here.

In Phase 1A, the CCRO ReFlex Max pilot unit was operated as a primary RO system treating the AWPF RO feed water (i.e., microfiltration effluent). The goal of this phase was to determine the maximum recovery that can be achieved when treating the microfiltered wastewater while maintaining a clean-in-place (CIP) frequency greater than 30 days over multiple operating cycles, for the purpose of developing information and operational criteria to serve the upcoming phase that would use primary RO system concentrate as the feed water to CCRO. The CCRO unit was operated for two consecutive sequences at five recovery set points between 85 and 92 percent and a permeate flux of 8.0 gallons/ft^2/day (gfd) (which is equal to the 3rd stage flux in the AWPF primary RO) in a series of short-term fixed recovery tests. Following extended runs at 92 percent recovery, several adjustments were performed on the CCRO unit, both independently and concurrently, to optimize operation. Of these adjustments, the most beneficial were operation at reduced flux (6.4 gfd) and increased recirculation flow rate (52 gallons per minute [gpm]), with the purpose of the latter to maintain the same crossflow velocity as operation at 8 gfd flux. Under these conditions, 92 percent overall recovery was determined as the maximum sustainable recovery limited by silica mineral scaling and fouling associated with silts/clays when CCRO was operated with AWPF RO feed as the feed source. This recovery established the benchmark recovery for test phases 1B and 1C. Figure 3 shows the recovery and pressure profile of the CCRO pilot during stabilized performance (92 percent recovery), where volumetric recovery is achieved in time and only the absolute minimum pressure required to desalinate the feed source to the membrane array is exerted at any given point in time (Gu et al. 2018). As the salinity of the feed source increases due to the return (recirculation) of the CCRO concentrate, the required pressure increases in turn. This not only provides lower energy costs when compared to an energy recovery device, as there is no energy to recover (Stover 2015), but also provides a dynamic environment in terms of pressure and salinity, which can inhibit organic fouling on the membrane surface (Stover 2015). It is hypothesized that scaling was mitigated by operating the RO equipment in CC (closed-circuit) mode with periodic side conduit flushing and refill. The side conduit is a physical component of the CCRO system (described in Appendix B).

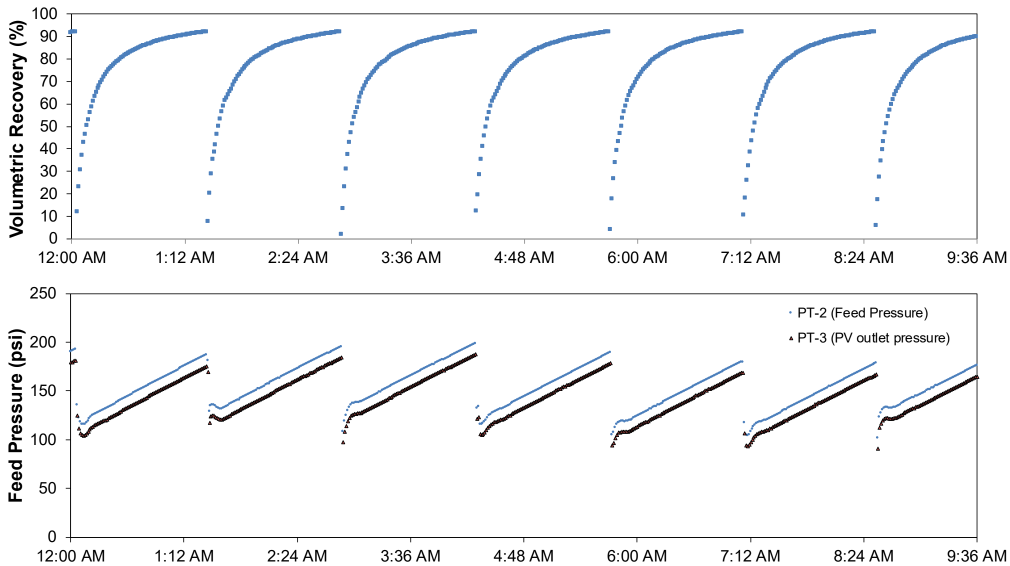

Figure 3. CCRO pilot volumetric recovery and membrane feed/outlet array pressure profile at stabilized performance (92 percent recovery) during Phase 1A, where AWPF microfiltration effluent is feedwater to CCRO; operation data taken December 12, 2017

Figure 4 illustrates a case where higher recovery (93 percent) was attempted for 10 sequences, which resulted in an increase in feed pressure. Recovery was reduced to 92 percent recovery, after which stable performance was observed. Instantaneous recovery and specific flux at 93 percent and 92 percent recovery were also shown in Figure 4 (Gu et al. 2018).

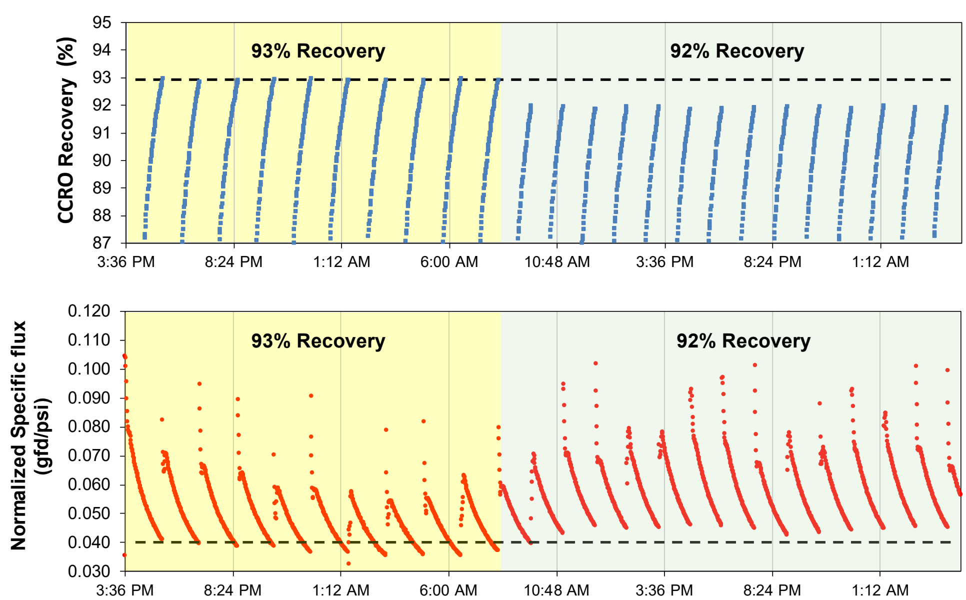

Figure 4. CCRO pilot volumetric recovery and normalized specific flux decline at 93 percent and 92 percent recovery during Phase 1A, where AWPF microfiltration effluent is feedwater to CCRO; operation data taken December 9 to 11, 2017

1.3.2 CCRO Pilot Study Treating RO Concentrate at OCWD

Direct treatment of RO concentrate by CCRO pilot was attempted in Phase 1B of the previous pilot study without satisfactory results (Hwang et al. 2020). Online TOC data were collected for the AWPF RO feed (microfiltration [MF] effluent) for select periods of Phase 1B, which showed that the concentration varied from 7 to 9 mg/L. Assuming complete TOC rejection by the primary RO system operating at 85 percent recovery, these levels would translate into 46 to 60 mg/L of TOC in the CCRO feed water (primary RO concentrate), which represents a significant potential organic fouling load to the CCRO membranes.

In this phase, the CCRO pilot unit was operated to treat and recover a portion of the concentrate from the AWPF RO system, with the objective of determining the CIP interval while achieving an overall recovery of 92 percent (defined as the combined primary RO and CCRO systems recovery) that was demonstrated in Phase 1A. The only difference between operating as a primary RO compared to operating as a fourth stage RO is the amount of time the CCRO pilot skid would be in CC mode to achieve the target recovery and the target CCRO concentrate electrical conductivity (EC)[1].

The membrane crossflow rate (velocity) was increased from 40 to 65 gpm by increasing the recirculation rate of the pilot. The higher velocity of water flow across the membrane surface was thought to assist with dislodging the silts/clays and deposited organics from the membrane surface through increased turbulence in the membrane spacers. The impact of increased crossflow velocity on specific flux during CCRO operation at 90 to 91 percent recovery is illustrated in Figure 5 (Gu et al. 2018). However, increasing the crossflow rate provided no real benefit to allow the CCRO to achieve an operating cycle of greater than 30 days between CIPs (where the CIP trigger is a decline in specific flux to 0.04 gfd/psi). This minimum 30-day interval was a goal of the operational optimization trials, since greater frequency of CIPs was considered likely undesirable by OCWD plant staff.

Based on this result, additional operational changes were required, which included switching the source of side conduit make-up water from AWPF RO concentrate (i.e., the CCRO feed water) to primary RO feed water (i.e., AWPF microfiltration effluent) which was explored in Phase 1C (the current study). In practical terms, this means that a full-scale CCRO system (operating as a fourth stage RO system to treat RO concentrate) would receive RO concentrate under pressure as its feed but also receive a smaller, but significant, flowrate of microfiltration (MF) effluent into its side conduit. Filling the side conduit with MF effluent rather than RO concentrate was found to enable a sustainable recovery setpoint and a CIP interval no smaller than 30-days. MF effluent, which has much lower TOC and EC, was thought to provide a “mini wash” during the purge mode to disrupt scale/fouling formation and make operation more sustainable.

[1] The goal of the CCRO process is to achieve a certain recovery and permeate quality. The concentrate EC is monitored as a setpoint only.

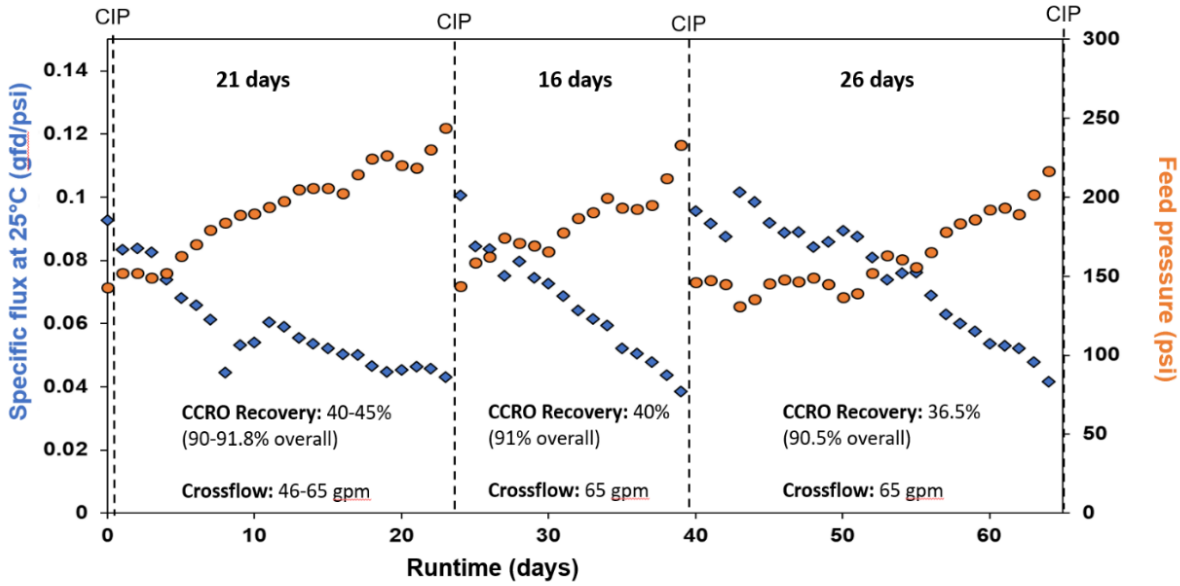

Figure 5. CCRO pilot average specific flux and feed pressure during Phase 1B of the study, where AWPF primary RO concentrate is the feed water to CCRO and CIP trigger is normalized specific flux of 0.04 gfd/psi

1.3.3 Previous FO-RO Pilot Testing at OCWD

Trevi Systems conducted a 2.5-year project funded by the California Energy Commission (CEC) from 2013 to 2016 at OCWD treating GWRS AWPF RO concentrate water using their custom-designed small- and medium-size FO systems (immersed hollow fiber outside-in design) (Mancuso et al. 2019). A thermally-responsive draw solution was tested initially but later switched to a salt-based draw solution recovered by a RO system. Medium scale operation (100 m3/day [18.35 gpm] permeate capacity) was found not to be sustainable due to fiber breakage issues of the FO membrane. The cleaning interval was determined to be approximately four weeks for 50 percent recovery operation at 1.1 liter/m^2/h (LMH) [0.65 gfd] permeate flux.

Prior to the start of the current project, in a separately funded project by the CEC, Porifera completed preliminary offsite laboratory (membrane coupon) scale testing of their FO technology using OCWD RO concentrate (Desormeaux et al. 2019). Following the preliminary lab tests, Porifera designed and constructed a dprShield pilot system based on a previous tankless FO-RO system design. Approximately one year of operational testing and optimization of the FO-RO pilot was completed at OCWD beginning in January 2017. A process flow diagram of the system is shown in Figure 6. The project allowed Porifera to demonstrate continuous system operation and the Breach-activated Barrier™ concept.

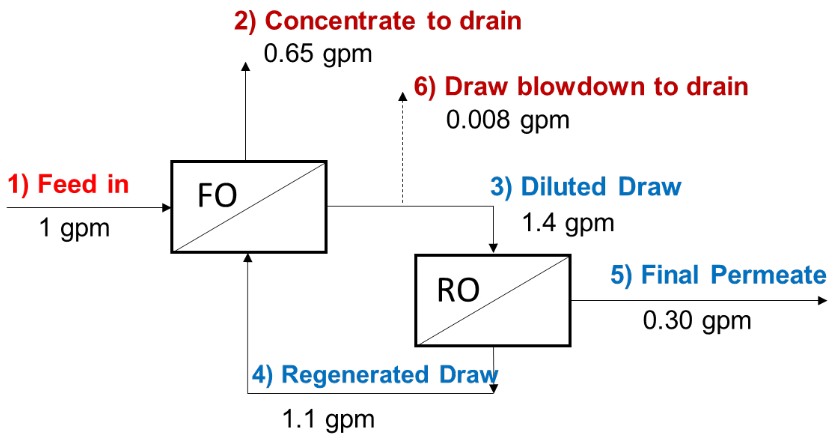

Figure 6. Porifera dprShield FO-RO pilot process flow diagram

System apparent recovery based on pilot study data was 30 to 35 percent and RO recovery was 30 percent. The apparent recovery is the ratio of the FO system permeate volume leaving the RO process (i.e., final permeate), to the total volume, where the total volume is the FO system feed (Figure 6). Porifera performed water quality sampling with a research team from Stanford University. Fifteen organic compounds, including 1,4 dioxane, pharmaceuticals, and other contaminants of emerging concern (CECs), were spiked into the feed water to evaluate emerging contaminant rejection ability of the FO-RO pilot. Rejection of the compounds by the FO membranes correlated primarily with molecular volume (Figure 7) and showed excellent rejection at >95 percent for nearly all of the compounds (Desormeaux et al. 2019; Szczuka et al. 2020).

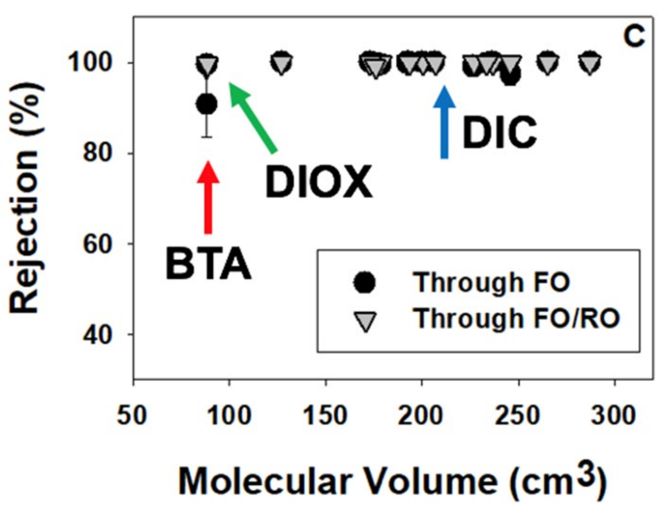

Figure 7. Percent rejection of 15 organic contaminants by the FO membrane alone (i.e., comparing the concentrations in the FO influent and draw solution) and by the combined FO/RO system (i.e., comparing the FO influent and RO permeate concentrations) for treatment of RO concentrate. Error bars represent the standard deviation of three sampling events. BTA= benzotriazole, DIOX = 1,4-dioxane, and DIC=diclofenac (Desormeaux et al. 2019; Szczuka et al. 2020).

1.4 Project Objectives and Goals

The project's overall objective was to evaluate two alternative treatment technologies at pilot scale to recover water from RO concentrate generated from an advanced potable reuse treatment facility. There were two phases of the study. Approximately 12 months of CCRO and FO-RO pilot operational testing and optimization was completed at OCWD during Phase I (Pilot Operation) funded by OCWD (for the CCRO) and CEC (for the FO-RO) prior to the start of Phase II (Pilot Performance) funded by Reclamation. For completeness, both phases are described in this Reclamation report.

The objectives of the Phase I study included determining the maximum system recovery for optimal operation, ideal operating flux (and in the case of CCRO, ideal crossflow velocity), average cleaning interval and cleaning chemical, and average general permeate quality in terms of salt rejection. After demonstrating the necessary operating conditions for CCRO and FO-RO that enabled sufficiently sustainable operation in Phase I, the Phase II evaluation of water quality, treatability by UV-AOP, and cost enables consideration of CCRO and FO technologies by utilities and regulators.

The objectives of the Phase II study were divided into four main tasks:

- Comprehensive water quality testing of the RO product water for chemical constituents and microorganisms;
- Determination of virus log removal via challenge (spike) testing;
- Confirmation of suitability for subsequent UV-AOP treatment; and
- Cost and physical footprint analysis.

1.4.1 Chemical and Microbial Water Quality Evaluation

In a full-scale potable reuse application, the CCRO or FO-RO permeate would be blended with permeate from the three-stage RO (primary RO) system. The current OCWD AWPF permit requirements for the RO permeate quality are limited to turbidity and percent ultraviolet transmittance at 254 nanometers (%UVT254) and the plant finished product water (FPW) (after UV-AOP and post-treatment lime/decarbonation) is subject to a set of permit and monitoring requirements by California Regional Water Quality Control Boards (RWQCB) per Order Nos. R8-2004-0002 amended by R8-2008-0058, R8-2014-0054, R8-2016-0051, and R8-2019-0007, as listed in Appendix A of the 2018 GWRS Annual Report (Burris 2018). Additionally, OCWD must demonstrate at least 2-log removal of TOC by the RO system as a proxy for virus removal, through the use of online feed and permeate TOC analyzers. Furthermore, OCWD observes an internal RO permeate critical control point limit of <0.1 mg/L permeate TOC via the online analyzer as indicative of normal operating conditions. The primary objective of the study, with respect to water quality, was to characterize the quality of the CCRO and FO-RO permeates and, in the case of CCRO, how it varies during the closed-circuit sequence; and secondarily, to characterize feed quality (primary RO system concentrate) in order to estimate constituent removal.

Permeate quality of both pilots were sampled and analyzed with respect to concentration of minerals (salts), nitrogen, microorganisms, disinfection byproducts, and wastewater-derived organic compounds (e.g., CECs such as pharmaceuticals and personal care products (Fairbairn et al. 2016)). During advanced treatment using RO, most CECs are completely removed from the wastewater during the RO process. Of the 45 CECs that OCWD routinely monitors in the primary system RO feed and permeate, fewer than 5 are regularly detected in the RO permeate. The significant rejection indicates that many of these compounds would be present in the RO concentrate that is the feed water to the CCRO and FO pilot systems. In particular, N-nitrosamines, halogenated disinfection byproducts (DBPs), and 1,4-dioxane represent challenge chemicals for potable reuse trains because, compared to other organics, they are inefficiently removed by RO membranes (Agus and Sedlak 2010).

Microbial water quality in pilot permeates was also assessed to determine if microbial indicators and pathogens are removed or inactivated through the treatment process. Implementation of CCRO or FO-RO for potable reuse necessitates that adequate controls are in place to protect public health from exposure to pathogens. For example, California requires the overall treatment process to consistently achieve 10-log10 reduction of Giardia, 10-log10 reduction of Cryptosporidium, and 12-log10 reduction of viruses (CDPH 2014). For monitoring purposes, it is impractical to test water for all possible pathogens that could be present; therefore, indicator organisms such as fecal coliform, which are associated with the presence of fecal matter, serve as surrogates for pathogen monitoring. For this study, the U.S. EPA's recommended indicators that are indigenous to wastewater and MF-treated effluent were monitored. These microbial indicators include fecal indicator bacteria (FIB), male-specific (MS) and somatic (SOM) coliphage, and enteric viruses. These indicators were measured in the feed and FO-RO and CCRO pilot system permeates.

1.4.2 Male-Specific Virus Log Removal Determination

Microbial testing is regularly used for water reuse technologies to establish removal credits and to verify that the reuse processes are producing a specified water quality on a continual basis. The objective of this task was to evaluate microbial removal capabilities of both FO-RO and CCRO systems by seeding the feed to the pilot systems with a relatively high concentration of Male-Specific (MS) coliphage. For treatment technologies that use membrane processes, membrane pore size is an important consideration for microorganism removal because size exclusion is the predominant removal mechanism. Compared to bacteria, viruses are of major concern in reuse due to the large numbers present in wastewater and their small size, which can vary from 0.01 to 0.1 µm. The concentrate feed water will have been treated by MF upstream of the RO, but MF membranes are not an effective barrier for viruses based on the nominal pore size (≤ 0.1 µm)—though some virus removal is possible (Rodriguez et al. 2009). RO membranes have a nominal pore size ≤ 0.001 µm that is small enough for virus rejection. However, complete removal of viruses is not always obtained (Antony et al. 2012). Therefore, to assess the integrity of membrane treatment processes, a known concentration of organisms is first dosed into the feed water and monitored by measuring the concentration before and after the treatment (Rodriguez et al. 2009). Challenge testing with bacteriophage (surrogate for viruses) seeding is currently used as the predominant method to assess virus removal when the intrinsic concentration of viruses is low in the feed solution (Antony et al. 2012). Such a test was conducted for this project.

1.4.3 UV-AOP Treatment Suitability

UV-AOP treatment is commonly applied as the final purification step at an advanced reuse facility (e.g. full advanced treatment [FAT] train featuring MF or UF, RO, and UV-AOP). Therefore, if a RO concentrate treatment technology were implemented at full scale, the product water from the process would likely be treated by UV-AOP or equivalent depending on local regulations and approaches. Here, the objective was to confirm that UV-AOP is capable of treatment of the product water from the CCRO and FO-RO pilot units and thus can be a suitable approach. There was no reason to suspect otherwise; rather, the project team considered such a test of UV-AOP treatment of these unique waters to be worthwhile for basic demonstration purposes. To assess UV-AOP treatment suitability, UV-AOP removal of N-nitrosodimethylamine (NDMA) and 1,4-dioxane was determined by spiking these compounds into the RO permeate produced from the CCRO and FO-RO pilots and treating the water using a UV-AOP pilot system.

1.4.4 Cost and Physical Footprint Evaluation

A key objective of the study was to establish the conceptual cost and physical footprint requirements for the two technologies. Footprint is a critical concern for potable reuse facilities, particularly if there is limited space available at an existing site. Establishing the required footprint is an important factor in determining whether implementation of a technology is feasible. To this end, preliminary plant layouts were developed to determine space requirements for the technologies.

Planning level capital, O&M, and life-cycle costs for theoretical 10- and 20-mgd systems (feed water flow rate; i.e., RO concentrate flow treated) were developed for each of the two treatment alternatives. Capital costs included estimates for the internal plant pumping and pipeline requirements. A challenge with the capital cost estimate is determining whether the figures are realistic given the limited application of these processes at full scale.

Cost estimates focused on the concentrate treatment technologies only. If the product water (CCRO or FO-RO permeate) is blended with primary system RO permeate in a FAT facility for further treatment in the train, there would be additional capital and O&M costs associated with downstream treatment in the UV-AOP system (post-stabilization) and final pumping, which have not been included in this assessment.

2 Technical Approach and Methods

2.1 Test Site at OCWD Advanced Water Purification Facility (AWPF) for Potable Reuse

The project testing site was OCWD GWRS AWPF in Fountain Valley, California. The AWPF produces high quality recycled water as part of the GWRS, a potable reuse project jointly operated by OCWD and the Orange County Sanitation District (OCSD). The GWRS AWPF is currently the world's largest water reclamation facility (approximately 100 mgd production) for potable reuse and a recognized industry standard. Figure 8 shows a schematic of the OCWD AWPF treatment train. The plant treats municipal secondary wastewater generated by OCSD with microfiltration (MF), RO, and UV-AOP to create a high quality product water.

With respect to chemical addition, the AWPF takes steps to minimize membrane biofouling by maintaining a chloramine residual in the feedwater to the treatment plant. Sodium hypochlorite (12.5 percent NaOCl) is added to the secondary wastewater influent that rapidly form chloramines—resulting in approximately 60 percent monochloramine and 40 percent dichloramine. Downstream of the MF process, sulfuric acid is added to the RO feedwater to a targeted pH of 6.9 and antiscalant (AWC A-108, 2.5 mg/L) is added to control inorganic scaling. After UV-AOP, partial decarbonation (20 percent of flow) and lime addition are used to reduce the corrosiveness of the water. There is no finished water disinfection; however, a low residual chloramine as well as hydrogen peroxide remain in the finished water as a result of the upstream treatment process.

The final product water (FPW) is injected (via injection wells) or percolated (via recharge basins) into the groundwater basin to provide drinking water via various city-owned production wells and to provide a robust barrier to seawater intrusion.

The AWPF was originally designed with a capacity of 70 mgd. In 2015, the plant was expanded to produce up to 100 mgd of finished product water. When the plant is expanded to its full capacity of 130 mgd by 2023, the RO concentrate flow (waste discharge stream) will increase to 23 mgd. Currently, the RO concentrate is discharged into the Pacific Ocean via OCSD's ocean outfall at no cost to OCWD. The current RO recovery (85 percent) is limited by the traditional multi-stage hydraulic array along with the saturation of sparingly soluble salts in the RO concentrate, namely calcium carbonate and silica.

For this study, RO concentrate from the AWPF process was used as the feed water to the two pilot units (CCRO and FO-RO). A slipstream of RO concentrate was plumbed to continuously supply two feed tanks for the pilot units.

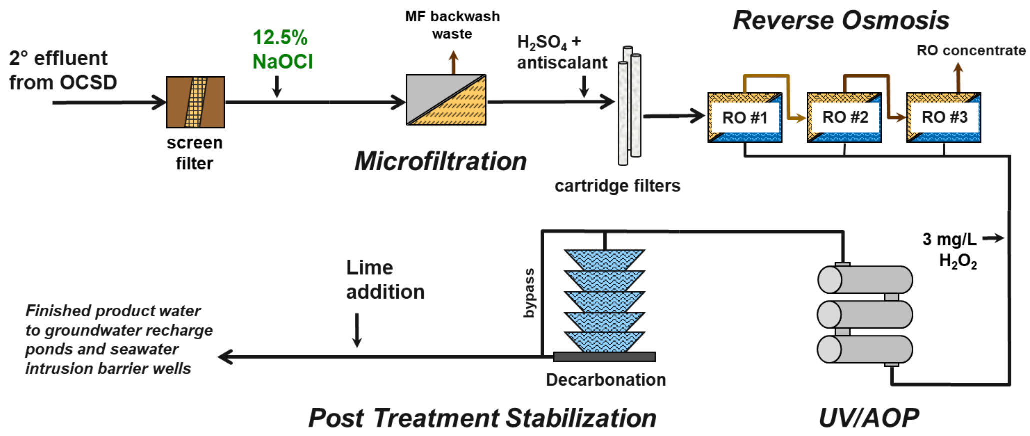

Figure 8. Simplified schematic of the OCWD GWRS advanced treatment system

2.2 FO-RO Pilot General Description

Porifera's FO-RO technology, patent-pending dprShield, was pilot tested at OCWD for recovery of water from the AWPF primary RO system concentrate. FO and Porifera's technology was described previously in Section 1.1 and a more detailed description of the pilot is provided in Appendix A. A photograph of the pilot is shown in Figure 9.

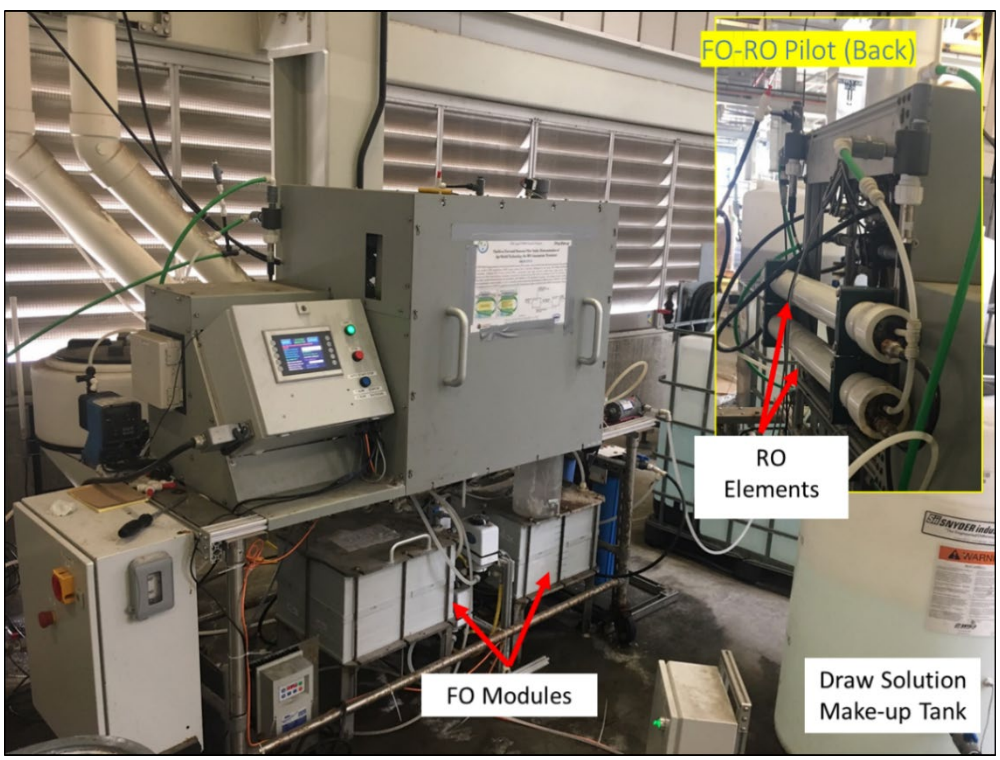

Figure 9. Photograph of the Porifera dprShield FO-RO pilot operating at the OCWD AWPF; insert shows RO elements at the backside of the FO-RO pilot

2.3 CCRO Pilot General Description

The Desalitech (now Dupont Water Solutions) patented CCRO technology was pilot tested at OCWD for recovery of water from the AWPF primary RO system concentrate. CCRO and Desalitech's technology were described previously in Section 1.1 and a more detailed description of the pilot is provided in Appendix B. A photograph of the pilot is shown in Figure 10. This study utilized the Desalitech ReFlex Max system (different from the ReFlex system piloted in other studies), which isolates the CCRO concentrate in a side-conduit before purging to waste without breaking pressure, thereby reducing the energy required for desalination, and also allows higher recovery to be achieved. Schematics showing the flows during closed circuit versus plug flow modes are shown in Appendix B (Figure B-1 through Figure B-3).

Figure 10. Photo of the ReFlex Max CCRO pilot at the OCWD GWRS RO facility

2.4 UV-AOP Pilot General Description

The OCWD R&D Department maintains and operates a Trojan Technologies single-lamp pilot UV reactor. The UV reactor is operated under conditions that emulate the advanced oxidation performance of the full-scale 6-reactor Trojan UVPhox at OCWD's AWPF. The pilot UV reactor is equipped with the same 257-watt low-pressure high-output mercury amalgam lamp emitting at 254 nm that is used in the UVPhox. The lamp is housed within a quartz sleeve inside the annular 316 stainless steel reactor with an internal diameter of 9.62 cm. The distance from the outer surface of the quartz sleeve to the wall of the reactor is 3.40 cm, and there is a 58-inch length between the electrodes of the UV lamp that is considered the active volume of the reactor.

For this study, the UV-AOP pilot reactor was operated with feed water generated by the CCRO or FO-RO pilots (which in turn was generated by treating primary RO concentrate feed to the CCRO or FO-RO pilots). The system is operated at 100 percent ballast with the flow of water through the reactor adjusted to alter the applied UV dose (mJ/cm^2).

2.5 Experimental Approach

This section describes the experimental approach for pilot operation and optimization, water quality sampling, MS coliphage challenge testing, UV-AOP treatability evaluation, and cost/footprint determination.

2.5.1 FO-RO Pilot Operation and Optimization

Testing of the FO-RO pilot was divided into three major phases in the CEC funded study conducted by Porifera (Table 1). The later part of the Phase 3 study coincided with the current study funded by Reclamation and led by OCWD. The Reclamation scope of work built on and directly benefited from the CEC scope of work.

The test equipment, treatment process, and site modifications were primarily designed, installed, and operated by Porifera with some assistance from OCWD. Draw solution and other chemicals were supplied by Porifera. The majority of pilot operation was unmanned with remote support and occasional onsite support provided by Porifera with assistance from OCWD staff.

Table 1. FO-RO pilot test phases

Test Phase	Main Tasks	Time Period
Phase 1	Preliminary lab testing (offsite)	October 1, 2015 to October 1, 2016
Phase 2	Site assessment; pilot system fabrication and installation	October 1, 2015 to December 1, 2016
Phase 3	Site demonstration, optimization, and water sampling	December 1, 2016 to November 1, 2019

As is common with pilot projects, there were some unplanned site issues and equipment component failures that impacted the assessments and required troubleshooting and modifications to either the pilot equipment or the approach to provide realistic assessments. During Phase 3, the plan was to initially investigate the ideal (maximum sustainable) water recovery for the system so that the system could operate at a stable recovery for long-term demonstration and for stable conditions during sampling events.

Several minor modifications were made to change where certain water quality parameters were monitored in the process to better automate the blowdown frequency, improve draw overpressure, and to reduce nuisance alarms and shutdowns. One objective of the study was to conduct a long-term demonstration of the use of dye in the draw solution as part of dprShield to demonstrate this additional (monitoring) barrier; however, use of the dye proved challenging and required further optimization and troubleshooting by Porifera. Eventually addition of the dye was discontinued (stopped) to assess the impact of dye on membrane fouling.

Following initial optimization, the system was adjusted to the final operating values which were held mostly constant until the final two months of operation when the FO module was upgraded with a 1-micron pre-filter and a recirculation pump to increase surface velocity on the feed side of the FO membrane; a new type of dye was also injected into the system.

2.5.2 CCRO Pilot Operation and Optimization

Portions of this section of the report were reproduced from Desalitech/Jacobs operational report with permission from Desalitech and Jacobs (Hwang et al. 2020). The operational goal of the CCRO pilot testing was to evaluate the performance of the ReFlex Max CCRO configuration for recovery of water from AWPF RO concentrate. The pilot testing was completed in three distinct phases as shown in Table 2, which lists the duration and number of recovery and flux conditions that were evaluated for each phase. In each phase, system performance was evaluated with regard to the following: recovery, specific flux, clean-in-place (CIP) frequency, and performance as defined by changes in three normalized membrane parameters: specific flux, salt passage, and differential pressure. In Phase 1A, CCRO was operated as a primary RO unit treating the AWPF RO feedwater (chloraminated MF filtrate chemically conditioned by acidification and antiscalant addition). In Phase 1B, CCRO was operated as a 'fourth' RO stage treating AWPF RO concentrate. Results from Phase 1A and 1B were summarized previously in Section 1.3. Lastly, in Phase 1C, CCRO was operated as a 'hybrid' fourth RO stage treating AWPF RO concentrate while primary RO feed water (MF filtrate) was used to fill the side conduit.

Phase 1A included several closed circuit sequence runs to identify the optimum 'baseline' recovery. The pilot was subsequently operated for extended runs at the selected baseline recovery for the remainder of the phase. For Phases 1B and 1C, extended runs at the target recovery determined in previous phases was completed.

Table 2. Phase 1 duration, recovery, and flux test conditions and feed water location for each test phase for CCRO pilot

Parameter	Pilot Study Phase		
	Phase 1A	Phase 1B	Phase 1C
Feed Water (to Membrane Array)	Primary RO Feed	3rd Stage RO Concentrate	Diluted 3rd Stage Concentrate
Feed Water (to Side Conduit)	Primary RO Feed	3rd Stage RO Concentrate	Primary RO Feed
Permeate Flux (gfd)	6.4 (11.0 LMH)	6.4 (11.0 LMH)	6.4 (11.0 LMH)

Parameter	Pilot Study Phase		
	Phase 1A	Phase 1B	Phase 1C
Pilot Period	October 9, 2017 to February 27, 2018	March 2, 2018 to July 12, 2019	July 12, 2018 to February 21, 2019; February 21 to November 30, 2019[a]
Pilot Duration (weeks)	24	19	31; 40

[a] Testing during this period toward the end of the study was completed using the Dupont Filmtec BW30XFRLE elements; all other testing shown was completed using Hydranautics ESPA2-LD elements

The performance metrics used to determine whether a test condition was considered a success were stability of normalized specific flux, normalized salt passage, and normalized differential pressure. The operational metric for the extended testing was to demonstrate that the CCRO system could operate for a minimum of 30 days between CIP events while achieving the following:

1) Normalized specific flux decline less than 60 percent;
2) Normalized salt passage increase of less than 30 percent; and
3) Normalized differential pressure increase of less than 30 percent.

In addition to the above, each CIP was intended to restore any loss of specific flux and/or reduce any increases in salt passage and differential pressure.

There are two factors used to determine the recovery of the CCRO system. The apparent recovery was defined as the ratio of the permeate volume to the total volume, where the total volume is the CCRO permeate volume plus the waste stream volume, or the permeate volume plus the side-conduit feed flowrate:

$$: \textbf{Apparent CCRO recovery}\ (\%) = \frac{\textbf{CCRO Permeate Flow}}{\textbf{CCRO Permeate Flow+ CCRO Concentrate Flow}} \boldsymbol{x100} \qquad (1)$$

The GWRS Overall Recovery was defined as the theoretical full-scale, overall recovery of the entire AWPF system downstream of the MF processes based on the additional water produced by CCRO (i.e., accounting for the additional recovery by CCRO), calculated as:

$$\textbf{GWRS Overall Recovery}\ (\%) = \frac{\textbf{Total RO Permeate + CCRO Permeate}}{\textbf{MF Effluent Flow}} \boldsymbol{x100} \qquad (2)$$

2.5.3 Chemical Water Quality Assessment

The chemical water quality of permeate produced by the CCRO and FO-RO pilot units was characterized in four sampling events (Table 3). The sampling locations are shown in Figure 11. Appendix C includes information on the sampling and analytical methods. In order to calculate percent rejection, the feed (primary RO system concentrate) water quality was also characterized for two sampling events (Table 3). The RO concentrate was directed to feed tanks serving each pilot unit.

Table 3. Dates and laboratories for chemical water quality sampling

Sampling Date	Sampling Event No.	Weck Lab Analytes	OCWD Lab Analytes	R&D Lab Analytes
February 21, 2019	1	Permeate	Permeate	Permeate
April 15, 2019	2	Permeate	Feed, Permeate	Feed, Permeate
April 15, 2019	3	Feed, Permeate	Feed, Permeate	Feed, Permeate
September 25, 2019	4	Permeate	Permeate	Permeate

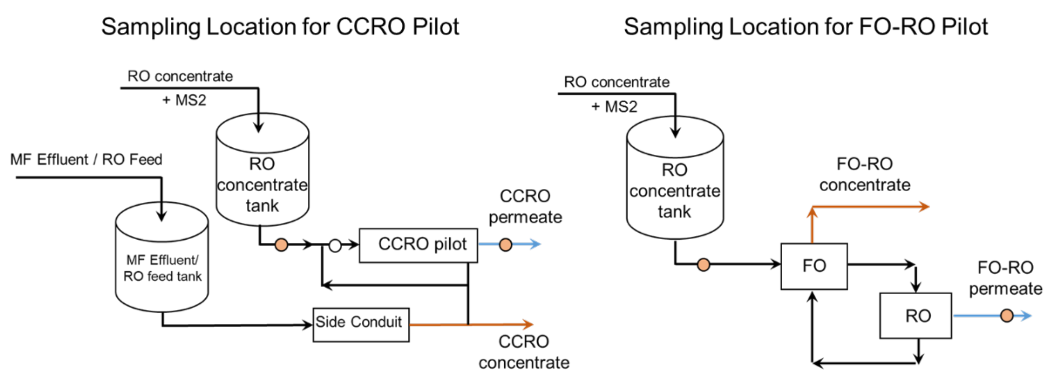

Figure 11. Sampling locations for the CCRO and FO-RO pilots. Samples collected for the chemical water quality assessment and native microbial enumeration (Section 2.5.4) are indicated by the yellow circle. The CCRO pilot has a 300-gallon RO concentrate tank. An additional CCRO sampling site was incorporated for the MS coliphage challenge test (Section 2.5.5); this additional site is indicated by the white circle. Note that there is no RO concentrate tank for the FO-RO pilot during the chemical water quality samplings.

Dissolved chemicals measured in the feed and permeate from each pilot system included: general water quality (e.g., total organic carbon [TOC], pH, electrical conductivity); general minerals (e.g., cations, anions such as sodium and chloride); trace metals; nitrogen and phosphorus compounds (e.g., ammonia, nitrate, orthophosphate); selected regulated compounds from California Title 22 and drinking water quality regulations; disinfection byproducts (e.g., total trihalomethanes [TTHMs], haloacetic acids [HAA5], N-nitrosodimethylamine [NDMA]); wastewater-derived organic compounds (e.g., 1,4-dioxane, pharmaceuticals, and excitation-emission matrix [EEM] spectroscopy as an indicator of organic character and "wastewater identity"). The analytes are listed in Appendix C, Table C-1. To avoid unnecessary sampling, several Title 22 constituents were excluded from the sampling plan based on review of historic plant data indicating compounds that are not typically detected in OCWD AWPF RO feed and thus unlikely to be present in the RO concentrate serving as the feed water to the FO-RO and CCRO pilots.

Analysis was completed by the OCWD Philip L. Anthony Water Quality Laboratory in Fountain Valley, California, a U.S. Environmental Protection Agency-certified and California ELAP-certified analytical laboratory, or by a commercial laboratory (Weck Laboratories, Inc. in Industry, California) as shown in Appendix C, Table C-2. EEM spectroscopy was conducted by the OCWD R&D Department laboratory.

Approximately 18 months of CCRO pilot operation was completed before the sampling events started in order to establish stable operations to ensure the representativeness of the water quality measurements. General water quality (e.g., electrical conductivity) was evaluated continuously or frequently (depending on the constituent). Pilot optimization was still ongoing for the FO-RO pilot; hence, the water quality data was collected during somewhat different operating criteria for both pilots.

To obtain a more uniform sample and avoid the cyclic (transient) nature of the CCRO pilot, the project team adapted a "mini-composite" approach to characterize the average water quality composition of the CCRO feed and permeate for a number of CCRO cycles. Details of this sampling approach are described in Appendix C. The FO-RO pilot does not operate in a semi batch mode; thus, the permeate quality does not vary with time. However, the FO-RO was sampled in a similar "mini-composite" approach for consistency. The water quality data were reviewed and compared to the water quality of conventional RO permeate from the primary RO system for reference.

2.5.4 Microbial Water Quality Assessment

The objective of this task was to characterize the native microbial quality of the pilot feed water and subsequent removal in CCRO permeate and FO-RO permeate by measuring microbial constituents that are common indicators in potable water reuse treatment studies. To accomplish this, a series of microbial detection methods was performed on grab samples taken from each pilot unit. Each sampling event consisted of one OCWD AWPF RO concentrate grab sample (which is the common feed water to both pilots), one CCRO pilot permeate grab sample, and one FO-RO pilot permeate grab sample taken on the same day. This sampling scheme was repeated for a total of three sampling days to obtain native microbial data using EPA standard methods. Microbial targets included total coliform, E. coli, enteric viruses, and MS and SOM coliphage (Table 4).

Prior to any microbial analysis, total residual chlorine for all samples was quenched with 50 mg/L of sodium thiosulfate and confirmed using the N,N-diethyl-p-phenylenediamine (DPD) colorimetric method with a handheld Hach fluorometer. Experimental enumeration of each microbial target was performed by a certified laboratory as described in Table 4, below.

Table 4. Microbial targets for water quality assessment

Microbial Target	Detection Method	Analytical Laboratory
Total Coliform	IDEXX Colilert Quanti-Tray 2000 (SM9223B)	OCWD
E. coli		
Male-Specific Coliphage (MS)	EPA 1602 double-agar overlay	Michigan State University Water Quality and Environmental Microbiology Laboratory
Somatic Coliphage (SOM)		
Enteric Viruses	EPA 1615 cell culture only	IEH-BioVir Laboratories

Enterococci, Cryptosporidium and Giardia cysts were excluded from this assessment. Enterococci, a gram-positive facultative anaerobic bacterium, and E. coli are typically surveyed as surrogates for fecal indicator bacteria (EPA 2015). Since both total coliform (which includes fecal coliform) and E. coli are enumerated by SM9223B, an additional fecal indicator was considered unnecessary. With respect to Cryptosporidium and Giardia cysts, microfiltration and reverse osmosis treatment generally exclude particles larger than 2 µm and 1 nm, respectively. Cryptosporidium oocysts and Giardia cysts are approximately 4.0 to 6.0 µm and 5.0 to 18.0 µm in size, respectively; thus, oocysts and cysts are expected to be efficiently rejected by size exclusion during microfiltration treatment at the OCWD AWPF (and thus not expected in the pilots' feed water). Therefore, rather than evaluating pilot performance using larger microbial particles such as Cryptosporidium and Giardia cysts, MS and SOM coliphage were measured in feed and permeate water as surrogates due to their smaller size at approximately 25 nm (Jofre et al. 2016; Mann et al. 2019; Metcalf & Eddy 2007).

An overview of sampling locations for the microbial water quality assessment on both CCRO and FO pilot units is illustrated in Figure 11. For additional details and a general description of the FO and CCRO pilot units, refer to Sections 2.1.2 and 2.1.3, respectively. Due to the cyclic operation of CCRO, sampling locations were selected in accordance with the following procedure. Native microbial enumeration grab samples were taken from a sampling port located immediately after the RO concentrate tank and from a CCRO permeate sampling port, as indicated by the orange circles in Figure 11. For uniformity amongst CCRO samples, all composite grabs were collected over the duration of one cycle as noted previously. This was done by collecting 4 liters of CCRO feed and permeate in the presence of 50 mg/L sodium thiosulfate to quench chlorine; the 4 liters were mixed, then aliquoted into an appropriate collection bottle for subsequent microbial analysis. FO pilot feed and permeate samples were directly collected in 250 mL bottles containing 50 mg/L sodium thiosulfate to quench chlorine and submitted for microbial analysis.

2.5.4.1 MS Coliphage Die-Off Study

As a quality control measure, an MS coliphage decay (die-off) assessment was performed to account for sample degradation resulting from transit times during delivery to the Michigan State

University (MSU) Water Quality Laboratory. This assessment was performed because of limited guidance in the literature for the types of water samples being collected and shipped in this study (concentrate and permeate).

The objective was to evaluate whether the addition of a preservative agent (a buffer solution of potassium dihydrogen phosphate and magnesium chloride) would help minimize the natural rate of MS coliphage die-off that may occur during transit conditions. To evaluate die-off, GWRS RO concentrate and permeate from the CCRO pilot (assumed to be sufficiently representative of the FO-RO pilot permeate) was equally split into "buffered" and "unbuffered" replicates, then shipped to MSU for MS coliphage analysis. Upon arrival at MSU, these samples were further divided such that each buffered and unbuffered sets were processed with a native and seeded quantity of MS coliphage. The seeded sets were seeded (spiked) with MS coliphage by MSU after arrival. To best simulate expected sample concentrations, the feed (GWRS RO concentrate) samples were seeded at a target concentration of 106 PFU/mL, while the permeate samples were seeded at a target concentration of 500 PFU/mL. This ensured results to be above the limit of detection. Once prepared, both native and seeded sample sets were incubated in a cooler, on ice, and were monitored at 0, 6, and 24 hours for MS coliphage concentration as a time-course experiment designed to simulate the expected transit time of approximately 24 hours. This allowed for a determination of whether MS coliphage tends to significantly die-off in concentrate, or in permeate, and whether buffering the sample as a preservative helps to minimize this die-off. A detailed methodology for buffering of MS coliphage for die-off assessment is presented in Appendix J.

2.5.5 MS Coliphage Log Removal Challenge

Three MS coliphage challenge tests were performed to evaluate performance with respect to virus removal for both CCRO and FO-RO pilots. The small size of MS coliphage, at approximately 20 nm, makes it a conservative indicator compared to other microbial targets including viruses and thus it is commonly used for evaluation of potable reuse water treatment technologies. Both CCRO and FO-RO membranes are expected to achieve high log removal of MS coliphage, e.g., greater than 6-log. To perform this experiment, both pilot units were temporarily shut down to ensure feed tanks were filled to maximum capacity (Figure 11). With respect to the FO-RO pilot, a 100-gallon feed tank was installed upstream of the pilot feed (RO concentrate) line prior executing the MS challenge test. For a reliable determination of virus log removal for each treatment process, a feed tank seeded with a target concentration of 108 PFU/mL of MS coliphage was generated. Each feed solution was mixed with a PVC plunger for approximately 20 minutes prior to pilot start-up. For MS challenge events 2 and 3, mixing of the seeded feed tank continued during pilot operation throughout the sample collection period. A detailed methodology for MS challenge test is presented in Appendix J.

All samples were collected in duplicate to assess analytical reproducibility. Sampling sites for both CCRO and FO-RO concentrate and permeate samples were taken as previously described in Section 2.5.3. For CCRO, one exception includes the addition of a CCRO blended feed sampling port which consists of the blend of GWRS RO concentrate and CCRO concentrate (refer to Section 2.5.3 for further details). Furthermore, CCRO feed and permeate samples were obtained at the beginning and end of one treatment cycle rather than in a composite format, as performed with the native coliphage enumeration, in order to compare MS coliphage removal at different times within the CCRO cycle. All grab samples were immediately dechlorinated with 50 mg/L of sodium thiosulfate to avoid MS coliphage degradation, chilled, and shipped to MSU for analysis.

Log reduction values were calculated as the log base 10 quotient of the concentration of MS coliphage after treatment (permeate) and before treatment (feed water which is GWRS RO concentrate):

$$\boldsymbol{R} = -\log_{10}\left(\frac{[MS]RO\ Permeate}{[MS]RO\ Concentrate} \right) \quad \textbf{(3)}$$

Percent reduction was calculated in the following manner:

$$\boldsymbol{P} = 100 \times \left(\frac{[MS]RO\ Concentrate - [MS]RO\ Permeate}{[MS]RO\ Concentrate}\right) \quad \textbf{(4)}$$

where R = log-reduction, P = percent reduction, and [MS] refers to the concentration of MS coliphage in PFU/mL.

2.5.6 UV-AOP Treatment Suitability

UV-AOP treatment suitability experiments were conducted using the single-lamp pilot UV reactor (described in Section 2.4) operated under conditions that emulated the advanced oxidation performance of the full-scale 6-reactor Trojan UVPhox at OCWD's AWPF.

RO permeate (240 gallons) from the CCRO and FO pilot units was collected in separate 275-gal polyethylene totes. These source waters were gravity fed to the pump (Grundfos pump, 0.75 HP, ML 80AB-2) through 50 feet of vinyl tubing that delivered the feedwater to the UV reactor. The source water was not recirculated through the reactor and was passed through to waste. A flow rate of 6 gpm was utilized to deliver a UV dose estimated at 850 ± 50 mJ/cm^2 to match the advanced oxidation of 1,4-dioxane and consumption of hydrogen peroxide achieved by the full-scale UV-AOP in the presence of 3 mg/L of H_2O_2.

NDMA (Sigma-Aldrich) and 1,4-dioxane (14DIOX) (certified ACS, Fisher) were spiked into the RO permeate produced from each pilot unit. The contents of the tote were manually mixed with a PVC plunger. Hydrogen peroxide (H_2O_2) (30 percent w/w; Sigma-Aldrich) was diluted with distilled water to a concentration of 3 percent (w/v) and delivered by peristaltic pump (Masterflex; Cole-Parmer) equipped with Norprene food tubing into a static inline mixer (Koflo Model 1-80-4-4-9.1; Cary, Illinois) at a flow rate of 1.9 mL/min that equated to a targeted dose of 3 mg/L H_2O_2 in the feedwater to the UV reactor to match full-scale AWPF UV-AOP dosing.

Duplicate feedwater (UVF) and product water (UVP) paired samples were collected in 2.5-L amber bottles. Immediately after collection, source water was transferred to 1-L amber bottles for NDMA analysis that contained 100 mg sodium thiosulfate to quench the residual chlorine (chloramines). UVF and UVP source waters were also transferred to three separate 40 mL amber vials for 14DIOXanalysis. NDMA, 14DIOX, and general water quality for constituents relevant to the UV-AOP were measured by OCWD's laboratory based on standard methods of analysis. NDMA was measured by a modified EPA 521 solid-phase extraction method. 14DIOX was measured by modified EPA 524 method utilizing a purge-and-trap GC/MS technique (Yoo et al. 2002; Yoo et al. 2003). Total chlorine (Method 10070) and monochloramine (Method 10171) were measured by colorimetry with a DR6000 spectrophotometer (Hach; Loveland, Colorado). UV percent transmittance (UVT) was measured at 254 nm. Hydrogen peroxide was measured by the titanium oxalate method (Sellers 1980; USP Technologies 2019).

2.5.7 Cost and Footprint Evaluation

The OCWD team worked with Carollo Engineers, Inc. (Carollo) to complete a Class 5 cost estimate in accordance with the Association for the Advancement of Cost Engineering (AACE) International's definitions of the five "class estimates" in AACE International Recommended Practice No. 18R-97. The expected accuracy of any estimate is 50 percent over the estimate to 30 percent under the estimate. Process Flow Diagrams (PFDs) were prepared for the CCRO and FO technologies to show the unit processes required for a full installation. Using the PFDs and information provided by the vendors and other similar projects, a conceptual layout was developed at feed flowrates of 10 and 20 mgd to illustrate the required footprint to accommodate each system. Details of the conceptual layouts used for cost estimation are included as an appendix to this report (Appendix L).

Capital costs consist of all items that will be constructed/purchased for the evaluated case. The cost of major equipment for the CCRO system was obtained from Desalitech. FO system cost estimates were obtained from Porifera. Historical costs from other Carollo projects or scale-up or scale down of similar sized projects were also used. O&M costs include the labor, power cost, chemicals, and membrane replacement, along with an allowance for on-going maintenance needs. O&M cost estimates were based on historical costs from recent Carollo projects, pilot study experience for chemical usage and pilot cleaning frequency, electrical power usage based on conceptual design criteria and pressure estimates from the pilot study, and labor cost estimates from OCWD.

3 Results and Discussion

3.1 FO-RO Pilot Operational Optimization and Challenges

The Porifera FO-RO pilot system initially operated well and continued to produce high quality water. However, as operation continued, there were some programming bugs and design issues that eventually required repairs and adjustments to keep the system running continuously. During Phase 3 of the pilot study, the experimental plan was to initially investigate the ideal (maximum sustainable) recovery so that the system could operate at a stable condition for sampling events. However, due to the operational challenges of operating the pilot system in draw overpressure mode, the system operated between 30 and 35 percent recovery for most of the testing. Figure 12 shows the months of operation and run time of the pilot system as well as the operating recovery of the FO and RO processes. Overall, the system piloted at OCWD for more than 18 months (December 2017 to August 2019), with continuous operation for approximately less than half of that time.

The FO-RO pilot encountered several operational challenges as identified below.

- FO and RO membrane fouling due to initial use of fluorescein dye in the system.
- FO fouling due to clay with some minor general organic fouling based on autopsy results. There was also very minor scaling where the membrane came in contact with the feed spacer.
- FO membrane delamination due to rapid spikes in draw overpressure often caused by power outages, cleaning, or other maintenance that occurred at the AWPF.
- Intermittent draw pressure relief valve malfunction (issue that was misinterpreted as other types of failure due to its intermittent nature). This malfunction would bleed salt from the draw loop; hence, greater-than-normal draw salt make-up was often necessary during piloting.
- Failure or otherwise required maintenance of other mechanical parts including the RO feed pump, FO feed pump, pressure transmitters, and conductivity sensors.

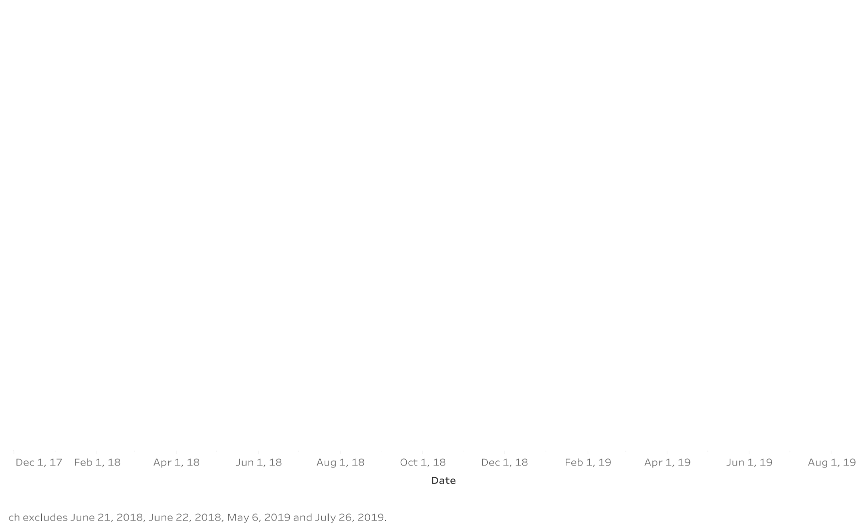

Figure 12. FO-RO pilot run time and unit process recovery for RO (top) and FO (bottom). The FO recovery equals the overall system water recovery (Desormeaux et al. 2019).

The representative range of operating parameters during optimization is provided in Table 5.

Table 5. Representative range of operating parameters during pilot operation (Desormeaux et al. 2019)

Stream/Parameter		Feed In	Reject Concentrate Out	Dilute Draw		Regenerated Draw[1]		Permeate Out	Draw Blowdown Out[2]
Number in Figure 1.6		1	2	3		4		5	6
Flow (gpm)	Avg.	0.97	0.65	1.4		1.1		0.32	0.0008
	Max.	1.1	0.7	1.8		1.5		0.45	0.006
	Min.	0.9	0.5	1.2		0.9		0.27	0
Pressure (psi)	Avg.	5	3	6 FO	350 RO	8 FO	340 RO	<10	<10
	Max.	8	5	10 FO	450 RO	13 FO	430 RO		
	Min.	3	2	5 FO	270 RO	6 FO	260 RO		
Conductivity (mS/cm)	Avg.	9.6	13.4	28		37		0.3	Same as dilute draw
	Max.	11.5	16.5	35		42		0.6	
	Min.	8.0	10.9	22		28		<0.1	

[1]The regenerated draw pressure was controlled by the RO pump within the draw loop to maintain approximately 3 psi draw overpressure compared to the Feed In pressure for the majority of pilot testing. Higher draw overpressures were tested; however, this increased the likelihood of glue line failures during GWRS RO flush and power variation events.
[2]Blowdown is shown at representative continuous flow rates. Blowdown was evaluated at rates of 0% to 2% of system permeate flow in both continuous and intermittent mode. Blowdown was set at 0.25% in intermittent mode for the majority of pilot operation.

3.1.1 Establishment of FO-RO Cleaning and Maintenance Frequency

Initial operation with and without fluorescein dye suggested that the presence of the dye was reducing the FO cleaning frequency from once every 4 to 8 weeks to once every 2 to 3 weeks with the dye present. Thus, choice of dye was reconsidered for this project. Uranine dye, which exhibits similar fluorescent properties to fluorescein, did not appear to have the same negative impact over a period of less than two months. After the fluorescein dye was discontinued there were multiple runs with no dye with cleaning periods of 4 weeks and one run of 8 weeks before the FO membranes were replaced due to membrane delamination associated with AWPF maintenance events.

The "tankless system design" for this pilot system can maintain stable draw overpressure and achieve a small-footprint and energy efficient operation. However, the lack of a dedicated draw equalization tank made it very difficult to manage draw overpressure when there were abrupt changes in RO concentrate water quality. This was especially true when power outages, cleaning, or other maintenance occurred at the AWPF such as when full-scale RO skids were flushed, which caused low-salinity water to enter the RO concentrate line which fed the FO-RO pilot.

This low-salinity water would cause the FO flux to spike and cause FO membrane delamination due to rapid changes in draw overpressure.

Two modifications during the final two months of testing appeared to extend the cleaning interval of FO to about once every 4 to 8 weeks: 1) operate FO in feed circulation mode (recycle part of the FO concentrate back to the FO feed side) to maximize crossflow velocity; and 2) perform feed water flush of the FO occasionally. These modifications could be applicable at full-scale, but additional testing is required.

The RO cleaning frequency is conservatively estimated to be once every 6 months; however, the data showed that without the fluorescein dye the RO membrane tested had near new permeability (+10 percent) when autopsied after 8 months of continuous operation. There were only two RO cleanings performed during the entire study and one was directly linked to the fluorescein dye problem and the second cleaning was performed proactively after 6 months of operation (with little apparent change) as a part of troubleshooting an issue that turned out to be related to a faulty valve. There were also two events of RO replacements due to installing new RO elements that did not perform well immediately after installation, but these replacements did not adversely affect cleaning assessment.

Additional piloting is recommended to better assess the technology before commercial installation. However, while the pilot data are incomplete for portions of the test due to replacement of FO membranes, useful data was collected at times throughout the study.

3.2 CCRO Pilot Operational Feasibility and Recovery Optimization

Portions of this section of the report were reproduced from Desalitech/Jacobs operational report with permission from Desalitech and Jacobs (Hwang et al. 2020).

During the last phase (Phase 1C) of the CCRO pilot operational study, the CCRO unit continued to operate as a '4th stage' treating AWPF RO concentrate. In this phase, the side conduit was filled with AWPF RO feed (ROF) rather than RO concentrate. The purpose of this phase of testing was to determine whether CCRO operation using the ROF for flushing would reduce the rate of specific flux decline. When CCRO was operated with AWPF RO concentrate as the sole feed source, rapid specific flux (permeability) decline (60 percent decline within 3 to 4 weeks) was observed in Phase 1B. Use of a ROF flush has two potential benefits over a RO concentrate flush. First, it displaces the CCRO concentrate from the loop with a lower salinity water which is then introduced to the CCRO feed when closed circuit mode begins (acting to potentially disrupt scaling as a mini-clean). Second, it increases the duration of the closed-circuit mode of the sequence to achieve an equivalent overall recovery and CCRO concentrate salinity, so the pressure and salinity swings the membrane exposed over a sequence is extended.

In the case of this technology being implemented as an add-on to a conventional RO facility to increase recovery, there is an individual '4th stage' CCRO recovery versus the overall facility recovery that now includes this additional production. However, if the CCRO Reflex Max side conduit is filled with some of the primary RO facility's ROF (MF effluent) for side conduit flushing, this must be accounted for in the overall recovery calculation since this source water is no longer available for RO permeate production in the primary RO facility. The alternative would be to increase the capacity of the CCRO to account for the lost permeate production of the primary RO so overall recovery wasn't negatively impacted.

The derivation based on mass balance around the CCRO system and the entire AWPF + CCRO is presented in Appendix G. Six different recovery scenarios using either the AWPF ROF or RO concentrate for side conduit supply are listed in Table 6 (Gu et al. 2018). The values illustrate that higher CCRO recovery is required when using the AWPF ROF as feed compared to use of RO concentrate in order to achieve a comparable overall recovery. The overall RO system recovery is the hypothetical maximum overall recovery for the entire (AWPF + CCRO) system. It assumes all the AWPF RO concentrate is treated by the CCRO system. Overall recovery may be less than this number if a project design does not elect to treat all the facility's available RO concentrate with the CCRO system (see Section 3.7 for overall AWPF RO recovery samples from a 10- and 20-mgd concentrate treatment).

Table 6. Individual CCRO and overall RO system recoveries using AWPF ROF and RO concentrate for CCRO side conduit (SC) feed

Case	AWPF Primary RO Recovery	CCRO Recovery	Overall AWPF RO System Recovery	
			CCRO SC Supply = AWPF RO Concentrate	CCRO SC Supply = AWPF ROF
1	85.0%	40.0%	91.0%	81.6%
2	85.0%	45.0%	91.8%	84.5%
3	85.0%	57.5%	93.6%	90.0%
4	85.0%	60.5%	94.1%	91.1%
5	85.0%	61.0%	94.2%	91.2%
6	85.0%	66.0%	94.9%	92.8%

RO concentrate water quality fluctuations created a major challenge for maintaining RO membrane performance in the CCRO pilot. For OCWD, the AWPF RO feed water conductivity experiences diurnal variations which were mirrored by variations in CCRO recirculation loop conductivity as shown in Figure 13 (Gu et al. 2018).

The RO concentrate has a typical EC range of 8,200 to 12,000 µs/cm (6 to 7 times the RO feed concentration) and an estimated TOC of approximately 40 to 54 ppm; these values were observed to vary rapidly on an hourly basis. In addition to diurnal variations, AWPF RO feed water conductivity was observed to be lower on Sundays and Mondays (Figure 13). Although not shown in the figure, during these two-day periods CCRO fouling potential increased as measured by consistent declines in normalized specific flux. It is also noted that following a CIP of one of the AWPF RO trains, displaced foulants present in the AWPF RO concentrate would cause a decline in CCRO specific flux when the concentrate was processed by the CCRO.

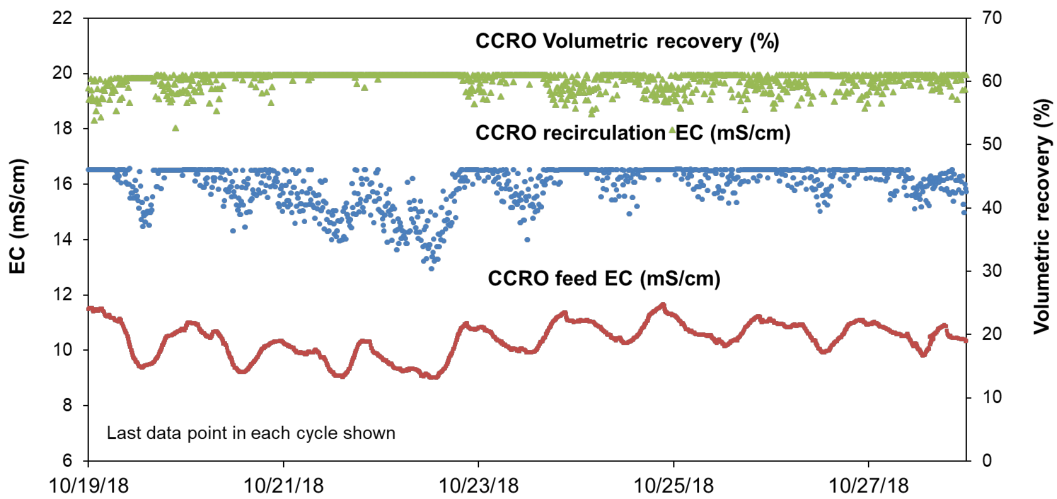

Figure 13. Illustration of adaptive control strategies for the CCRO pilot during Phase 1C

In order to mitigate the impacts of the above factors on CCRO performance, the adaptive control setpoints listed below were added to the control software in the CCRO pilot unit at start of Phase 1C operation.

- CCRO concentrate conductivity (CIT-2) was used as a trigger to enter purge mode. Testing was conducted up to a conductivity of 19.5 mS/cm; however, fouling increased when conductivity exceeded 16.5 mS/cm. CCRO recovery would adapt to the changes in the concentrate (and feed) conductivity in real time, thereby maximizing the overall system recovery while avoiding the point of failure (16.5+ mS/cm in the concentrate) (Figure 13).
- Volumetric recovery of 61 percent was also used as a threshold to trigger purge mode. Optimization testing included recoveries of 61.5, 62.0, 62.5 and 63.0 percent. A threshold of 61.0 percent provided the best protection against the Sunday and Monday low-conductivity episodes that exhibited higher fouling potential, as operating up to 16.5 mS/cm in the concentrate on these days resulted in fouling of the membranes. Figure 14 and Figure 15 show the evolution of feed and recirculation concentrate EC and volumetric recovery for several CCRO cycles.
- A high feed pressure of 220 psi was used to trigger purge mode and start the end of a closed-circuit cycle. This set-point was added to indicate that feed pressure had reach a trigger point for a CIP. By limiting operation to this pressure, the degree of fouling/scaling (measured by feed pressure increase and flux decline) could be minimized such that a CIP would successfully remove the fouling/scaling and specific flux would be fully recovered.

- The pilot was also programmed to automatically reduce recovery to 55 percent when feed conductivity (CIT-1) was less than 8.5 mS/cm and, further, to shut down when CIT-1 was less than 6.5 mS/cm. These set-points were added to minimize the impact of excessive foulants in the CCRO feed water assuming that the reduced CCRO feed conductivity reflects the initial portion of high-foulant AWPF RO concentrate resulting from a primary RO train CIP.

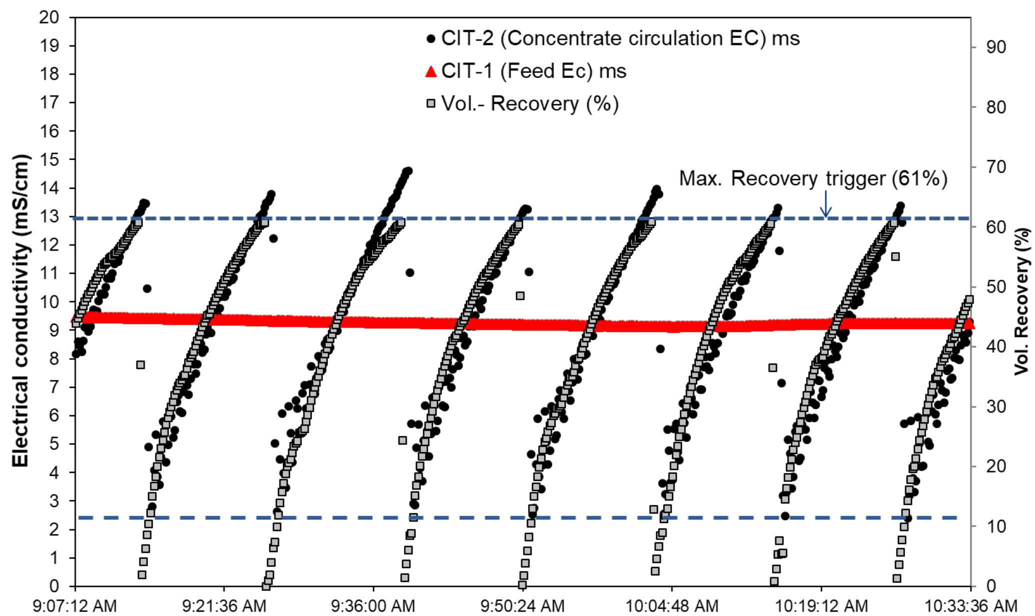

Figure 14. Evolution of feed and recirculation concentrate EC and volumetric recovery for several CCRO cycles; the lower blue line indicates the initial (lowest) EC the system sees when GWRS ROF enter the pressure vessel during purge mode

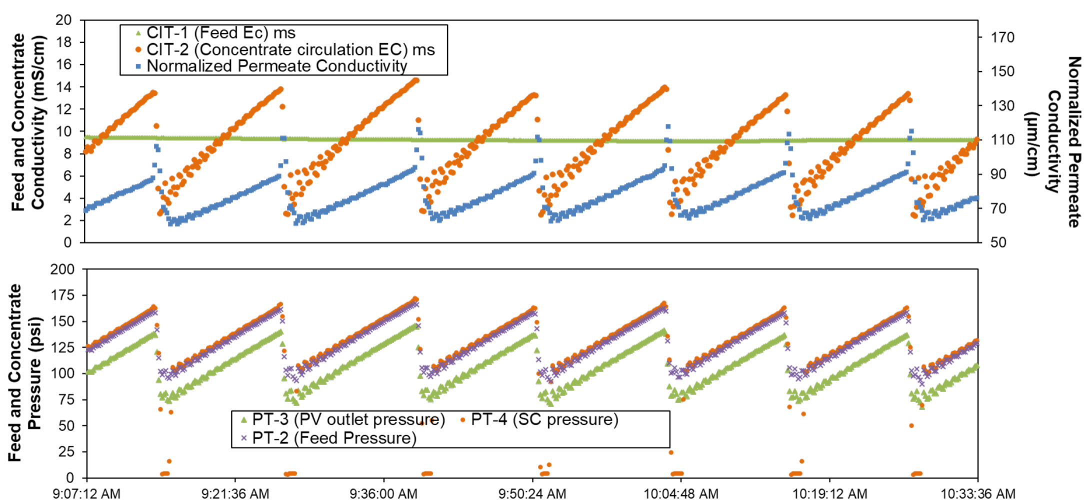

Figure 15. Evolution of feed and permeate EC and pressures across several CCRO cycles

After switching the feed source to the side conduit from AWPF RO concentrate to ROF, together with the above programming changes, the CCRO was successfully operated continuously for 55 days before a CIP was required, which was then conducted using a modified CIP protocol. Figure 16 presents the specific flux and feed pressure for the first Phase 1C run. The final optimized set-points as summarized above were implemented after the CIP. The additional programming changes to enable optimization of unit operation resulted in the CCRO unit operating for 62 days before requiring a CIP, meeting the goal of minimum CIP interval of 30 days. During this run, CCRO recovery ranged from 59.0 to 61.0 percent, corresponding to an overall RO system recovery range of 90.6 to 91.2 percent. Upon successful completion of the two extended runs, the Hydranautics ESPA2-LD elements were removed from the CCRO and the tail element was packaged and shipped to AWC for performance testing and membrane autopsy. The autopsy identified the primary foulants as silts/clays and organics as discussed in Appendix F.

DuPont Filmtec BW30XFRLE-400/34 RO elements were next installed in the CCRO unit due to some concern that the Hydranautics ESPA2-LD membranes may have inadvertently exceeded pressure recommendations (potential compaction) during the multi-phase early trials, and to explore any benefit of the DuPont membranes. The DuPont membranes were selected based on successful performance in the GWRS AWPF RO system and due to the product's ability to maintain stable salt rejection following repeated CIPs. The CIP dates and protocol are summarized in Appendix E (Table E-1). Given that concentrate treatment is a challenging application that will require a higher frequency of CIPs, the ability of an element to maintain salt rejection over time is a critical requirement.

As shown in Figure 16, the CCRO fitted with the DuPont elements was operated continuously at 59.0 to 61.0 percent recovery for 71 days prior to requiring a CIP. Specific flux was restored by the CIP after which a second run was completed for 73 days. The comparable run periods demonstrated that CCRO operation is sustainable at approximately 60 percent recovery. After the second CIP, a third run was initiated at 59.0 to 61.0 percent recovery. After 30 days, recovery was increased to 66 percent, corresponding to an overall RO system recovery of 92.8 percent, and the unit was operated for an additional 33 days (63 days total). At the higher recovery, feed pressure increased and specific flux decreased at greater rates, indicating a greater rate of fouling similar to that observed in Phase 1A during operation at 93 percent recovery. The four extended runs conducted with the Hydranautics and DuPont elements demonstrate that overall recovery can be sustained at around 91 percent recovery (92 percent could be achieved while meeting the 30-day interval). A greater than 2-month CIP interval was more attractive from an operation perspective. All CIPs performed during Phase 1C used the modified CIP protocol (refer to Appendix E, Table E-1).

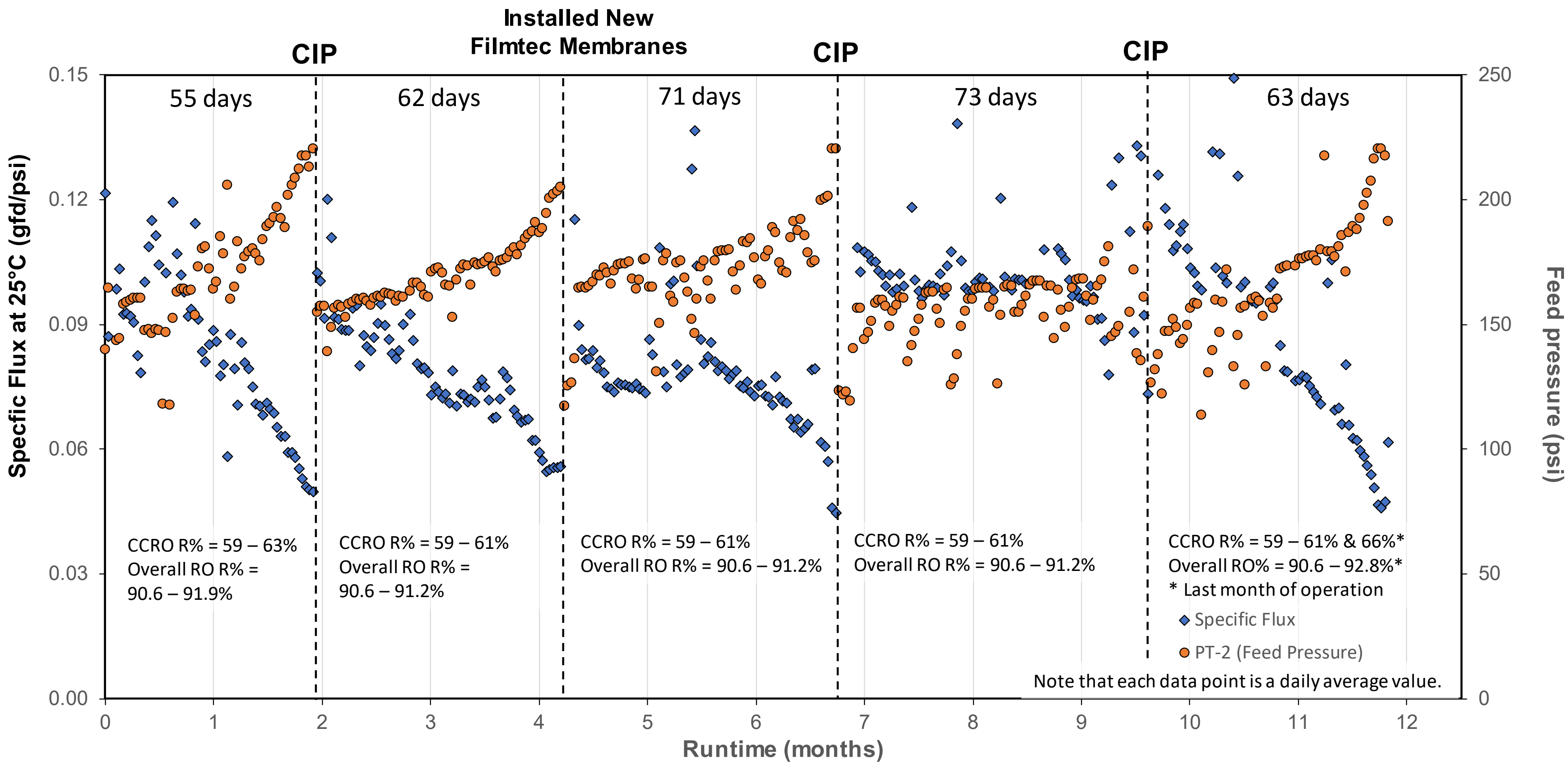

Figure 16. CCRO pilot average specific flux and feed pressure (detailed CIP dates and protocol are summarized in Appendix E, Table E-1)

3.3 Chemical Water Quality Assessment

As shown in Figure 15 (Section 3.2), there is a noticeable difference in CCRO permeate water quality (e.g., conductivity and TOC) between the start of a cycle versus the end of a cycle, which is expected due to the nature of CCRO. To average out this variable quality, a cycle composite approach was used as described in Appendix C.

Figure 17 presents a bar chart of selected general water quality parameters and other constituent concentrations in CCRO and FO-RO permeate, and for reference, in AWPF RO permeate. The permeate from the CCRO and FO-RO pilots is comparable to that generated by the AWPF primary RO treatment of microfiltered wastewater effluent, which is notable considering the much more challenging feed water to the pilots (RO concentrate). The CCRO and FO-RO permeate generally met permit limits for the OCWD AWPF finished water except for certain parameters discussed below. The average FO-RO permeate TOC is 0.37± 0.26 mg/L, and the average CCRO permeate TOC is 0.17± 0.049 mg/L. These values are low but slightly higher than the six-month average GWRS AWPF primary RO permeate TOC of 0.11± 0.03 mg/L. The pilot permeates are still below the GWRS final product water (FPW) permit requirement of TOC of < 0.5 mg/L and, in a theoretical full-scale application, would be expected to be reduced – perhaps significantly – through blending with primary RO system permeate.

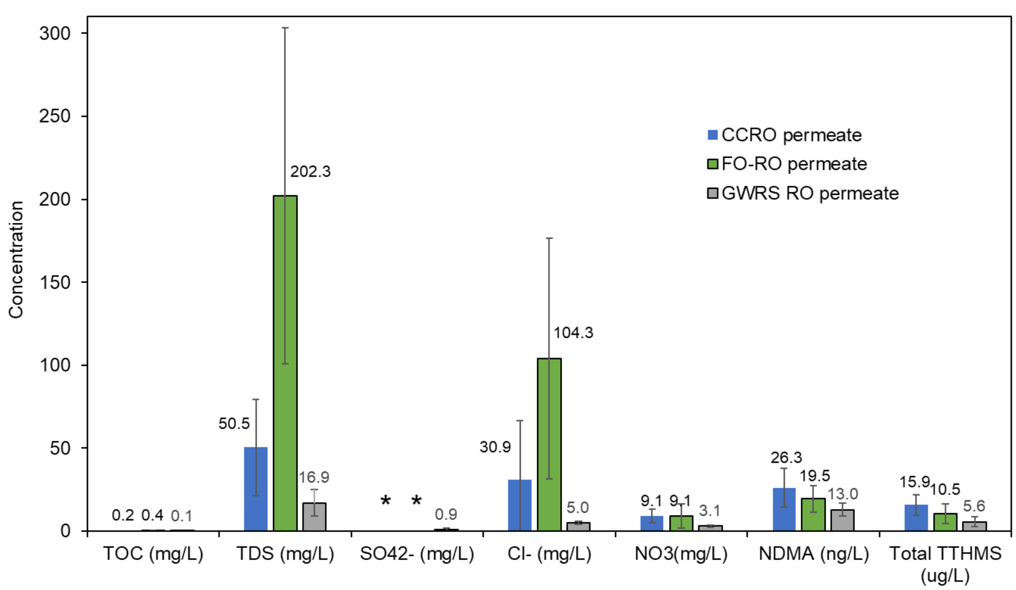

Figure 17. Average concentrations of selected key pilot permeate water quality parameters (n= 4 sampling dates in 2019) for CCRO and FO-RO pilot. OCWD GWRS AWPF water quality average in RO permeate is for March to June in 2019. * Indicates ND in sample (below reported detection limit). The error bars indicate plus or minus one standard deviation from the average value.

The average FO-RO permeate total dissolved solids (TDS) concentration is 202± 101 mg/L, much higher than the average CCRO permeate TDS of 50.5± 28.9 mg/L. Both are higher than the six-month average GWRS RO permeate TDS of 17.0 ± 8.0 mg/L; however, they are still well below the GWRS-FPW permit TDS requirement of 500 mg/L. Note that 2.5-inch diameter RO elements do not typically include the best membrane from RO membrane manufacturers and produce lower quality RO permeate than commercial 8-inch diameter RO membranes. Also, the RO system was not operating at ideal design parameters especially in terms of surface velocity, so a commercial scale dPRshield system would provide better permeate conductivity values at similar operating conditions. All sulfate (SO_4^{2-}) concentrations were below the detection limit of 0.5 mg/L except for one sample of CCRO permeate (0.7 mg/L; February 21, 2019) and one sample of FO-RO permeate (0.6 mg/L; September 25, 2019), which were well below the GWRS-FPW permit requirement of SO_4^{2-} of 100 mg/L.

As shown in Figure 17, the average FO-RO permeate chloride (Cl^-) level is 104 ± 72.5 mg/L, higher than the average CCRO permeate Cl^- concentration of 30.9 ± 35.7 mg/L. Both are higher than the six-month average GWRS RO permeate Cl^- value of 5.0 ± 0.98 mg/L. The FO-RO permeate Cl^- level is above the GWRS-FPW permit requirement of Cl^- of 55 mg/L. Nitrate levels in the FO-RO and CCRO permeates was low, though higher than GWRS RO permeate, still well below the GWRS-FPW permit requirement of 45 mg/L.

Total trihalomethanes (total TTHMs) in the CCRO and FO-RO permeates were higher than in GWRS RO permeate but still well below the GWRS-FPW permit requirement of 80 µg/L TTHMs. NDMA concentrations in FO-RO pilot permeate (19.5 ± 8.1 ng/L) and CCRO pilot permeate (26.3 ± 11.7 ng/L) exceeded the 10 ng/L OCWD permit Monitoring Trigger Level when the CCRO and FO-RO permeate was chloraminated. However, the NDMA concentrations in the GWRS RO permeate also exceeded this level (13.0 ± 4.0 ng/L). As with the primary RO facility, NDMA in CCRO and FO-RO permeate would be removed by UV-AOP as is commonly employed by potable reuse facilities (Marron et al. 2019). NDMA was further evaluated as part of the UV-AOP treatability study discussed in Section 3.5.

The findings for volatile and semi-volatile chemicals (including CECs and DBPs) and inorganic species from the four sampling events were organized according to groupings shown in Figure 18 through Figure 22. In addition, Figure H-1 through Figure H-31 in Appendix H provide complete results for each parameter list for the RO concentrate feed water (for a subset of sampling events on April 15 and June 25, 2019) and CCRO and FO-RO permeates. The percentage removal was estimated based on the feed (when available) and permeate chemical concentration. For the purpose of this report, the percent removal is characterized as “good” when the removal is above 90 percent, “fair” if the removal is above 50 percent, and “poor” if the percent removal is below 50 percent.

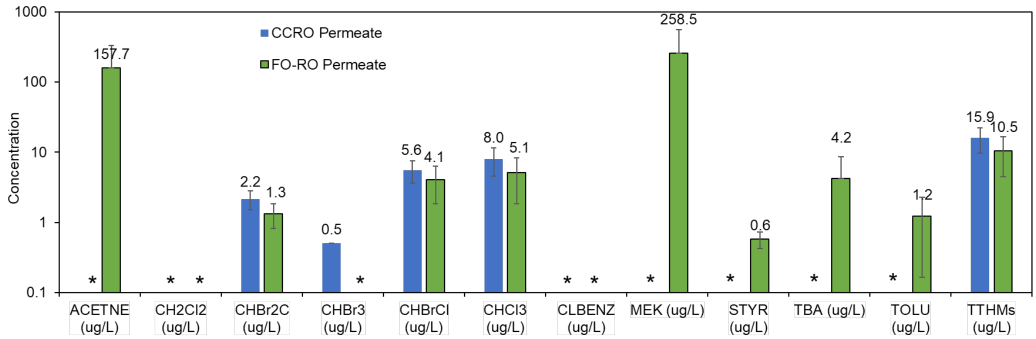

Figure 18. Average concentrations of VOCs (EPA Method 524.2) in CCRO and FO-RO pilot permeates from four 2019 sampling events. * Indicates ND in sample (below reported detection limit). The error bars indicate plus or minus one standard deviation from the average value. If data for all sampling dates were ND, then the average is shown as ND.

Figure 18 shows the average concentrations of volatile organic compounds (VOCs) using EPA Method 524.2 for CCRO and FO-RO permeate. FO-RO pilot permeate had slightly lower concentrations for most VOCs except for acetone, methyl ethyl ketone, styrene, and toluene where these compounds are not detected in CCRO permeate. Since methyl ethyl ketone, styrene, and toluene were also not detected in both GWRS RO concentrate sampling events (April 15 and June 19, 2019), significant concentrations of these compounds measured in permeate were unexpected. Oddly, acetone in the feed (40.3 and 26.1 ug/L) was less than the CCRO permeate. Contamination from the laboratory seems unlikely since both CCRO and FO-RO permeate samples went through the same analytical process (the laboratory matrix spike recovery results were also valid). Contamination within the FO-RO pilot system is suspected, such as leaks in draw solution loop and impurities in the dye solution unique to the FO-RO pilot.

Figure H-7 and Figure H-15 in Appendix H show the percentage removal of VOCs by CCRO and FO-RO pilot for April 15 and June 19, 2019. The FO-RO pilot showed better removal capability for VOCs compared to CCRO. FO-RO shows good removal capability of CHBR2C, CHBrCl, CHCL3, and TTHMS where CCRO pilot shows fair removal capability of CHBR2C, CHBrCl, CHCL3, and TTHMS. For the June 25, 2019 sampling event, the CCRO pilot exhibits slightly higher percent removal than the April 15, 2019 sampling event for CHBR2C, CHBrCl, CHCL3, and TTHMS. The variability may be related to the feed concentration on the sampling date.

Figure 19 shows the average CECs concentrations for CCRO and FO-RO permeate. Both pilots were effective in removing CEC compounds. The 47 measured CECs were not detected in any of the FO-RO permeate samples (four sampling events on different days). ACTMNP, CAFFEI, and DIURON were the only CECs detected in CCRO permeate. ACTMNP was detected in low concentration for just one of the four events. A total of 32 CECs were detected in the pilot feed water (RO concentrate) for the April 15, 2019 sampling event (Appendix H, Figure H-8). SUCRAL (241 µg/L) and IOHEXL (41.5 µg/L) were present in high concentrations in the RO concentrate. A total of 31 CECs were detected in the RO concentrate for the June 25, 2019 event (Appendix H, Figure H-16), again with SUCRAL (253 µg/L) and IOHEXL (24 µg/L) present in high concentrations. For the limited number of CECs for which rejection can be calculated given a detectable feed (RO concentrate) concentrations and using the detection limit as permeate concentration for ND results, the corresponding estimated percent removal of ACTMNP ranged from 69.5 to 94.9 percent, CAFFEI was 99.8 percent., and DIURON ranged from 98.8 to 99.9 percent.

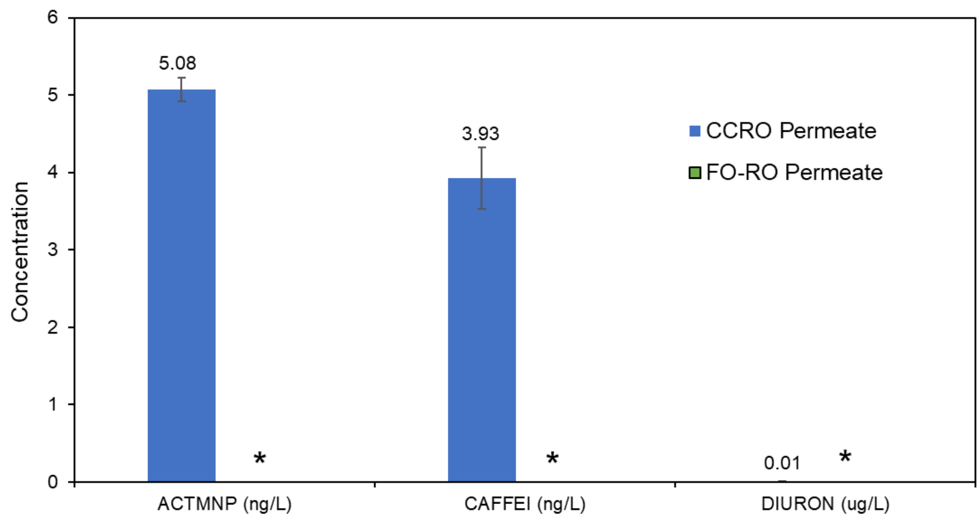

Figure 19. Average concentrations of CECs in permeate samples from CCRO and FO-RO pilot systems collected in four sampling events in 2019. * Indicates ND in sample (below reported detection limit). The error bars indicate plus or minus one standard deviation from the average value.

Figure 20 presents average inorganic species concentration and physical properties for CCRO and FO-RO permeate (mineral salts, silica, N-compounds, TOC, turbidity, pH, EC, and TDS). EC, TDS, Na^+, Cl^-, and K^+ in FO-RO pilot permeate is about 4 to 5 times higher than the CCRO pilot permeate. The average FO-RO permeate sodium (Na^+) concentration was 90.0 ± 55.8 mg/L, twice the GWRS-FPW permit requirement of 45 mg/L (Burris 2018). The higher TDS, sodium, and chloride concentrations are partly due the FO-RO pilot system use of a high salinity draw solution (NaCl) coupled with use of two 2.5-inch by 21-inch seawater RO membrane elements for draw solution separation which feature lower rejection compared to brackish water membranes.

It is noted that the FO-RO pilot permeate also exhibited higher TOC values than CCRO pilot permeate on all four sampling occasions. The TOC percent removal for the FO-RO and CCRO pilots was determined for two sampling dates (when pilot feed quality was measured). TOC removal was 99.5 percent for FO-RO and 99.7 percent for CCRO (April 15, 2019; Appendix H, Figure H-11) and 99.3 percent for FO-RO and 99.4 percent for CCRO (June 25, 2019; Appendix H, Figure H-19), corresponding to greater than 2 logs, similar to the AWPF primary RO system.

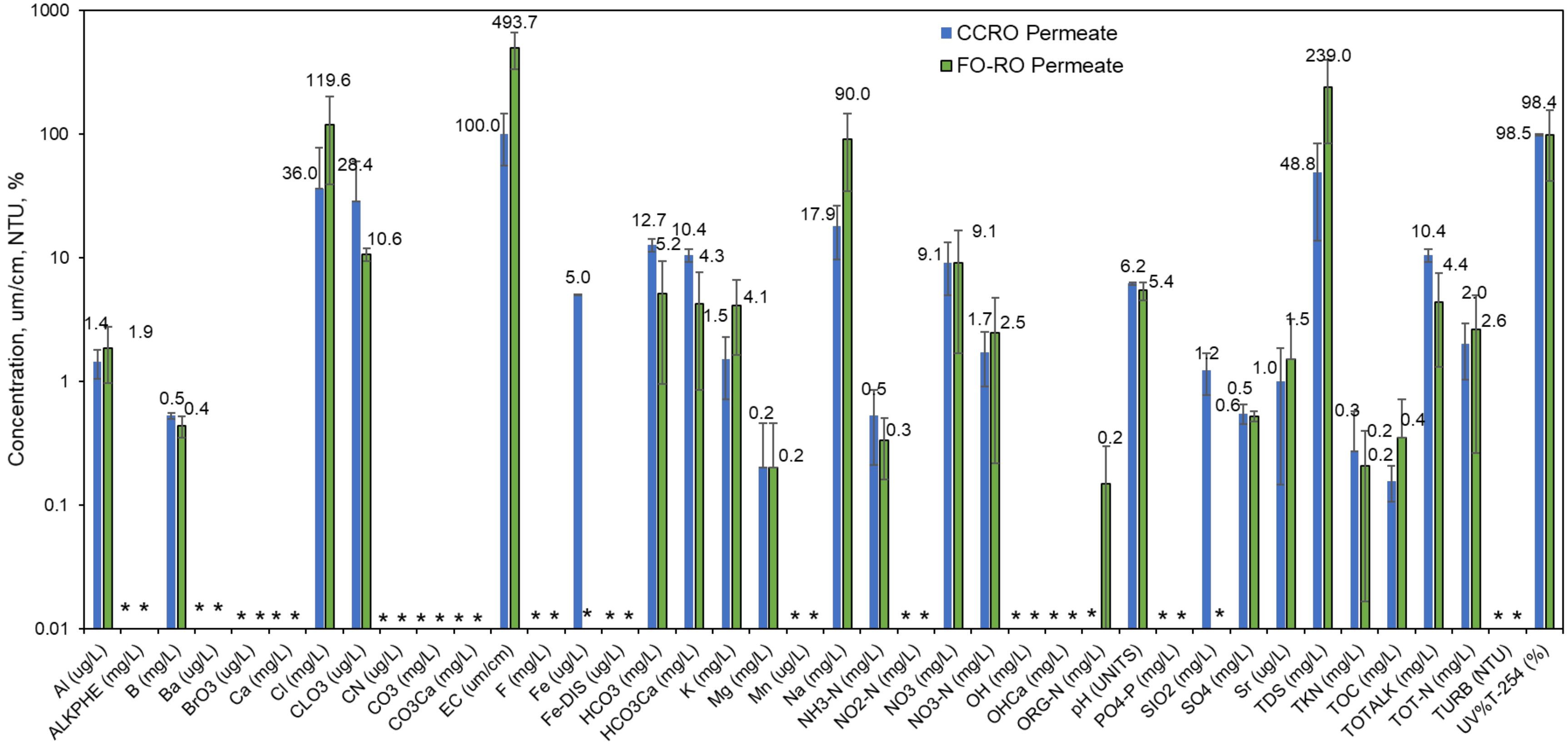

Figure 20. Average values for a list of inorganic species concentration and physical properties of permeate samples from CCRO and FO-RO pilot systems collected in four sampling events in 2019. * Indicates ND in sample (below reported detection limit). The error bars indicate plus or minus one standard deviation from the average value.

Figure 21 shows the average concentration of metals and inorganics in CCRO and FO-RO permeate analyzed using EPA Methods 200.7 and 200.8. Only 5 out of 31 dissolved metal and other ions were above the detection limit in the CCRO and FO-RO pilot permeates (boron, copper (FO-RO only), phosphorus, sodium, and strontium). Like the results shown in Figure 17, sodium in FO-RO pilot permeate (75,250 ± 35,132 µg/L) is about 4 to 5 times higher than in the CCRO pilot permeate (17,750 ± 6,994 µg/L). The sampling performed on June 25, 2019 showed sodium removal for the FO-RO pilot was only 91.5 percent and for the CCRO pilot was 98.7 percent (Appendix H, Figure H-23). Phosphorus was present in low concentrations in both FO-RO and CCRO permeates in all sampling events, however it was not detected as orthophosphate (PO4-P). Boron was present in both FO-RO and CCRO permeates in all sampling events; it is poorly rejected by both membrane processes (as shown in Appendix H, Figure H-23; 56.7 percent removal by CCRO pilot and 66.7 percent removal by FO-RO pilot).

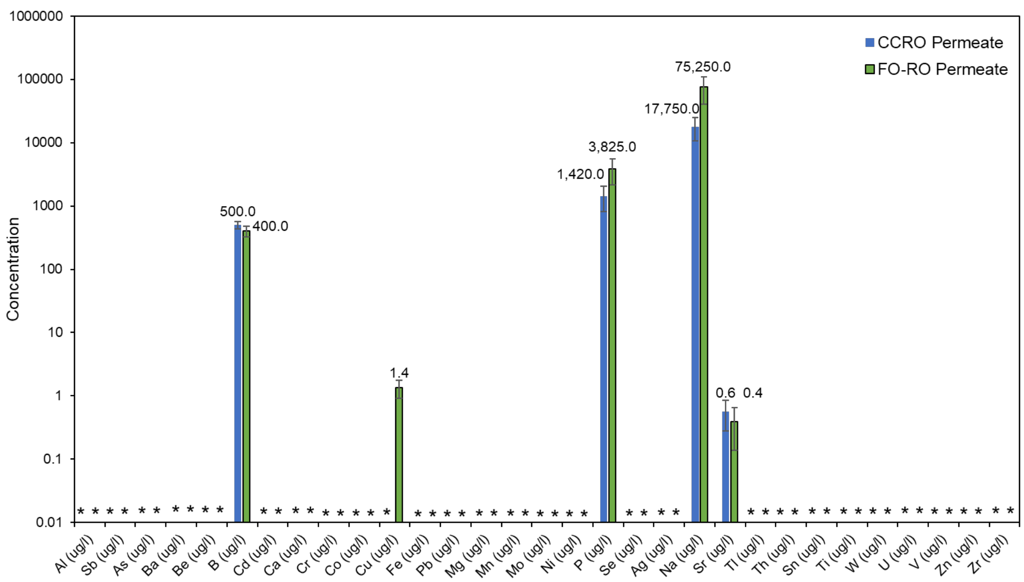

Figure 21. Average concentrations of metals (EPA Methods 200.7 and 200.8) and inorganics in permeate samples of CCRO and FO-RO pilot system for four sampling dates in 2019. * Indicates ND in sample (below reported detection limit). The error bars indicate plus or minus one standard deviation from the average value.

Figure 22 presents organics that were detected in CCRO and FO-RO pilot permeate for the four sampling events. For several standard methods, no organics were detected (EPA 508 Organochlorine Pesticides and PCBs, EPA 625 SVOCs and Priority Pollutants, EPA 8330A Explosives Residues, EPA 8015 Ethylene Glycol, and asbestos) for GWRS RO concentrate (pilot feed), CCRO and FO-RO permeate samples. PFAS (EPA 537.1), PFOA (73.0 ng/L), and PFOS (66.0 ng/L) were detected in the GWRS RO concentrate sample (June 25, 2019) but not in the permeate samples for the pilots. 1,4-dioxane (14DIOX) was detected in the GWRS RO concentrate sample (June 25, 2019) but not in the permeate samples for the pilots. The results showed the FO-RO pilot permeate has slightly lower concentrations for most organic compounds compared with CCRO pilot permeate sample. This is likely attributable to the FO-RO double-membrane system versus the CCRO single membrane system.

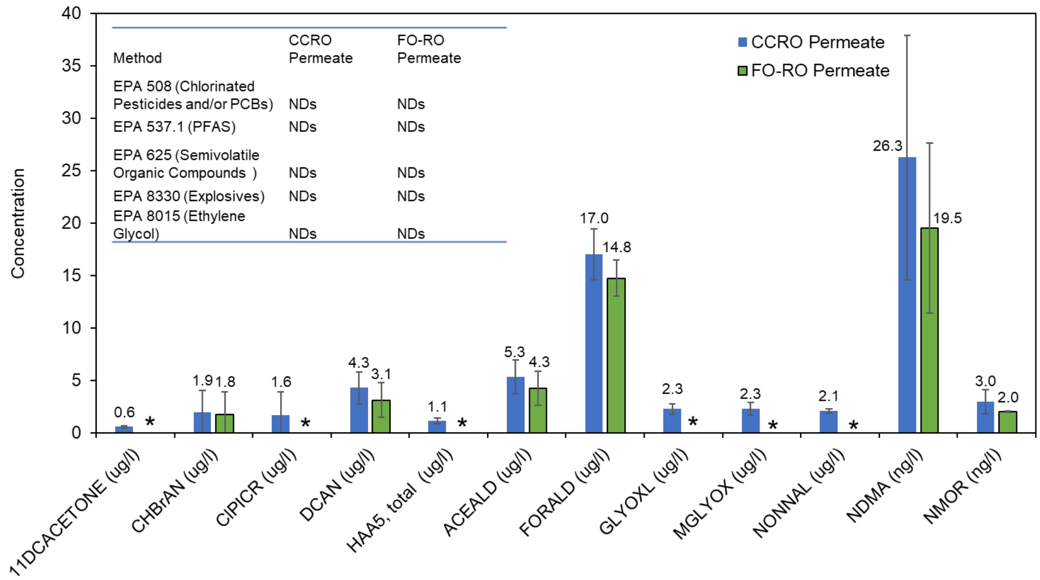

Figure 22. Average concentrations of organic compounds in permeate samples from CCRO and FO-RO pilot systems for four sampling dates in 2019. Methods: EPA 537.1 (PFAS), EPA 8015 (Ethylene Glycol), EPA 625 (SVOCs & Priority Pollutants), EPA 508 (Organochlorine Pesticides & PCBs), EPA 551.1 (Haloacetonitrile DBPs), EPA 556 (Aldehydes), EPA 552.2 (HAA5), Nitrosoamines-1625M, 8330A explosives residues, 1,4-dioxane, and Asbestos. * Indicates ND in sample (below reported detection limit). The error bars indicate plus or minus one standard deviation from the average value.

NDMA was detected in CCRO (26.3 ± 11.7 ng/L) and FO-RO (19.5 ± 8.1 µg/L) permeate samples for all four events. For the June 25, 2019 event with detectable NDMA in the feed water (GWRS RO concentrate; see Appendix H, Figure H-20), the corresponding estimated NDMA removal for the CCRO pilot was 82.5 percent and for the FO-RO pilot it was 90.0 percent. N-Nitrosomorpholine (NMOR) was detected at very low concentrations (2 to 3 ng/L) for two of four events for CCRO pilot permeate. NMOR was only detected in one of four events for FO-RO permeate. Formaldehyde (FORALD) was detected at low concentrations in both CCRO (17.0 ± 2.4 µg/L) and FO-RO permeate samples (14.8 ± 1.7 µg/L) for all four events; from the pilot feed (RO concentrate) concentration for June 25, 2019 event (see Appendix H, Figure H-20), the corresponding estimated formaldehyde removal for FO-RO was 78.5 percent and for CCRO was 74.7 percent.

Total haloacetic acids (HAA5) and chloropicrin (ClPICR) were detected in very low concentrations for one of four events for CCRO pilot permeate (1.1 and 1.6 µg/L, respectively), well below the GWRS-FPW permit requirement of total HAA5 of 60 µg/L. Total HAA5 and ClPICR were not detected in all four events for FO-RO permeate. Acetaldehyde (ACEALD) was detected in both CCRO (5.3 ± 1.6 µg/L) and FO-RO permeate samples (4.3 ± 1.6 µg/L) for all four events, with an estimated removal for the FO-RO pilot of 80.7 percent and a removal of 78.7 percent for CCRO. 1,1-Dichloro-2-propanone (11DCACETONE) was detected in low concentrations for two of four events for CCRO pilot permeate (0.62 µg/L). 11DCACETONE was not detected in all four events for FO-RO permeate. Bromochloroacetonitrile (CHBrAN) was detected in low concentration for two of four events for CCRO pilot permeate (1.9 µg/L) and three of four events for FO-RO pilot permeate (1.8 µg/L). 11DCACETONE was not detected in all four events for FO-RO permeate.

Dichloroacetonitrile (DCAN) was detected at low concentrations in both CCRO (4.3 ± 1.5 µg/L) and FO-RO permeate samples (3.1 ± 1.7 µg/L) for three of four events, with a measured removal of 89.5 percent for the FO-RO pilot and 83.9 percent for CCRO during the June 25, 2019 event (see Appendix H, Figure H-20).

Excitation Emission Matrix Spectroscopy (EEMS) results for the CCRO permeate, FO-RO permeate, and AWPF ROC from the June 25, 2019 water sampling event are included in Appendix I. Both treatment processes were able to remove microbial products and proteins, fulvic-like acid compounds, and humic acid compounds in the AWPF ROC.

3.4 Microbial Water Quality Assessment

In general, pilot feed water (GWRS RO concentrate) was observed to be relatively free of microbes as represented by fecal indicators. One exception was a CCRO feed grab sample taken on September 25, 2019, where 3 MPN/100 mL of total coliform was detected. Note, however, that a positive total coliform result merely suggests the presence of a bacterial organism that may or may not be associated with fecal matter or E. coli. Aside from this total coliform result, both somatic coliphage and E. coli were not detected.

MS coliphage was detected in all CCRO and FO-RO feed water grab samples. Detection of MS coliphage varied from 4.2 to 94 PFU/mL and appeared to vary by sampling day, with September 25, 2019 reporting the highest values of 94 PFU/mL and 92 PFU/mL for CCRO feed and FO-RO feed, respectively (Table 7).

All permeate grab samples from the CCRO pilot and the FO-RO pilot were free of all microbial indicators; total coliform, E. coli, somatic coliphage, and MS coliphage were not detected as shown in Table 7.

Table 7. Native microbial assessment for feed water (which is GWRS RO concentrate) and CCRO and FO-RO pilot permeate waters for three sampling events in 2019. Values with a "<" symbol represent the limit of detection for their respective methods.

Parameter	Sample Date	CCRO Feed	CCRO Permeate	FO-RO Feed	FO-RO Permeate
MS-2 Coliphage (PFU/mL)	Aug. 26	19	<0.1	--	--
	Sept. 25	94	<0.1	92	<0.1
	Oct. 23	4.2	<0.1	8.2	<0.1
	Nov. 6	--	--	55	<0.1
Somatic Coliphage (PFU/mL)	Aug. 26	<0.1	<0.1	--	--
	Sept. 25	<0.1	<0.1	<0.1	<0.1
	Oct. 23	<0.1	<0.1	<0.1	<0.1
	Nov. 6	--	--	<0.1	<0.1
Total Coliform (MPN/100 mL)	Aug. 26	<0.1	<1.0	--	--
	Sept. 25	3	<1.0	<1.0	<1.0
	Oct. 23	<0.1	<1.0	<1.0	<1.0
	Nov. 6	--	--	<1.0	<1.0
E. coli (MPN/100 mL)	Aug. 26	<0.1	<1.0	--	--
	Sept. 25	<0.1	<1.0	<1.0	<1.0
	Oct. 23	<0.1	<1.0	<1.0	<1.0
	Nov. 6	--	--	<1.0	<1.0

3.4.1 MS Coliphage Die-Off Study

Native enumeration of MS coliphage revealed a low concentration present in CCRO feed ranging from 0.5 to 2 PFU/mL. A reduction in viable MS coliphage was observed within the first 6 hours (0.6-log reduction) with little to no additional change (decay) by 24 hours (Table 8). Native MS coliphage enumeration results for CCRO permeate grab samples were below the limit of detection (EPA Method 1602) resulting in values below 0.1 PFU/mL. Due to the limit of detection for EPA Method 1602, these observations limited the understanding of the fate of MS coliphage inactivation at low concentrations residing in CCRO permeate matrix.

In samples where MS coliphage was supplemented, CCRO buffered and unbuffered feed samples were initially seeded with 106 PFU/mL of MS coliphage. After 6 hours, no MS inactivation was observed for samples with and without buffering agent (Figure 23, Panel B). After 24 hours, 0.1-log and 0.16-log MS coliphage reductions were observed for buffered and unbuffered samples, respectively. This result suggests that buffering feed or permeate samples with KH_2PO_4:$MgCl_2$ does not significantly improve the preservation of MS coliphage. Most notably, this effect was also apparent in CCRO permeate samples for which a relatively low seeding target of 500 PFU/mL was used to ensure measured values were above the detection limit. Surprisingly, no MS inactivation was observed after 6 and 24 hours in both buffered and unbuffered CCRO permeate, where decay was expected to occur.. All measurements remained constant at around 500 PFU/mL over 24 hours. Thus, buffering did not improve preservation for permeate samples. Log reduction values are reported in Table 8.

It should be noted that while there was a measurable decline in MS coliphage concentration with sample storage in the case of (not spiked) feed water (concentrate), the log reduction is small compared to the much higher (>5-log) MS coliphage removal observed during the pilot scale treatment study (see next section). Thus, the die-off study found that MS coliphage decay related to sample shipment is not significant.

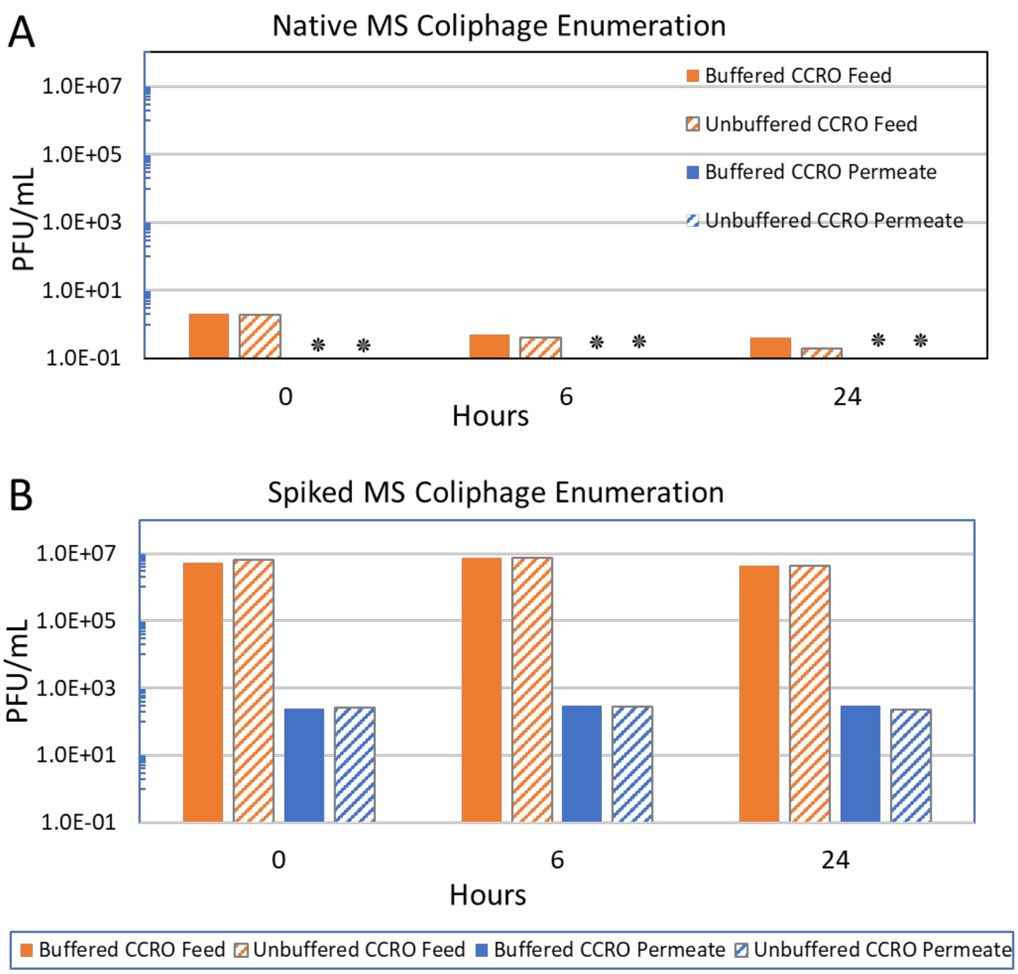

Figure 23. MS Coliphage die-off observed for native (A) and spiked (B) CCRO feed (orange) and permeate (blue) assessed at 0, 6, and 24 hours for buffered (solid) and unbuffered (textured) samples. The spiked feed and permeate samples were seeded with a target concentration of 106 PFU/mL and 500 PFU/mL, respectively. * Indicates a value below the detection limit of 0.1 PFU/mL.

Table 8. Log reduction of MS coliphage after 6 and 24 hours under buffered and unbuffered conditions for CCRO feed and permeate. Notes: ND indicates a non-detect result (< 0.1 PFU/mL); negative values indicate higher MS coliphage concentrations (PFU/mL values) at t = 6 and 24 hours compared to t = 0, likely due to measurement analytical error/variability (i.e., no significant change in MS coliphage concentration over time).

MS Coliphage	Sample	Buffered		Unbuffered	
		6 Hours	24 Hours	6 Hours	24 Hours
Native	CCRO Feed	0.62	0.72	0.68	0.98
	CCRO Permeate	ND	ND	ND	ND
Spiked	CCRO Feed	-0.13	0.1	-0.05	0.16
	CCRO Permeate	-0.09	-0.09	-0.01	0.06

3.5 MS Coliphage Log Removal Challenge

MS coliphage challenge tests were performed on the CCRO and FO-RO pilot units by seeding the feed tanks with a target of 10^8 PFU/mL in three separate events (for replication) after 1 hour of operation to ensure steady conditions. For CCRO, MS coliphage samples were collected at the beginning and end of a treatment cycle to assess log removal. Results for these samples are shown in Figure 24. Throughout all three events, measurements obtained for the CCRO pilot unit at the beginning of the treatment cycle were steady with 5.2-log (average) removal of MS coliphage for both the pilot feed and the blended feed (recirculated feed). At the end of cycle, an average of 4.3-log MS coliphage removal was determined, suggesting an average of 0.9-log reduction in performance compared to the beginning of the cycle (Table 9).

Results for the FO-RO challenge tests are shown in Figure 24 (Panel C). Permeate samples for the first two events resulted in non-detect values, while Event 3 resulted in a 270 PFU/mL detection corresponding to 6-log removal of MS coliphage. Given the double membrane barrier and higher log removal observed in the first two events (which is based on detection limit of MS coliphage in permeate to calculate estimated log removal), this result may indicate lesser than expected integrity of the membrane(s) on this day. Without further testing it is unknown whether the lower LRV of approximately 6.0-log is representative of normal operation (Table 9)

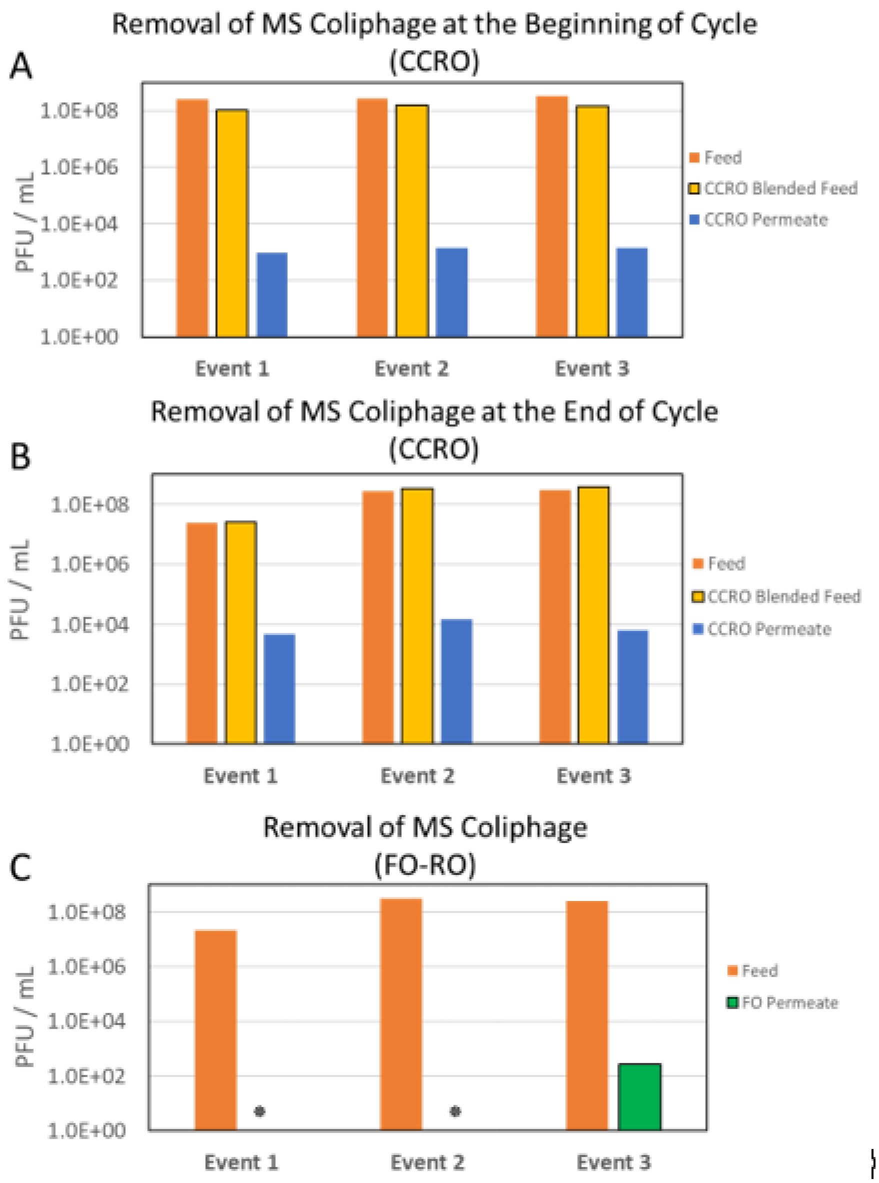

Figure 24. MS coliphage log removal challenge test of CCRO and FO-RO pilots. MS coliphage removal for the CCRO pilot was evaluated at the beginning (A) and end (B) of the cycle. The average virus log removal values observed were 5.3 and 5.0 for pilot feed and blended feed (recirculation point), respectively. MS challenge data for grabs taken from Porifera's FO-RO pilot unit are shown in panel C. Virus removal for the FO-RO unit was greater than 6.0-log for Events 1 and 2; Event 3 showed a 6.0-log removal. All grab samples were measured with experimental replicates (n=2) and the averages are shown. Events 1, 2, and 3 correspond to October 8, October 30, and November 12, respectively.

Table 9. MS coliphage log removal values from challenge tests performed on CCRO and FO-RO pilots

Pilot	Sample	Event 1	Event 2	Event 3
CCRO (Beginning of Cycle)	CCRO Feed	5.4	5.3	5.4
	CCRO Blended Feed	5.1	5	5
CCRO (End of Cycle)	CCRO Feed	3.7	4.3	4.7
	CCRO Blended Feed	3.7	4.4	4.8
FO-RO	FO-RO Feed	>6.0	>6.0	6

3.6 UV-AOP Treatment Suitability

3.6.1 Regulations and Full-Scale UV-AOP Performance for NDMA and 1,4-Dioxane

Four N-nitrosamines are regulated in the State of California in either drinking water and/or recycled water. NDMA, N-nitrosodiethylamine (NDEA), and N-nitrosopropylamine (NDPA) all have state drinking water Notifications Levels of 10 ppt (ng/L), for which exceedances in both drinking water and recycled water for potable reuse require response actions; these compound also have drinking water Response Levels for which additional recommendations apply. NDMA and N-Nitrosomorpholine (NMOR) also have Monitoring Trigger Levels set in the state's 2018 Recycled Water Policy, which updated constituents of emerging concern (CEC) monitoring requirements for potable reuse projects. Prior to 2014, the Drinking Water Program (DWP) of the California Department of Public Health (since transferred to the State Water Resources Control Board, Division of Drinking Water) administered draft regulations for groundwater recharge reuse projects (GRRPs). Versions of the draft GRRP regulations going back to the early 2000s required potable water reuse facilities to demonstrate 1.2-log removal of NDMA by an advanced treatment process. However, this requirement was removed from the Final GRRP regulations established in 2014, with the NDMA Notification Level applicable as described above.

Currently, the CASWRCB recycled water regulations for advanced treatment require testing to (1) demonstrate the removal of a suite of indicator compounds from 0.3 to 0.5 log, depending on the class of compound or in lieu to (2) demonstrate 0.5-log removal of 1,4 dioxane by an advanced oxidation process for permitting (CASWRCB 2018).

Historically, 1.4-log removal of NDMA has been achieved by the full-scale, six-reactor Trojan Technologies UVPhox train at an electrical energy dose (EED) between 0.23 and 0.25 kWh/kgal. Validation tests were performed at the AWPF in October of 2008 by Trojan Technologies (Brown 2008). For UV-AOP system validation purposes, removal of 1,4-dioxane from the AWPF RO permeate by the UVPhox reactor train was measured in December 2007 by OCWD and a second test was conducted on October 2008 with removals reported as 0.45 and 0.47 log, respectively.

3.6.2 CCRO and FO-RO Permeate Water Quality

The first UV-AOP pilot test was completed on June 24, 2019 and the second on August 26, 2019. Data for the general water quality of the CCRO and FO permeate feed water to the pilot UV reactor are shown in Table 10. On these days, the FO permeate had significantly more chloride than the CCRO permeate; this was related to the sodium chloride draw solution for the FO system described elsewhere in this report. The TOC concentration was also higher in the FO permeate. The chloride concentration in the FO-RO permeate was significantly higher when the second test was conducted (Table 10) due to FO membrane fouling issues of the pilot.

Table 10. General water quality of CCRO and FO-RO permeates that were utilized for UV-AOP treatment suitability testing

Constituent	UV-AOP Pilot Test June 24, 2019		UV-AOP Pilot Test August 26, 2019	
	CCRO (mg/L)	FO-RO (mg/L)	CCRO (mg/L)	FO-RO (mg/L)
Chloride (Cl^-)	14.6	126	13.2	465
Bicarbonate (HCO3)	10.3	14.3	8.8	12
Bicarbonate (HCO3Ca)	8.5	11.8	7.2	9.8
Ammonia (NH3-N)	0.4	2.0	<0.1	2.2
Nitrite (NO2-N)	<0.002	<0.002	<0.002	<0.002
Nitrate (NO3-N)	3.23	2.23	2.79	2.65
pH	6.2	6.4	6.1	6.5
Total organic carbon (TOC)	0.16	0.33	0.18	0.39
Total Alkalinity (TOTALK)	8.5	11.8	7.2	9.8

3.6.3 Removal of NDMA and 1,4-Dioxane from CCRO and FO-RO Permeate by UV/H_2O_2 AOP

Both UV-AOP pilot tests yielded removal of NDMA near 1.4 log and removal of 14DIOX near 0.5 log, comparable to the historical performance of the full-scale OCWD AWPF UV-AOP that treats the RO permeate (Table 11 and Figure 25). These results were also comparable with historical data from past UV/H_2O_2 AOP pilot-scale studies conducted on the permeate from the AWPF under similar UV reactor settings (data not shown).

Table 11. Removal of target compounds by UV/H_2O_2 AOP process

Pilot Unit	**NDMA**			**1,4 Dioxane**		
	UVF (ng/L)	**UVP (ng/L)**	**Log Removal**	**UVF (ng/L)**	**UVP (ng/L)**	**Log Removal**
Pilot Test on June 24, 2019						
CCRO	480	19.8	1.38	3.36	0.815	0.61
	500	18.6	1.43	3.45	0.775	0.65
No UV light	--	490	--	--	3.72	--
FO	500	20.7	1.38	0.491	0.17	0.46
	510	20.4	1.40	0.519	0.15	0.54
No UV light	--	500	--	--	0.595	--
Pilot Test on August 26, 2019						
CCRO	450	15.8	1.45	38.1	6.7	0.75
	480	16.3	1.47	35.7	7.2	0.70
No UV light	--	470	--	--	37.9	--
FO	440	23.3	1.28	38.8	13.4	0.35
	430	22.3	1.29	42.1	14.3	0.47
No UV light	--	480	--	--	38.2	--

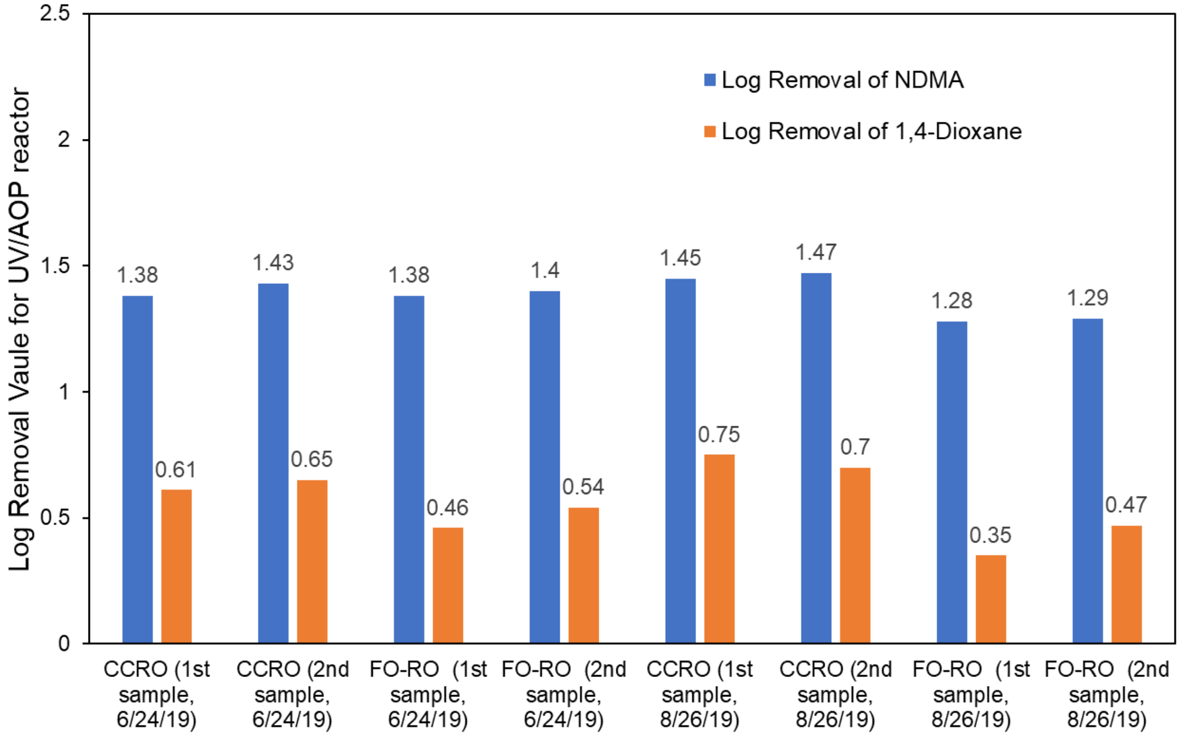

Figure 25. NDMA and 1,4-dioxane log removal values for UV-AOP reactor treating CCRO and FO-RO pilot permeate water; experiments performed on June 24, 2019 and August 26, 2019

Slightly more 14DIOX removal was measured from the CCRO permeate than observed in the full-scale AWPF plant. This may be due to the presence of less monochloramine in the CCRO permeate with a UVT that was 98 percent T compared to 97 percent T in the full-scale plant, whereby photolysis of H_2O_2 would be expected to be slightly more efficient due to less photon scavenging by monochloramine.

Less removal of 14DIOX from the FO-RO permeate was measured (Table 11) compared to removal from the CCRO permeate. This could be a result of the high concentration (126 mg/L) of chloride (Table 10), as the chloride concentration in CCRO RO permeate was significantly lower at 14.6 mg/L. Historically, the AWPF RO permeate chloride concentration has been between 4 and 6 mg/L.

Chloramine is present in OCWD's AWPF UV-AOP feedwater (RO permeate) due to upstream chlorine addition for MF and RO biofouling control, which occurs in the form of either monochloramine or dichloramine. Monochloramine and dichloramine are both photolyzed at 254 nm and produce an amine radical ($\bullet NH_2$ and $\bullet NHCl$, respectively) and chlorine radical ($Cl\bullet$) (Patton et al. 2018) . Chloride reacts rapidly with the $Cl\bullet$ to form the chlorine dimer radical $Cl_2\bullet^-$ that can react with 14DIOX. Thus, the high concentration of chloride can shift the balance of radical formation from the hydroxyl radical toward the chlorine dimer ($Cl_2\bullet$-) radical (Patton et al. 2018). The $Cl_2\bullet^-$ reacts with 14DIOX at a much slower rate at $k = 3.3 \times 10^6$ $M^{-1}s^{-1}$ (Li and

Blatchley 2009) than the HO• at k = 3.1 x 10^9 $M^{-1}s^{-1}$ (Eibernberger 1980; Patton et al. 2018). Mangalgiri et al. did not observe a change in the rate of 14DIOX removal when the chloride concentration was increased from 85 mg/L to 216 mg/L, but the contribution of 14DIOX removal by the chlorine dimer radical did increase two-fold (Mangalgiri et al. 2018). Additional data and discussion related to the occurrence of monochloramine and dichloramine in the UV-pilot feed water are presented in Appendix K.

Results from the second FO-RO pilot UV test indicated a significant reduction in the removal of 14DIOX (Table 11). A larger concentration of chloride in the FO-RO permeate was measured (465 mg/L Cl^-) in this test compared to 126 mg/L Cl^- in the first test. This increase in chloride concentration would undoubtedly result in an increase in the reaction of chloride with the chlorine radical. However, it is not currently clear if this was solely responsible for the reduction in the removal efficiency of 14DIOX from the FO-RO permeate.

In conclusion, both pilot UV-AOP reactor studies, operated under conditions to emulate the full-scale UVPhox reactor train, yielded NDMA removal near 1.4 log and removal of 14DIOX near 0.5 log that was comparable to the historical performance of the full-scale OCWD AWPF UV-AOP system that treats an RO permeate. Thus, UV-AOP treatment of permeates from CCRO and FO-RO was shown to perform as expected and to be a suitable treatment approach for water quality polishing of these waters.

3.7 Cost and Physical Footprint Evaluation

As part of the research feasibility assessment, Carollo Engineers prepared a preliminary cost and footprint evaluation of CCRO and FO-RO concentrate treatment technologies for theoretical full-scale installation at OCWD AWPF to treat a portion (10 mgd or 20 mgd) of the RO concentrate produced by the primary RO system. The key conclusions are summarized below. Schematics for the hypothetical 10-mgd and 20-mgd FO-RO and CCRO system design are included in Appendix L. The full Carollo report is attached in Appendix M.

From the information provided by the two vendors (Desalitech for CCRO system and Porifera for FO-RO system), and the assumptions used to establish the building dimensions, it should be possible to accommodate both technologies on the OCWD site at both 10 mgd and 20 mgd treatment capacity. The estimated footprint requirements for the Porifera FO-RO facilities at 10 mgd (16,000 ft^2) and 20 mgd (24,000 ft^2) scale are smaller than the Desalitech CCRO facilities at the same scale (10 mgd at 26,000 ft^2; 20 mgd at 51,500 ft^2). The side conduit accounts for 44.2 percent of the CCRO footprint. However, the CCRO system would be expected to recover more potable water compared to the Porifera FO system; about 5,260 AFY and 10,400 AFY water production (i.e., 4.69 mgd and 9.28 mgd) for the 10-mgd and 20-mgd (feed water flow rate) CCRO systems, respectively, compared with 3,920 AFY and 7,840 AFY (i.e., 3.50 mgd and 6.99 mgd) for the 10-mgd and 20-mgd FO-RO systems.

Recovery of the CCRO system was assumed to be 61.0 percent (based on pilot testing) for both the 10-mgd and 20-mgd systems. At this recovery, and assuming the buildout capacity of 130 mgd to be completed in 2023 for the primary facility, a full-scale CCRO system would increase overall AWPF recovery from 85 percent to 88 percent or 91 percent for the 10-mgd or 20-mgd systems, respectively. The projected overall AWPF recovery differs whether the CCRO system is fed 10 mgd or 20 mgd of primary RO concentrate because treating a larger volume of the available primary RO concentrate (23 mgd available by 2023) produces more permeate and thus the "overall" recovery is greater (refer to Appendix L and Appendix M for additional information).

The FO-RO system is expected to achieve a recovery of 30 to 35 percent based on pilot testing. With a full-scale system, the overall AWPF recovery is expected to increase from 85 percent to 87.3 percent or to 89.5 percent for the 10-mgd or 20-mgd systems, respectively.

Based on equipment cost estimates received from the two vendors (Desalitech provided listing price, not competitive bid price), the FO system would cost less than the CCRO system. However, the equipment cost estimate provided by Porifera is significantly lower than expected. So, it is likely that if an FO system were designed, the capital cost would be higher, given that it includes both FO membrane stacks and the conventional high-pressure RO system (as shown in Figure 26).

Based on information provided by the vendors, electrical power cost estimates, and pilot chemical usage, the CCRO system is expected to have the lower annual O&M cost (as shown in Figure 26).

Overall, assuming that the capital cost is funded over a 30-year loan period at a fixed annual interest rate of 5 percent, the unit cost of water produced by the two technologies is expected to be in the range of $1,126 per acre-foot to $1,382 per AF, depending on the volume of RO concentrate that is treated and the technology used. For the CCRO process, the total unit cost is expected to be between $1,126 and $1,216/acre-foot for systems treating 20 mgd and 10 mgd of RO concentrate, respectively. For the FO-RO process, the total unit cost range is expected to be similar but slightly higher at between $1,287 and $1,382/acre-foot for systems treating 20 mgd and 10 mgd of RO concentrate, respectively (Figure 26). In comparison, the current total cost for the OCWD GWRS AWPF water treated with MF, RO, UV-AOP, and post-treatment stabilization is about $850/AF.

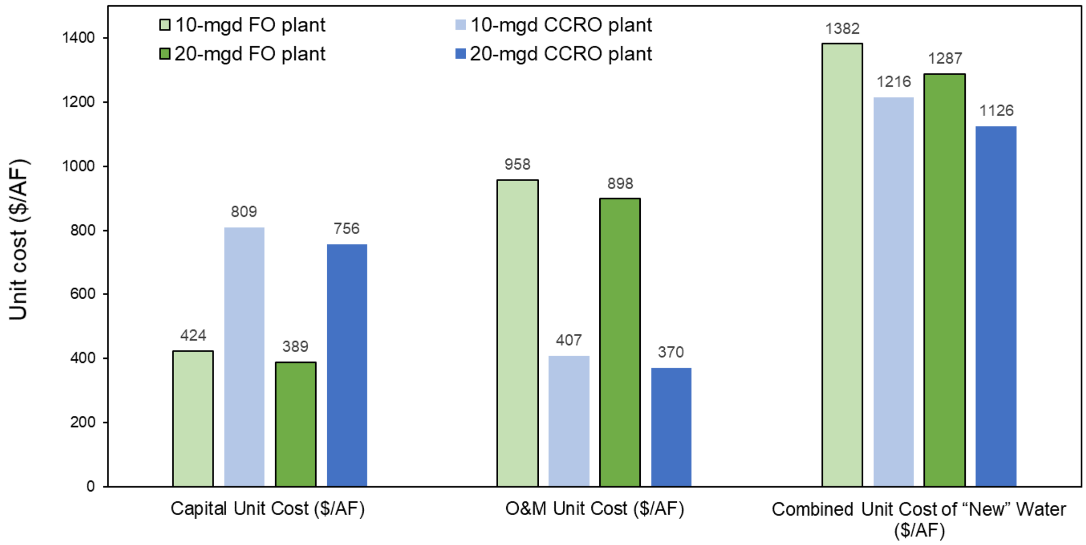

Figure 26. Estimated capital, O&M, and combined total unit cost ($/AF) for producing additional water using 10-mgd and 20-mgd CCRO and FO-RO systems

Treating a higher percentage of the RO concentrate will reduce the overall unit cost of the product water. Despite the significantly lower capital cost estimate for the FO-RO process, this process is expected to have slightly higher total unit costs due to the higher relative O&M costs compared with the CCRO process. Given the +50 percent/-30 percent accuracy of the Class 5 cost estimate, the estimated overall costs of the two technologies are the same on a dollar per acre-foot basis (total unit costs). The total unit costs are remarkably similar and seem reasonable for treating RO concentrate bearing in mind that the final disposal cost for the concentrate is already in place (zero in the case of OCWD due to partnership with OCSD allowing use of the OCSD ocean outfall) and thus does not contribute any additional cost. For other projects evaluating technologies for concentrate treatment/recovery, concentrate disposal costs must be accounted for with respect to discharge of the CCRO or FO-RO concentrate, which, in the case of an existing project adding concentrate recovery as a 'fourth stage,' improves the economics due to cost savings associated with reduced discharges from enhanced recovery.

4 Conclusions

A CCRO pilot unit was operated as a "4th stage RO" treating GWRS AWPF RO concentrate. The pilot demonstrated sustainable operation at a recovery range of 57 to 61 percent over a long-term run (up to 66 percent recovery in a short-term run), corresponding to an overall theoretical GWRS recovery of 90 to 92 percent. The pilot side conduit was supplied with AWPF RO feed water rather than RO concentrate at the end of each CCRO cycle. This configuration was shown to extend the interval between chemical cleanings (CIPs) to between 63 and 73 days, two times greater than the 30-day minimum CIP interval recommended by plant managers. Instead of running at a preset maximum recovery, the pilot operated in a variable recovery mode where the CCRO cycle trigger was controlled by the maximum CCRO concentrate conductivity and maximum recovery setpoint to cope with fluctuating feed water quality. Membrane autopsies identified the primary foulants as silts/clays and organics.

The FO-RO pilot unit was similarly operated as a "4th stage RO" treating GWRS AWPF RO concentrate. FO-RO was shown to be technically feasible at a recovery of 30 to 35 percent, although there were several operational challenges during pilot trials, including organic fouling and silica/clay scaling of the FO membrane, as well as FO membrane delamination due to rapid spikes in draw overpressure. These challenges limited the pilot to recoveries between 30 and 35 percent for most of the testing period, corresponding to approximately 89.5 to 90.3 percent overall theoretical GWRS recovery at full scale. On average, a four- to eight-week chemical cleaning interval was achieved. Additional piloting is recommended to continue to optimize the dprShield process, to confirm uranine as the preferred draw marker, and to confirm cleaning frequencies and reliability once upgrades are made to the FO-RO pilot design and to the FO elements.

Both treatment technologies produced high quality permeate with low concentrations of inorganic, organic, and microbiological constituents. At full scale, the permeate could be blended with the existing GWRS primary RO permeate to subsequently undergo UV-AOP treatment and thereby increase overall water production. With respect to microbial water quality, all permeate grab samples from the CCRO and the FO-RO pilot units were free of native microbial targets, including total coliform, E. coli, and somatic and MS coliphage. The MS coliphage sample die off assessment revealed that the addition of a preservative agent (a potassium-magnesium buffer solution) to samples prior to shipment for coliphage analysis did not significantly enhance MS coliphage preservation or contribute to microbial decay. For all three MS coliphage challenge tests (as an indicator of virus removal), MS coliphage removal for the CCRO pilot unit at the beginning of the treatment cycle was 5.2 log (average) for both ROC feed and blended feed (recirculated feed), with a 4.3-log (average) removal at the end of cycle for both feed sampling sources. These removal values show an average of 0.9-log reduction in CCRO performance when comparing reduction values from beginning to the end of one cycle. MS coliphage removal for the FO-RO unit was greater than 6.0 log for two of three challenge tests. MS coliphage removal for the third challenge test resulted in 6.0-log removal due to detection of MS coliphage in FO-RO permeate. Overall, greater log removal (above 6.0 log) for FO-RO is likely attributed to the double membrane barrier.

Based on spike tests of two common indicators of UV-AOP performance (NDMA and 1,4-dioxane), the pilot-scale UV/H_2O_2 treatment of CCRO and FO-RO permeate yielded similar log removal values as the full scale GWRS UV-AOP system that treats a conventional primary RO permeate.

Based on a Class 5 cost analysis, FO-RO is estimated to have lower capital cost but higher O&M cost, while CCRO is estimated to have a higher capital cost but lower O&M cost. The combined unit cost (capital plus O&M) of water produced by the CCRO system is slightly lower than (or comparable) the FO-RO system. CCRO is expected to recover more product water than FO-RO system. Overall, assuming that the capital cost is funded over a 30-year loan period at a fixed annual interest rate of 5 percent, the unit cost of product water produced by the two technologies is expected to be in the range of $1,126 to $1,382 per AF, depending on the volume of RO concentrate that is treated and the technology used. Given the +50 percent/-30 percent accuracy of the Class 5 cost estimate, the estimated capital plus O&M costs of the two technologies are the same on a dollar-per-acre-foot basis (total unit costs).

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Yoo et al. 2003	Yoo, L., S. Fitzsimmons, and M. Wehner. 2003. "Simultaneous Determination of 1,2,3-Trichloropropane and 1,4-Dioxane in Drinking Water by GC/MS/MS Using Purge and Trap Techniques." Paper presented at the AWWA Water Quality Technology Conference, Philadelphia, Pennsylvania.
Zhang et al. 2019	Zhang, Z., Y. Chuang, N. Huang, and W. A. Mitch. 2019. "Predicting the Contribution of Chloramines to Contaminant Decay during Ultraviolet/Hydrogen Peroxide Advanced Oxidation Process Treatment for Potable Reuse." *Environmental Science & Technology* 53(8), pp. 4416-4425.

Metric Conversions

Unit	Metric equivalent
1 gallon	3.785 liters
1 gallon per minute	3.785 liters per minute
1 gallon per square foot of membrane area per day	40.74 liters per square meter per day
1 inch	2.54 centimeters
1 million gallons per day	3,785 cubic meters per day
1 pound per square inch	6.895 kilopascals
1 square foot	0.093 square meters
°F (temperature measurement)	(°F–32) × 0.556 = °C
1 °F (temperature change or difference)	0.556 °C

Appendices

Appendix A – Porifera's dprShield Pilot System

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Appendix A

Porifera's dprShield Pilot System

Porifera's dprShield pilot system is a fully instrumented and automated FO-RO system with an integrated energy recovery device. It uses in-line monitoring of conductivity, temperatures, pressures, and flow rates for autonomous and high-efficiency operation. The system relies on Porifera's unique patented FO modules (Porifera FO modules) and patent-pending dprShield technology. Following laboratory testing at Porifera, the pilot unit was installed so that the AWPF RO concentrate was fed directly into the pilot system via the pressure in the pipeline without a feed equalization tank and a feed pump was selected to reduce feed pressure and control feed flow. The three outputs from the system (RO permeate, FO reject, and draw blowdown) were sent directly to the drain.

Porifera designed and constructed the dprShield pilot system based on a previous tankless FO-RO system design (Desormeaux et al.2019). This system was designed to fit within a small footprint and use commercial Porifera FO membrane module (stacked flat sheet design) with one or two PFO-100 elements each (7 or 14 m^2) (Figure 9). High-pressure pumps are required for the RO system. In the current study, sodium chloride was chosen as the draw solution and seawater RO (SWRO) membranes were used for the regeneration of the draw solution because of SWRO high efficiency and suitability to treat different types of draw solutions. The RO system featured two pressure vessels in series with one 2.5-inch diameter by 40-inch long seawater element (DuPont Filmtec SW2540) per vessel. Because some salt leakage occurs across semi-permeable membranes, a portion of the draw solution must be blown down periodically to retain its purity. Therefore, a sodium chloride brine solution is added to the draw solution periodically as make-up.

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Appendix B

ReFlex Max Closed-Circuit RO Pilot

Portions of this section of the report were reproduced from Desalitech/Jacobs operational report with permission from Desalitech and Jacobs (Hwang et al. 2020). The patented CCRO process utilizes standard RO membrane elements and components in a non-traditional design and control methodology (Bratt 1989; Efraty 2009 and 2010; Szucz 1991). Portions of this section of the report were reproduced from Desalitech/Jacobs operational report with permission from Desalitech and Jacobs (Hwang et al. 2020). The patented CCRO process utilizes standard RO membrane elements and components in a non-traditional design and control methodology (Bratt 1989; Efraty 2009 and 2010; Szucz 1991). As shown in Figure 1, the process is comprised of a high-pressure feed pump, a single-stage membrane array using standard 8-inch diameter by 40-inch long spiral wound RO elements, a concentrate recirculation pump, and process control valves. The CCRO system operates in two distinct modes: closed circuit and plug flow. In closed circuit, concentrate produced by the CCRO system is recirculated and blended with the pressurized feed water until the desired water production is reached (as indicated by reaching either a desired volumetric recovery set-point, maximum concentrate electrical conductivity (EC) set-point, or maximum feed pressure set-point). No concentrate is bled from the system during closed circuit. In plug flow mode, the concentrate is purged from the system when the recovery set point is reached and replaced with fresh feed water. This exchange is executed without stopping the high-pressure feed pump.

Under this unique configuration, CCRO systems operate with a lower lead element flux and higher crossflow velocities compared to traditional multi-stage RO systems, which provide better control of fouling and scaling. Frequent feed flushing helps limit or prevent scaling as the concentrate is flushed before the induction period for mineral precipitation is reached. Other advantages of CCRO include independent control of recovery, flux, and element cross flow velocity; these operating parameters are inherently interdependent in the design and operation of traditional multi-stage RO systems.

Desalitech manufactures two types of CCRO systems: the (1) ReFlex system (as shown in Figure 1), which purges the CCRO concentrate to atmosphere and the (2) ReFlex Max system, which isolates the CCRO concentrate in a side-conduit before purging to waste without breaking pressure, thereby greatly reducing the energy required for desalination. The side-conduit also provides the flexibility to operate at shorter sequence times (as low as 90 seconds) compared to a ReFlex product which requires a minimum sequence time of 6 minutes. This allows the ReFlex Max to operate at recovery rates ranging from 35 percent to 98 percent, providing the most flexible operational platform for RO applications. The subsequent text and figures provide further describes how the side-conduit is utilized in a ReFlex Max system during each step of the CCRO process.

In the ReFlex Max configuration, the volume of the side-conduit equals that of the membrane array and is filled with fresh feed under low-pressure at the start of a cycle (Figure B-1).

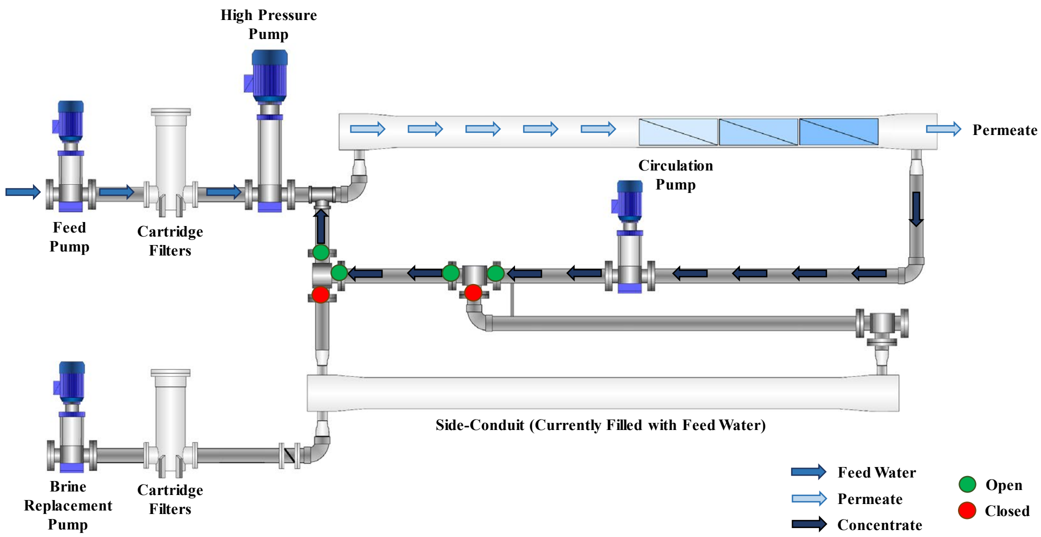

Figure B-1. Schematic of ReFlex Max operating in closed circuit mode

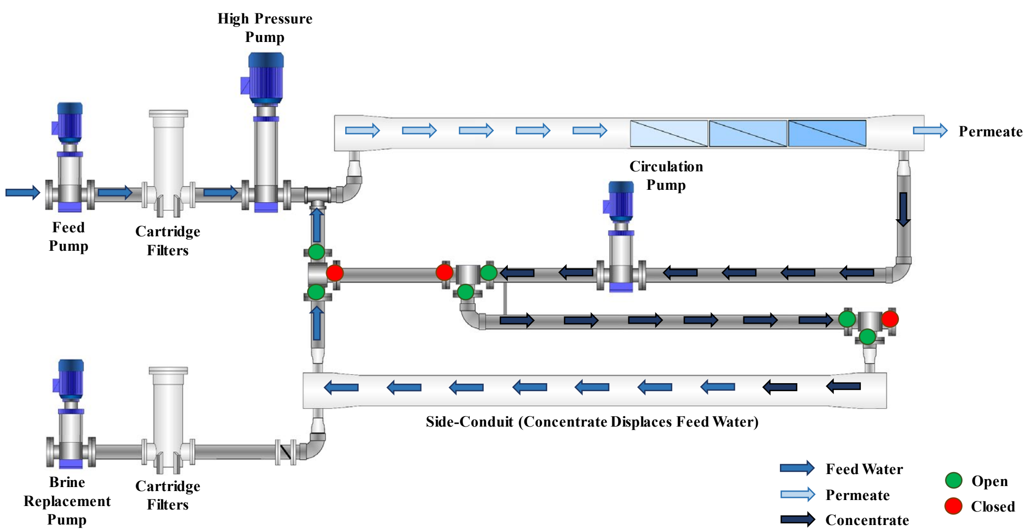

Figure B-2. Schematic of ReFlex Max operating in plug flow mode

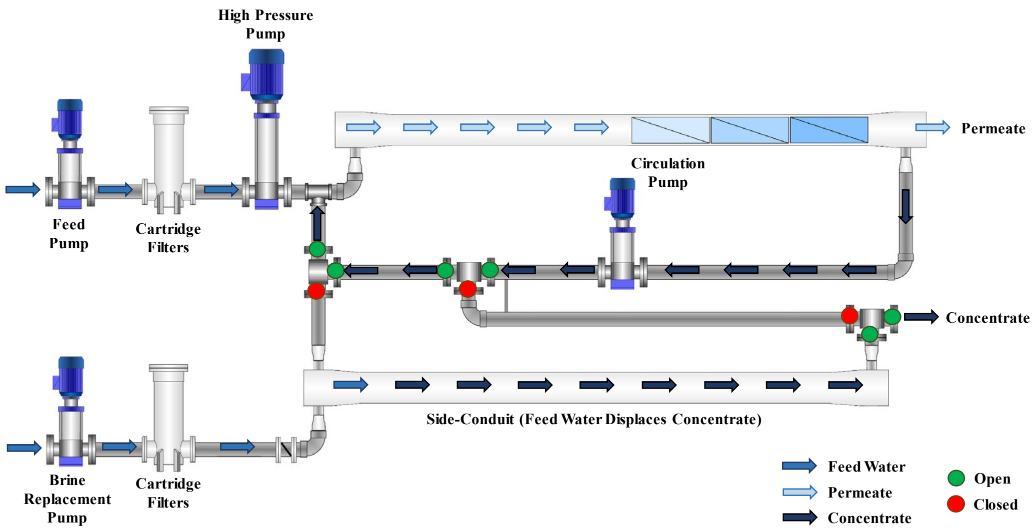

Figure B-3. Schematic of ReFlex Max operating in side conduit refill mode

Once the system reaches the desired recovery, the pressurized CCRO concentrate is purged from the membrane array into the side conduit, which displaces the fresh feed to the front of the membrane array (Figure B-2). After the CCRO concentrate has been purged from the membrane array and into the side-conduit, the side conduit is isolated, depressurized, and then flushed and re-filled with fresh feed under low-pressure for the next sequence (Figure B-3).

OCWD selected the ReFlex Max design to provide the flexibility to operate over a wide range of recoveries while reducing the energy required for treatment of concentrate from the existing AWPF 3-stage RO system. A photo of the OCWD's Reflex Max pilot is shown in Figure 10, while a screen shot of the HMI during operation is shown in Figure B-4. A 3-dimensional rendering of the unit, along with other equipment (feed and permeate tankage) to provide a fully operational CCRO system, is presented in Figure B-5. Major system components are listed in Table B-1 and key design specifications are summarized in Table B-2.

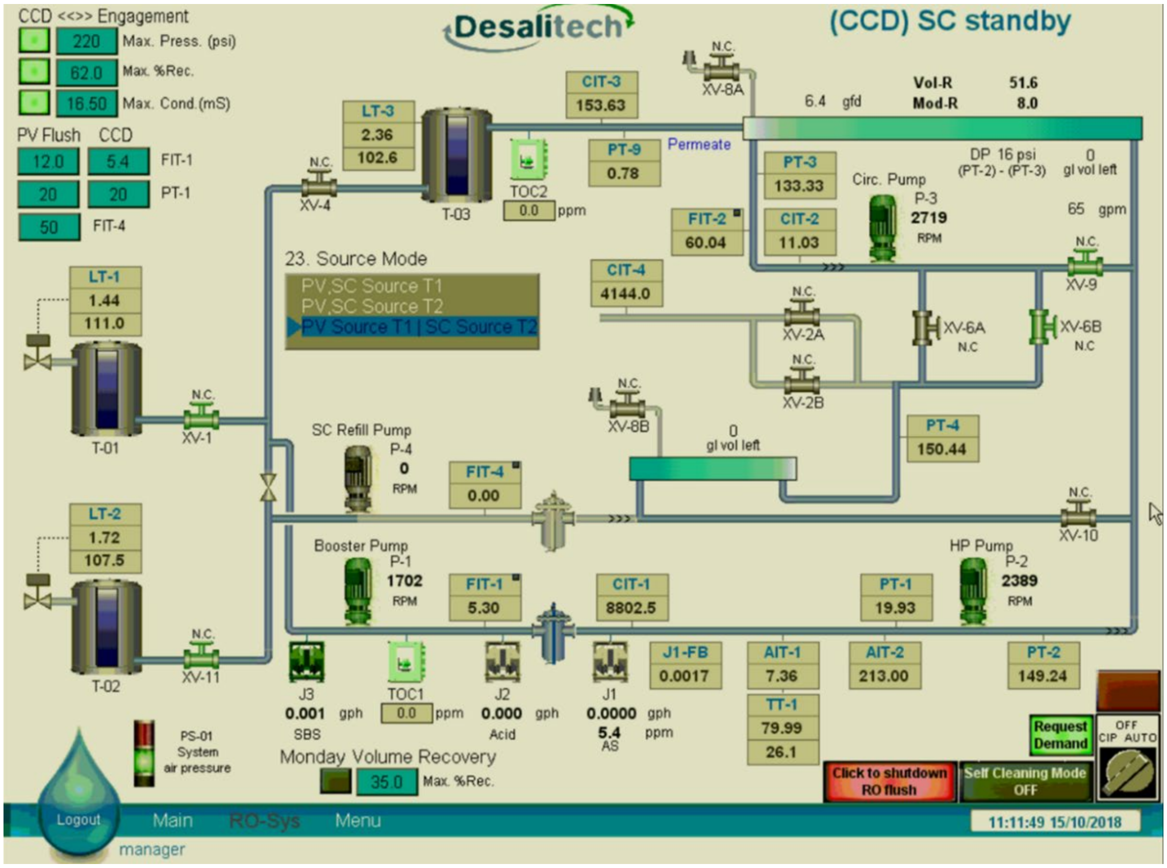

Figure B-4. Screen shot of the CCRO pilot HMI during operation

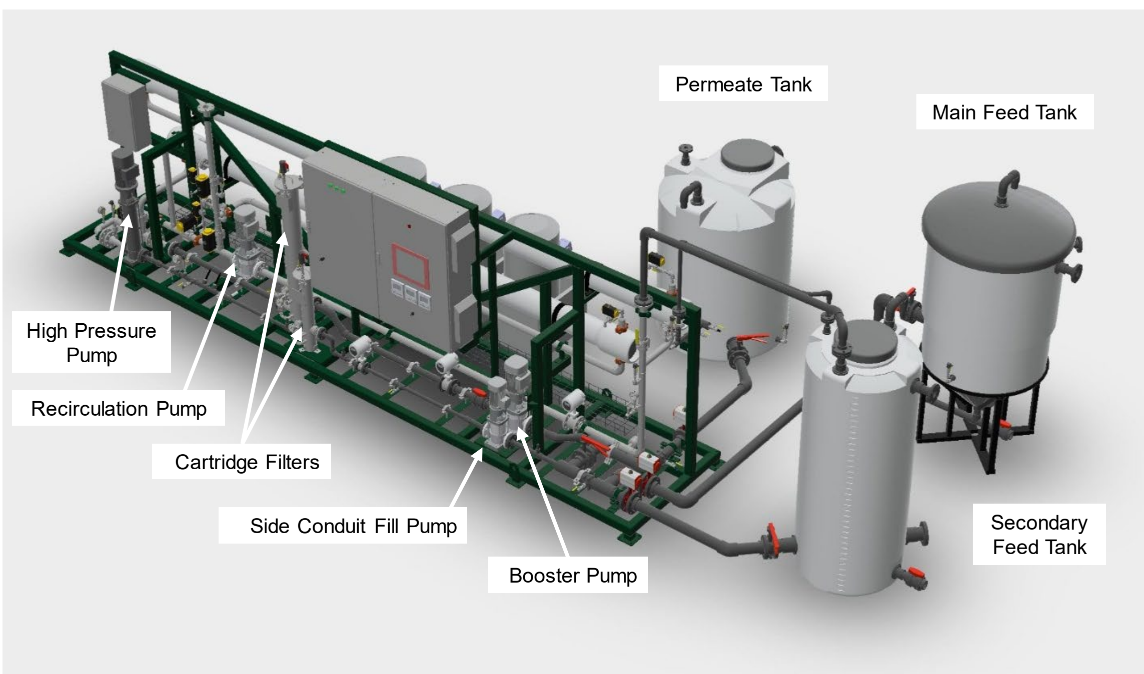

Figure B-5. Rendering of ReFlex Max CCRO system configured with ancillary equipment (described in Table B-1)

Table B-1. List of ReFlex Max CCRO pilot major equipment pilot system & ancillary equipment

Parameter	Value or Description
Membrane Feed Tank	300 gal conical bottom
Side-Conduit Feed Tank	300 gal flat bottom
Permeate Tank	300 gal flat bottom
RO Skid Quantity	One (1) Skid-Mounted
# of Cartridge Filter Housings	Two (2) – F-01: 20"x2.5", F-02: 40"x2.5"
# of Pressure Vessels (membrane array)	One (1) – 6M (450 psi)
# of Pressure Vessels (side-conduit)	One (1) – 5M (450 psi)
Booster Pump	Grundfos CRN 1-8 A-FGJ-G-E-HQQE
High-Pressure Pump	Grundfos CRN 1-27 A-FGJ-G-E-HQQE
Circulation Pump	Grundfos CRN 10-03 SF-FGJ-G-E-HQQE
Brine (Concentrate) Replacement Pump	Grundfos CRN 10-2 A-FGJ-G-E-HQQE
Process Logic Controller (PLC)	Allen Bradley
Power Supply	480V / 3 phase / 60Hz
Full Load Amps	25A

Table B-2. Design criteria for ReFlex Max CCRO system

Parameter	Value or Description
Cartridge Filters	10- and 1-micron
Design Permeate Flow Rate	5 – 9.2 gpm
Recovery	35 – 98%
Total # of Membranes Installed	Three (3)
Membrane Element Model	Hydranautics ESPA2-LD (October 2017 – February 2019) 8″ x 40″, 34 mil spacers DuPont Filmtec BW30XFRLE (February 2019 – November 2019) 8″ x 40″, 34 mil spacers
Antiscalant Product	AWC A-110 (October 2017 – March 2018) AWC A-108 (March 2018 – November 2019)
Antiscalant Dosing Range	2.5 ppm (included in ROF), unknown amount in RO concentrate
Acid	93% Sulfuric Acid (supplied in feed water, not dosed for RO concentrate)
Membrane Preservation Product	Sodium Bisulfite (SBS)
SBS Dosing Range	0 – 10 ppm[1]

[1] To be used when laying the membranes up for an extended shutdown.

Appendix C

Mini-Composite Water Quality Sampling Method for CCRO and FO-RO Pilot

To obtain a more uniform and avoid the cyclic (transient) nature of the CCRO pilot, the project team adapted a "mini-composite" approach to characterize the average chemical composition of the CCRO permeate and CCRO feed (same as GWRS AWPF RO concentrate) for a number of CCRO cycles. Note: FO-RO pilot's permeate quality does not vary with time but was sampled in this "mini-composite" approach to ensure consistency with the CCRO pilot. RO permeate from the CCRO and FO pilot units was collected in separate 4-L amber glass bottles.

Both pilots were operating in stable condition prior to sample collection. Due to the cyclic nature of the CCRO pilot, a mini composite sampling approach was adapted. The CCRO permeate sampling tap flow rate was adjusted in a few tests so that it take around 10 minutes to completely fill a 4-L amber glass bottle. This setting was selected to ensure the CCRO permeate to be around 380 to 400 ml/min. Similarly, the CCRO feed (GWRS RO concentrate) sampling tap flow rate was adjusted in a few times so that it took around 10 minutes to completely fill a 4-L amber glass bottle. This setting was selected to ensure the CCRO permeate to be around 380 to 400 ml/min.

For the April 15 and June 25, 2019 events, the feed sample results (GWRS RO concentrate) were also collected along with permeate sample results. Only one event was the most comprehensive (June 25), where three samples were collected (GWRS RO concentrate sample; see Table 3).

CCRO permeate, CCRO feed, and FO-RO pilot permeate of one CCRO cycle were collected concurrently in separate 4-L amber glass bottles containing 100 mg sodium thiosulfate to quench the residual chlorine (chloramines). At the beginning of a CCRO cycle (when the last cycle concentrate had been displaced and side conduit recharge was completed), CCRO feed and permeate and FO-RO permeate were collected using separate 4-L bottles (cycle 1). For the FO-RO permeate bottle, filling was stopped when the bottle is full. Filling was terminated for the CCRO feed and permeate bottles at the end of a cycle (usually ~10 minutes) to obtain about 4 L of water in each bottles. This sampling process was repeated for cycles (batches) numbers 2 to 8 in order to collect enough sample volume to fill all sampling bottles (Table C-2). A total of 8 (RO concentrate) or 6 (CCRO and FO permeate) cycles of sample water were collected. After the sample collection, each 4-L bottle was mixed on stir plate (Corning™ 6795220/EMD) for 2 minutes (~630 rpm).

Immediately after mixing, each 4-L batch bottle was transferred to Philip L. Anthony Water Quality Laboratory (OCWD Laboratory) and Weck lab sampling bottles and vials using plastic funnels; sampling information is summarized in Table C-2. The water samples were kept at 4°C in large ice coolers and delivered on the same day to the OCWD Laboratory and an outside commercial lab (Weck Laboratories, Inc., Industry, California). R&D staff measured and recorded each sampling start and finish time (for CCRO permeate and RO concentrate) and also measured the electrical conductivity and pH value for every 4-L batch bottle. Samples were also collected for Excitation Emission Matrix (EEMs) measurement by R&D staff. Inorganics, turbidity, N-compounds, TOC, Bromate (BrO3), Chlorate (CLO3), Ultraviolet percent transmittance @254nm (UV%T-254), CEC (full list), EPA 524.2 (VOCs include TTHMS), and general water quality for constituents were measured by OCWD's Philip L. Anthony Water Quality Laboratory based on standard methods of analysis. Metals (X200.7 and X200.8), Asbestos, Chlorate, Perchlorate, Fluoride, EPA 537.1 (PFAS), EPA 8015 (Ethylene Glycol), EPA 625 (SVOCs & Priority Pollutants), EPA 508 (Organochlorine Pesticides & PCBs), EPA 551.1 (Haloacetonitrile DBPs),EPA 556 (Aldehydes), EPA 552.2 (HAA5), EPA 1625M (Nitrosamines), EPA 8330A Explosives residues, and 1,4-dioxane were measured by an outside commercial lab (Weck lab) based on standard methods of analysis.

Table C-1. Analytes list for chemical water quality analysis

Outside Commercial Lab (Weck Lab)	OCWD Laboratory (Philip L. Anthony Water Quality Laboratory)	OCWD R&D Department Laboratory
Asbestos Metals (X200.7 and X200.8) Chlorate Perchlorate Fluoride EPA 537.1 PFAS EPA 8015 Ethylene Glycol EPA 625 (SVOCs & Priority Pollutants) EPA 508 (Organochlorine Pesticides & PCBs) EPA 551.1 (Haloacetonitrile DBPs) EPA 556 (Aldehydes) EPA 552.2 (HAA5) EPA 1625M Nitrosamines EPA 8330A Explosives residues 1,4-dioxane	RO-COMM[1] +PO4 (inorganics, Turbidity, N-compounds, TOC) Bromate (BrO3) Chlorate (CLO3) Ultraviolet percent transmittance @254nm (UV%T-254) Turbidity CEC (full list) EPA 524.2 (VOCs include TTHMS)	EEMS (excitation emission matrix spectroscopy)

[1] "RO-COMM" is OCWD nomenclature for a standard list of mostly inorganic species (mineral salts, silica, N-compounds, TOC) that are used to profile RO permeate quality. Parameters list: Alkalinity-Phenolphthalein, Boron, Barium, Calcium, Chloride, Carbonate (as CO3), Carbonate (as CaCO3), Electrical Conductivity, Fluoride, Bicarbonate (as HCO3), Bicarbonate (as CaCO3), Potassium, Magnesium, Sodium, Ammonia Nitrogen, Nitrite Nitrogen, Nitrate, Nitrate Nitrogen, Hydroxide (as OH), Hydroxide (as CaCO3), Organic Nitrogen, pH, Silica, Sulfate, Strontium, Total Dissolved Solids, Total Kjeldahl Nitrogen, Total Organic Carbon (Unfiltered), Total Nitrogen, Total Alkalinity (as CaCO3).

Table C-2. Sampling table for chemical water quality analysis

Lab	Water Source	Batch/Cycle Number	Method	Number of bottles/vials	Volume collected (L)
OCWD	CCRO permeate	1	RO-COMM +PO4	5	2.5
OCWD	CCRO permeate	1	Cyanide	1	0.5
OCWD	CCRO permeate	1	Turbidity	1	1
OCWD	CCRO permeate	2	CEC	1	2
OCWD	CCRO permeate	2	CEC	1	2
OCWD	CCRO permeate	3	CEC full list	1	2.5
OCWD	CCRO permeate	3	BRO3CLO3	1	0.5
WECK	CCRO permeate	3	Asbestos, water – TEM	1	1
OCWD	CCRO permeate	4	524 (VOC)	4	0.16
OCWD	CCRO permeate	4	BACTI	1	0.1
OCWD	CCRO permeate	4	UV254	1	0.25
WECK	CCRO permeate	4	1,4-Dioxane	2	1
WECK	CCRO permeate	4	EPA 537 PFAS	2	0.5
WECK	CCRO permeate	4	EPA 556 – Aldehydes	2	0.08
WECK	CCRO permeate	4	EPA 551 – Disinfection Byproducts	2	0.12
WECK	CCRO permeate	4	Nitrosamines low-level – EPA 1625M	2	1
WECK	CCRO permeate	4	Metal EPA 200.8 200.7	1	0.5
WECK	CCRO permeate	5	EPA 625 – Semivolatile Organic	2	2
WECK	CCRO permeate	5	EPA 508 – Organochlorine Pesticides & PCBs	2	2
WECK	CCRO permeate	6	EPA 552.2 – Haloacetic Acids (HAA5)	1	0.125
R&D	CCRO permeate	6	EEMS (Jana)	1	0.5
WECK	CCRO permeate	6	Perchlorate/Fluoride – EPA 314.0	1	0.06

Lab	Water Source	Batch/Cycle Number	Method	Number of bottles/vials	Volume collected (L)
WECK	CCRO permeate	6	Ethylene Glycol EPA 8015	2	0.08
WECK	CCRO permeate	6	Chlorate EPA 300.1	1	0.06
WECK	CCRO permeate	6	Explosives EPA Method 8330	2	2
OCWD	FO-RO permeate	1	RO-COMM +PO4	5	2.5
OCWD	FO-RO permeate	1	Cyanide	1	0.5
OCWD	FO-RO permeate	1	Turbidity	1	1
OCWD	FO-RO permeate	2	CEC full list	1	2
OCWD	FO-RO permeate	2	CEC full list	1	2
OCWD	FO-RO permeate	3	BRO3CLO3	1	0.5
WECK	FO-RO permeate	3	Asbestos, water – TEM	1	1
OCWD	FO-RO permeate	4	524 (VOC)	4	0.16
OCWD	FO-RO permeate	4	BACTI	1	0.1
OCWD	FO-RO permeate	4	UV254	1	0.25
WECK	FO-RO permeate	4	1,4-Dioxane	2	1
WECK	FO-RO permeate	4	EPA 537 PFAS	2	0.5
WECK	FO-RO permeate	4	EPA 556 – Aldehydes	2	0.08
WECK	FO-RO permeate	4	EPA 551 – Disinfection Byproducts	2	0.12
WECK	FO-RO permeate	4	Nitrosamines low-level – EPA 1625M	2	1
WECK	FO-RO permeate	4	Metal EPA 200.8 200.7	1	0.5
WECK	FO-RO permeate	5	EPA 625 – Semivolatile Organic	2	2
WECK	FO-RO permeate	5	EPA 508 – Organochlorine Pesticides & PCBs	2	2
WECK	FO-RO permeate	6	EPA 552.2 – Haloacetic Acids (HAA5)	1	0.125
R&D	FO-RO permeate	6	EEMS (Jana)	1	0.5

Lab	Water Source	Batch/Cycle Number	Method	Number of bottles/vials	Volume collected (L)
WECK	FO-RO permeate	6	Perchlorate/Fluoride – EPA 314.0	1	0.06
WECK	FO-RO permeate	6	Ethylene Glycol EPA 8015	2	0.08
WECK	FO-RO permeate	6	Chlorate EPA 300.1	1	0.06
WECK	FO-RO permeate	6	Explosives EPA Method 8330	2	2
OCWD	GWRS ROC	1	RO-COMM +PO4	5	2.5
OCWD	GWRS ROC	1	Cyanide	1	0.5
OCWD	GWRS ROC	1	Turbidity	1	1
OCWD	GWRS ROC	2	CEC full list	1	2.5
OCWD	GWRS ROC	3	BRO3CLO3	1	0.5
WECK	GWRS ROC	3	Asbestos, water – TEM	1	1
WECK	GWRS ROC	3	Nitrosamines low-level – EPA 1625M	4	2
OCWD	GWRS ROC	4	524 (VOC)	4	0.16
OCWD	GWRS ROC	4	BACTI	1	0.1
OCWD	GWRS ROC	4	UV254	1	0.25
WECK	GWRS ROC	4	1,4-Dioxane	4	2
WECK	GWRS ROC	4	EPA 537 PFAS	2	0.5
WECK	GWRS ROC	4	EPA 556 – Aldehydes	4	0.16
WECK	GWRS ROC	4	EPA 551 – Disinfection Byproducts	3	0.18
R&D	GWRS ROC	4	EEMS (Jana)	1	0.5
WECK	GWRS ROC	5	EPA 625 – Semivolatile Organic	4	4
WECK	GWRS ROC	6	EPA 508 – Organochlorine Pesticides & PCBs	4	4
WECK	GWRS ROC	7	EPA 552.2 – Haloacetic Acids (HAA5)	2	0.25
R&D	GWRS ROC	7	EEMS (Jana)	1	0.5

Lab	Water Source	Batch/Cycle Number	Method	Number of bottles/vials	Volume collected (L)
WECK	GWRS ROC	7	Perchlorate/Fluoride – EPA 314.0	2	0.12
WECK	GWRS ROC	7	Ethylene Glycol EPA 8015	4	0.16
WECK	GWRS ROC	7	Chlorate EPA 300.1	2	0.12
WECK	GWRS ROC	7	Metal EPA 200.8 200.7	2	1
WECK	GWRS ROC	8	Explosives EPA Method 8330	4	4

Appendix D

Onsite Clean in Place (CIP) Procedure for CCRO Pilot

OCWD conducted CIPs of the CCRO pilot unit when required by changes in the normalized specific flux and feed pressure, as well as after each phase of testing. The CIP protocol initially used was similar to that used by OCWD for cleaning all stages of the GWRS RO system and as summarized below. This approach was taken given that fouling and scaling in the CCRO was anticipated to be similar to fouling and scaling experienced in the GWRS system, particularly in the third stage.

OCWD RO CIP protocol:

- 2.0 percent Sodium Tripolyphosphate (STPP) and 0.20 percent SDDBS; solution pH raised to 11 using sodium hydroxide.
- For severely fouled membranes (typically 3rd stage), 2 percent AWC C-227; solution pH raised to 12 using sodium hydroxide.
- RO permeate used for cleaning solution make-up.
- CIP solution heated to, and maintained at, 30 to 35 degrees C.
- Cleaning solution recirculated through the membranes for 30 minutes (20 gpm per pressure vessel), followed by a 1-hour soak (repeat three times), followed by a 45-minute flush with RO permeate.

The above protocol using STPP and SDDBS was found to be effective during Phase 1A but not as effective during the first CIP conducted as part of Phase 1B performed on April 24, 2018. Consequently, the specialty cleaner (AWC C-227) was adopted for subsequent CIPs in place of STPP and SDDBS during Phases 1B and 1C and proved to be effective. The modified CIP procedure is summarized below and was implemented for all cleans performed after April 24, 2018.

The CIP return line was modified to enable heating of the cleaning solution at CIP skid during recirculation phase of the CIP process. The temperature regulated improved the cleaning effectiveness of the CIP in the second CIP.

Modified CCRO CIP protocol:

- 2 percent AWC C-227; pH raised to 12 using sodium hydroxide.
- CRO permeate used for solution make-up.
- CIP solution heated to, and maintained at, 35 to 39 degrees C.
- Cleaning solution recirculated through the membranes for 1 hour, followed by 1-hour soak (3 times) plus a 15-minute recirculation before flushing.

In addition, piping was installed to recirculate cleaning solution between the CIP tank and skid, and controls were added to maintain solution temperature using a heater.

In the event OCWD staff were not able to perform a CIP immediately after the completion of a given test phase, or if a CIP was required before such completion (due to performance degradation), the CCRO unit was be flushed with RO permeate upon shutdown until the CIP could be performed.

Appendix E

Onsite CIP Summary for CCRO Pilot

OCWD conducted CIPs of the CCRO pilot unit on an as-needed basis when the targets for extended testing were exceeded (primarily, loss of normalized specific flux) and also after key operating milestones during or at the close of each phase of testing. CIPs performed early in the pilot testing utilized the current OCWD RO CIP Protocol. However, this protocol was effective only in Phase 1A and not 1B. For Phases 1B and 1C, the Modified CIP Protocol was used exclusively.

Both CIP protocols included recirculation followed by soaking repeated three times prior to flushing while targeting an elevated temperature of 30 to 40 degrees C. Table E-1 presents a summary of the CIPs performed over the course of the pilot. As shown in the summary, the target temperature was never sustainably maintained during the CIPs performed in Phases 1A and 1B due to lack of effective temperature control with the OCWD pilot CIP skid. During Phase 1C, OCWD was able to modify the CIP skid to provide proper control and the target CIP temperatures were maintained.

Table E-1. Performance test (wet test results) of tail elements from Phase 1A and Phase 1C

Phase	Date	Membrane	CIP Regime	Average Conditions over 3 CIP Circuits		
				pH[1]	Temperature. (degrees C)[2]	Cross-Flow (gpm)[3]
1A	2/28/2018	ESPA2-LD	2% STPP/0.20% SDDBS	11.62	26.8	21.9
1B	4/24/2018	ESPA2-LD	2% STPP/0.20% SDDBS	11.40	26.3	23.0
1B	4/24/2018[4]	ESPA2-LD	2% STPP/0.20% SDDBS	11.40	26.7	23.0
1B	5/7/2018	ESPA2-LD	2% AWC C-227	12.04	23.3	30.0
1B	5/30/2018	ESPA2-LD	2% AWC C-227	12.29	31.4	46.7
1B	6/28/2018	ESPA2-LD	2% AWC C-227	12.21	31.0	50.0
1C	11/8/2018	ESPA2-LD	2% AWC C-227	11.97	27.7	52.0
1C	11/20/2018	ESPA2-LD	2% AWC C-227	12.24	31.0	52.0
1C	5/22/2019	BW30-XFRLE	2% AWC C-227	12.08	33.9	49.0

Phase	Date	Membrane	CIP Regime	Average Conditions over 3 CIP Circuits		
				pH[1]	Temperature. (degrees C)[2]	Cross-Flow (gpm)[3]
1C	9/12/2019	BW30-XFRLE	2% AWC C-227	11.91	38.0	48.0

[1]pH adjustment achieved with sodium hydroxide. Target pH was 11 for 2% STPP/0.20% SDDBS and 12 for 2% AWC C-227.

[2]Target temperature was 30 – 35 deg C for 2% STPP/0.20% SDDBS and 35 – 39 deg C for 2% AWC C-227.

[3]Target cross flow was 20 gpm for 2% STPP/0.20% SDDBS and 50 gpm for 2% AWC C-227.

[4]CIP on 4/24/2019 with 2% STPP/0.20% SDDBS was repeated due to ineffectiveness of first CIP. Second CIP was also ineffective and resulted in switch to 2% AWC C-227 for next CIP on 5/7/2018.

Appendix F

CCRO Pilot Membrane Autopsy

At the completion of Phase 1A on February 27, 2018, the Hydranautics ESPA2-LD tail element from the CCRO unit was removed, packaged, and shipped to American Water Chemicals (AWC) in Plant City, Florida for performance testing and autopsy. The purpose of these activities was to identify the primary cause of fouling/scaling during CCRO operation and to optimize feedwater chemistry program and pilot operating conditions (recovery, flux, and crossflow) during subsequent phases of testing.

The element performance testing included the measurement of sodium chloride rejection, permeate flowrate, and differential pressure during operation at standard conditions as defined by the membrane manufacturer. The test results were then be compared with the manufacturer's element specifications (including wet testing, if performed) to assess any changes from operation.

The membrane autopsy comprised external inspection of the element fiberglass shell and anti-telescoping devices, as well as inspection of the membrane leaves, feed spacers, permeate spacers, and glue lines (following element disassembly). Foulant harvested from the membrane surface was analyzed for loss of ignition (LOI) and humic and fulvic acid content. Sections of the membrane surface were analyzed by the following methods: electron microscopy and x-ray spectroscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) with superimposed elemental imaging (SEI®), and Fourier transform infrared spectroscopy (FTIR).

A second Hydranautics ESPA2-LD tail element was removed during Phase 1C, packaged, and shipped to AWC for similar performance testing and membrane autopsy on February 11, 2019. As previously described, the CCRO was subsequently reloaded with new DuPont Filmtec BW30XFRLE membranes for the remaining operating period of Phase 1C. No elements were removed for such testing in Phase 1B.

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Appendix G

CCRO Recovery Calculation

This section includes derivation for recovery calculation based on mass balance around the CCRO system and the primary RO + CCRO for two SC refill configurations. The recovery calculation results are shown in Table 6.

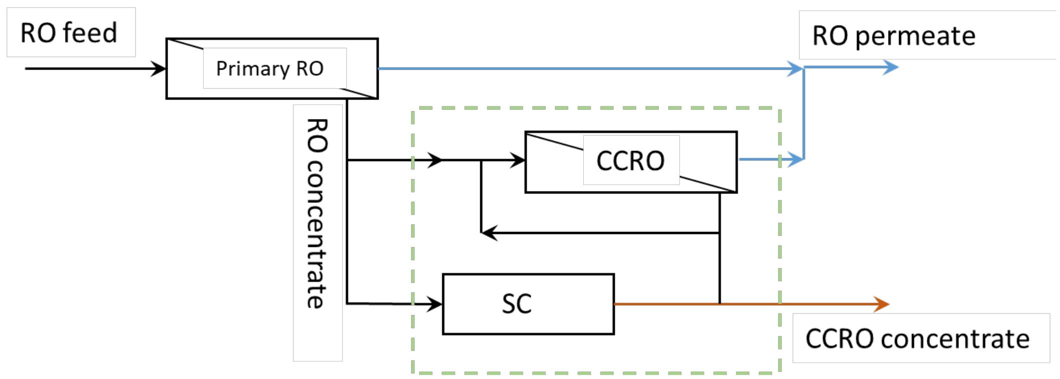

Figure G-1. Simplified schematic of the primary RO and a CCRO unit with SC filling from GWRS RO concentrate

SC filling from GWRS RO concentrate

$$\%VR\_CCRO = \frac{V_{P\_CCRO}}{V_{F\_CCRO}} = \frac{V_{P\_CCRO}}{V_{SC} + V_{P\_CCRO}}$$

$$\%VR\_RO = \frac{V_{P\_RO}}{V_{F\_RO}}$$

Mass balance on the CCRO unit:

$$V_{B\_RO} = V_{F\_CCRO} = V_{SC} + V_{P\_CCRO}$$

$$Y = \frac{V_{P\_RO} + V_{P\_CCRO}}{V_{F\_RO}} = \frac{V_{P\_RO} + V_{B\_RO} \cdot \%VR\_CCRO}{V_{F\_RO}}$$

$$Y = \%VR\_RO + (1 - \%VR\_RO) \cdot \%VR\_CCRO$$

Note: *%VR* is the percent volumetric recovery of a CCRO cycle. *V* represents volume. *P* stands for product or permeate. *F* represents feed. *B* represents the primary RO concentrate. *SC* stands for the side conduit. *RO* represents the primary RO in GWRS. *Y* is the overall recovery of the primary RO and the CCRO unit (with SC filling from primary RO concentrate), assuming the CCRO unit is able to treat 100 percent of the concentrate from the primary RO.

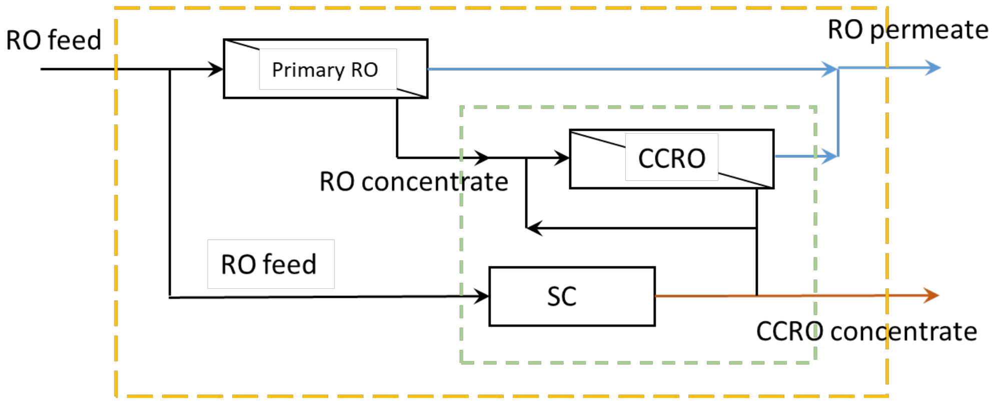

Figure G-2. Simplified schematic of the primary RO and a CCRO unit with SC filling from GWRS AWPF RO feed

$\underline{SC \text{ filling from GWRS RO feed}}$

$$\%VR\_CCRO = \frac{V_{P\_CCRO}}{V_{F\_CCRO}} = \frac{V_{P\_CCRO}}{V_{SC} + V_{P\_CCRO}}$$

$$V_{SC} = \frac{V_{P\_CCRO} \cdot (1 - \%VR\_CCRO)}{\%VR\_CCRO}$$

$$\%VR\_RO = \frac{V_{P\_RO}}{V_{F\_RO}}$$

Mass balance on the CCRO unit:

$$\cancel{V_{SC}} + V_{B\_RO} = \cancel{V_{SC}} + V_{P\_CCRO}$$

$$V_{B\_RO} = V_{P\_CCRO} = V_{F\_RO} \cdot (1 - \%VR\_RO)$$

$$Y' = \frac{V_{P\_RO} + V_{P\_CCRO}}{V_{F\_RO} + V_{SC}} = \frac{V_{F\_RO}}{V_{F\_RO} + V_{SC}} = \frac{V_{F\_RO}}{V_{F\_RO} + \dfrac{V_{P\_CCD} \cdot (1 - \%VR\_CCRO)}{\%VR\_CCRO}}$$

$$Y' = \frac{V_{F\_RO}}{V_{F\_RO} + \dfrac{V_{F\_RO} \cdot (1 - \%VR\_RO) \cdot (1 - \%VR\_CCRO)}{\%VR\_CCRO}} = \frac{1}{1 + \dfrac{(1 - \%VR\_RO) \cdot (1 - \%VR\_CCRO)}{\%VR\_CCRO}}$$

$$Y' = \frac{\%VR\_CCRO}{\%VR\_CCRO + (1 - \%VR\_RO) \cdot (1 - \%VR\_CCRO)}$$

Note: *Y'* is the overall recovery of the primary RO and the CCRO unit (with SC filling from primary RO feed), assuming the CCRO unit is able to treat 100 percent of the available concentrate from the primary RO.

Appendix H

Complete Chemical Water Quality Assessment Results

Table H-1 presents definitions for analyte abbreviations used in the complete chemical water quality assessment results shown in Figures H-1 through H-31.

Table H-1. Analyte abbreviations and names

Analyte Abbreviation	Analyte Name
OCWD Laboratory	
1112PC	1,1,1,2-Tetrachloroethane
111TCA	1,1,1-Trichloroethane
1122PC	1,1,2,2-Tetrachloroethane
112TCA	1,1,2-Trichloroethane
11DCA	1,1-Dichloroethane
11DCE	1,1-Dichloroethene
11DCP	1,1-Dichloropropene
123TCB	1,2,3-Trichlorobenzene
123TCP	1,2,3-Trichloropropane
124TCB	1,2,4-Trichlorobenzene
124TMB	1,2,4-Trimethylbenzene
12DCA	1,2-Dichloroethane
12DCB	1,2-Dichlorobenzene
12DCP	1,2-Dichloropropane
135TMB	1,3,5-Trimethylbenzene
13DCB	1,3-Dichlorobenzene
13DCP	1,3-Dichloropropane
14DCB	1,4-Dichlorobenzene
22DCP	2,2-Dichloropropane
2CLTOL	2-Chlorotoluene

Analyte Abbreviation	Analyte Name
4CLTOL	4-Chlorotoluene
4IPTOL	4-Isopropyltoluene
4nOCPH	4-n-Octylphenol
4tOCPH	4-tert-Octylphenol
ACETNE	Acetone
aESTRA	17a-Estradiol
aETEST	17a-Ethynylestradiol
ANDROS	4-Androstene-3, 17-dione
ASPATM	Aspartame
ATENOL	Atenolol
B2CLEE	bis (2-chloroethyl) ether
BENZ	Benzene
bESTRA	17b-Estradiol
BisPHA	Bisphenol A
BRBENZ	Bromobenzene
c12DCE	cis-1,2-Dichloroethene
c13DCP	cis-1,3-Dichloropropene
CCl2F2	Dichlorodifluoromethane
CCl3F	Trichlorofluoromethane (Freon 11)
CCl4	Carbon tetrachloride
CH2Br2	Dibromomethane
CH2BrC	Bromochloromethane
CH2Cl2	Methylene Chloride
CH3Br	Bromomethane
CH3Cl	Chloromethane
CHBr2C	Dibromochloromethane
CHBr3	Bromoform
CHBrCl	Bromodichloromethane
CHCl3	Chloroform

Analyte Abbreviation	Analyte Name
Cl3F3E	Trichlorotrifluoroethane (Freon 113)
CLBENZ	Chlorobenzene
ClETHA	Chloroethane
CS2	Carbon Disulfide
DBCP	1,2-Dibromo-3-chloropropane
DESTBL	Diethylstilbestrol
DICLFN	Diclofenac
DILANT	Dilantin
DIPE	Diisopropyl ether
EDB	1,2-Dibromoethane
EPITES	Epitestosterone (cis-Testosterone)
EQUILN	Equilin
ESTRIO	Estriol
ESTRON	Estrone
ETBE	Ethyl tert-butyl ether
EtBENZ	Ethylbenzene
FLUXET	Fluoxetine
FR123A	Freon 123a
FREN22	Chlorodifluoromethane
HClBut	Hexachlorobutadiene
IOHEXL	Iohexol
IOPRMD	Iopromide
ISPBNZ	Isopropylbenzene
LINURN	Linuron
MEK	Methyl Ethyl Ketone (MEK)
MEPROB	Meprobamate
MIBK	Methyl Isobutyl Ketone (MIBK)
mp-XYL	m,p-Xylene
MTBE	Methyl tert-butyl ether

Analyte Abbreviation	Analyte Name
NAP	Naphthalene
NAPRXN	Naproxen
nBBENZ	n-Butylbenzene
NEOTAM	Neotam
NONYPH	Nonylphenol
o-XYL	o-Xylene
pCBSA	para-Chlorobenzene sulfonic acid
PCE	Tetrachloroethene
PHNYPH	PhenylPhenol
PRGSTR	Progesterone
PRPBNZ	Propylbenzene
sBBENZ	sec-Butylbenzene
STYR	Styrene
SUCRAL	Sucralose
t12DCE	trans-1,2 Dichloroethene
t13DCP	trans-1,3-Dichloropropene
TAME	Tert-amyl methyl ether
TBA	tert-butyl alcohol
tBBENZ	tert-Butylbenzene
TBBISA	Tetrabromobisphenol A
TCE	Trichloroethene
TCEP	Tris-2-chlorethyl phosphate
TESTOR	Testosterone (trans-Testosterone)
TOLU	Toluene
TOTALX	Total Xylenes (m,p,&o)
TRIMTP	Trimethoprim
TTHMs	Total Trihalomethanes
VNYLCL	Vinyl chloride
x13DCP	Total 1,3-Dichloropropene

Analyte Abbreviation	Analyte Name
ACTMNP	Acetaminophen
ATRAZ	Atrazine
AZTMCN	Azithromycin
CAFFEI	Caffeine
CBMAZP	Carbamazepine
DEET	N,N-diethyl-m-toluamide
DIURON	Diuron
ERYTHN	Erythromycin
GMFIBZ	Gemfibrozil
IBPRFN	Ibuprofen
PCP	Pentachlorophenol (PCP)
PRIMDN	Primidone
SIMAZ	Simazine
SULTHZ	Sulfamethoxazole
TRICLN	Triclosan
F-EC	Field Electrical Conductivity
F-pH	Field pH
F-TEMP	Field Temperature
Al	Aluminum
ALKPHE	Alkalinity-Phenolphthalein
B	Boron
Ba	Barium
BrO3	Bromate
Ca	Calcium
Cl	Chloride
CLO3	Chlorate
CN	Cyanide
CO3	Carbonate (as CO3)
CO3Ca	Carbonate (as CaCO3)

Analyte Abbreviation	Analyte Name
EC	Electrical Conductivity
F	Fluoride
Fe	Iron
Fe-DIS	Iron (dissolved)
HCO3	Bicarbonate (as HCO3)
HCO3Ca	Bicarbonate (as CaCO3)
K	Potassium
Mg	Magnesium
Mn	Manganese
Na	Sodium
NH3-N	Ammonia Nitrogen
NO2-N	Nitrite Nitrogen
NO3	Nitrate
NO3-N	Nitrate Nitrogen
OH	Hydroxide (as OH)
OHCa	Hydroxide (as CaCO3)
ORG-N	Organic Nitrogen
pH	pH
PO4-P	Phosphate Phosphorus (orthophosphate)
SIO2	Silica
SO4	Sulfate
Sr	Strontium
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon (Unfiltered)
TOTALK	Total Alkalinity (as CaCO3)
TOT-N	Total Nitrogen
TURB	Turbidity
UV%T-254	Ultraviolet percent transmittance @254nm

Analyte Abbreviation	Analyte Name
Weck Lab	
Al	Aluminum, Total
Sb	Antimony, Total
As	Arsenic, Total
Ba	Barium, Total
Be	Beryllium, Total
B	Boron, Total
Cd	Cadmium, Total
Ca	Calcium, Total
Cr	Chromium, Total
Co	Cobalt, Total
Cu	Copper, Total
Fe	Iron, Total
Pb	Lead, Total
Mg	Magnesium, Total
Mn	Manganese, Total
Mo	Molybdenum, Total
Ni	Nickel, Total
P	Potassium, Total
Se	Selenium, Total
Ag	Silver, Total
Na	Sodium, Total
Sr	Strontium, Total
Tl	Thallium, Total
Th	Thorium, Total
Sn	Tin, Total
Ti	Titanium, Total
W	Tungsten, Total
U	Uranium, Total

Analyte Abbreviation	Analyte Name
V	Vanadium, Total
Zn	Zinc, Total
Zr	Zirconium, Total
F	Fluoride, Total
ClO	Chlorate
CLO4	Perchlorate
111TCACETONE	1,1,1-trichloro-2-propanone
11DCACETONE	1,1-Dichloro-2-propanone
CHBrAN	Bromochloroacetonitrile
CH	Chloral hydrate
ClPICR	Chloropicrin
DBAN	Dibromoacetonitrile
DCAN	Dichloroacetonitrile
TCAN	Trichloroacetonitrile
dbaa	Dibromoacetic acid
dcaa	Dichloroacetic acid
HAA5, total	Haloacetic acids, Total
mbaa	Monobromoacetic acid
mcaa	Monochloroacetic acid
tcaa	Trichloroacetic acid
ACEALD	Acetaldehyde
BENALD	Benzaldehyde
BUTAN	Butanal
CRTALD	Crotonaldehyde
CYCHXN	Cyclohexanone
DECNAL	Decanal
FORALD	Formaldehyde
GLYOXL	Glyoxal
HEPNAL	Heptanal

Analyte Abbreviation	Analyte Name
HEXNAL	Hexanal
MGLYOX	Methyl Glyoxal
NONNAL	Nonanal
PENTNL	Pentanal
PROPNL	Propanal
NDEA	N-Nitrosodiethylamine
NDMA	N-Nitrosodimethylamine
NDBA	N-Nitrosodi-n-butylamine
NDPA	N-Nitrosodi-n-propylamine
NMEA	N-Nitrosomethylethylamine
NMOR	N-Nitrosomorpholine
NPIP	N-Nitrosopiperidine
NPYR	N-Nitrosopyrrolidine
PFOS	Perfluorooctanesulfonic acid
PFOA	Perfluorooctanoic acid
ASBESTOS	Asbestos
14DIOX	1,4-Dioxane

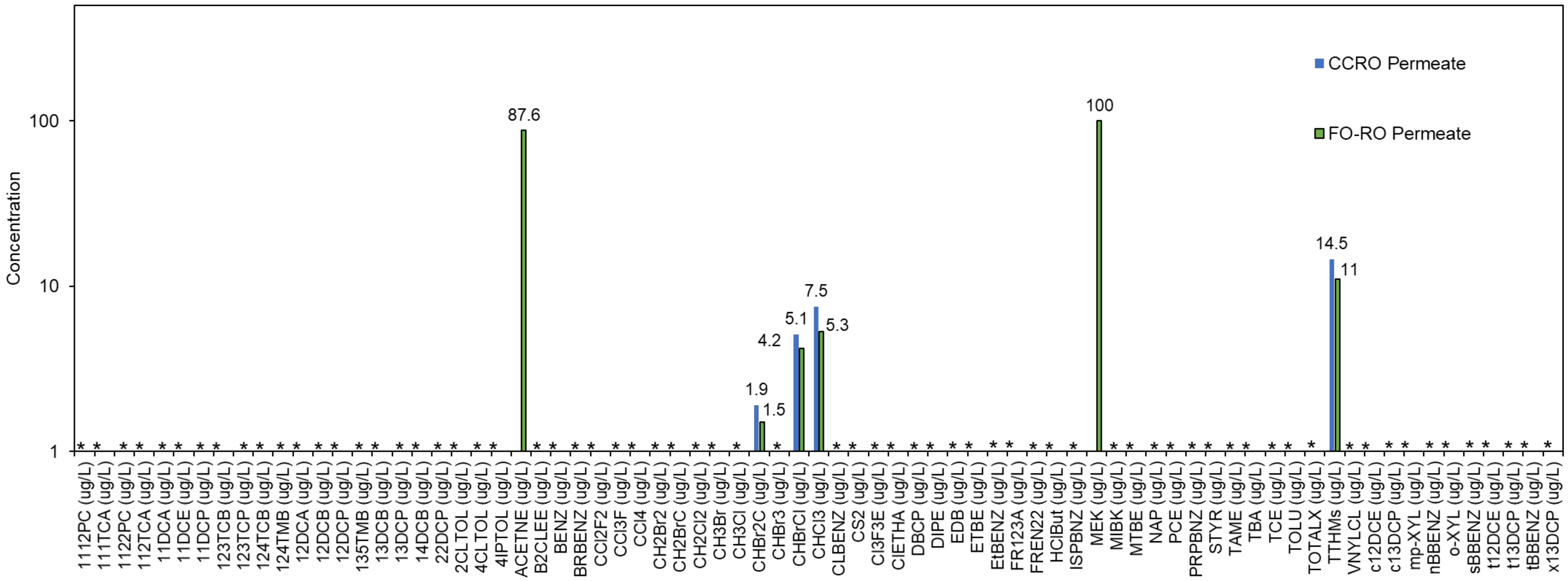

Figure H-1. Concentrations of EPA Method 524.2 (VOCs) compounds in CCRO permeate and FO-RO permeate. Based on water quality samples collected on 2/21/2019. * Indicates ND in sample (below reported detection limit).

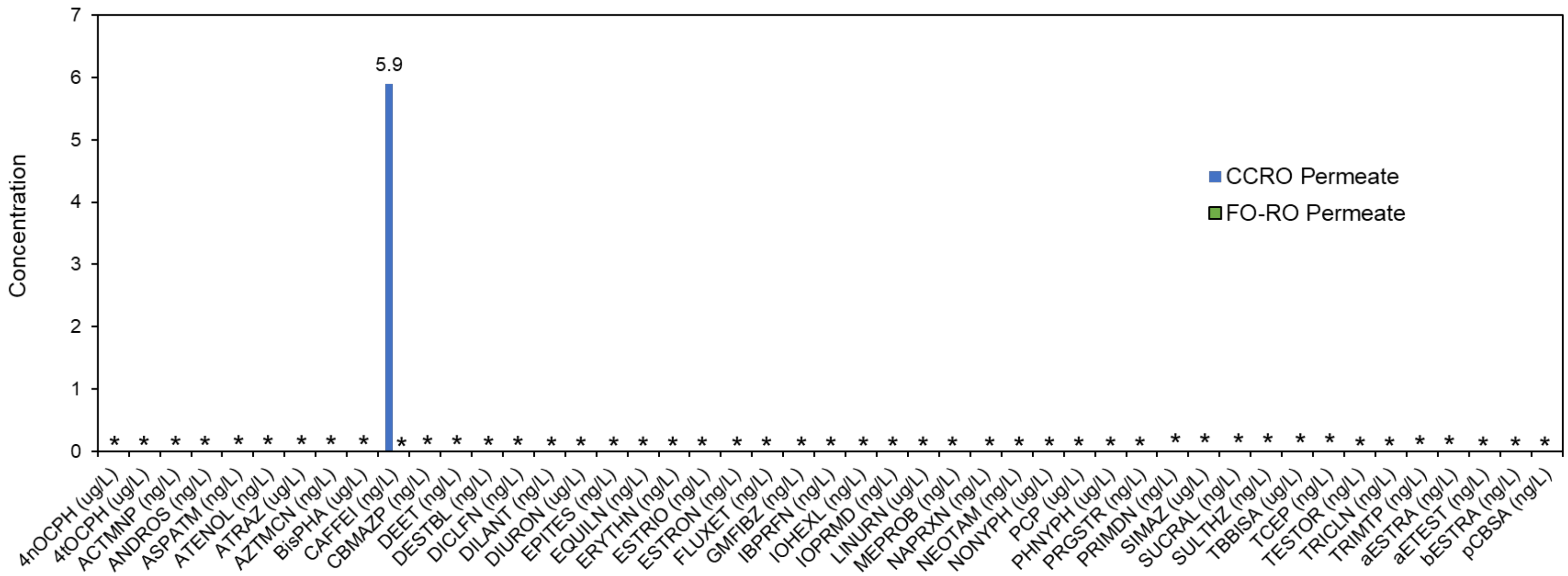

Figure H-2. Concentrations of CECs in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 2/21/2019. * Indicates ND in sample (below reported detection limit).

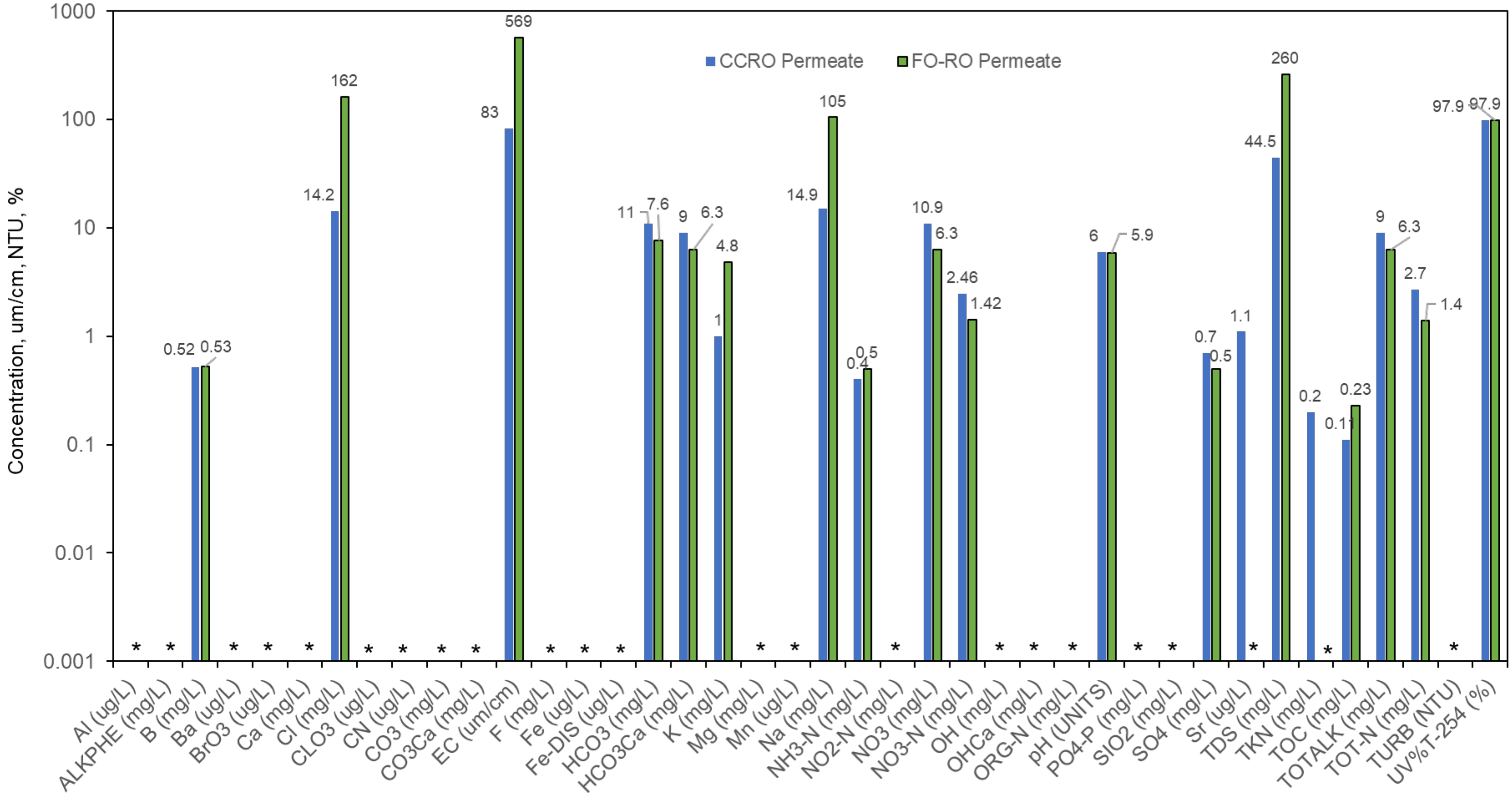

Figure H-3. Values for a list of inorganic species concentration and physical properties of permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 2/21/2019. * Indicates ND in sample (below reported detection limit).

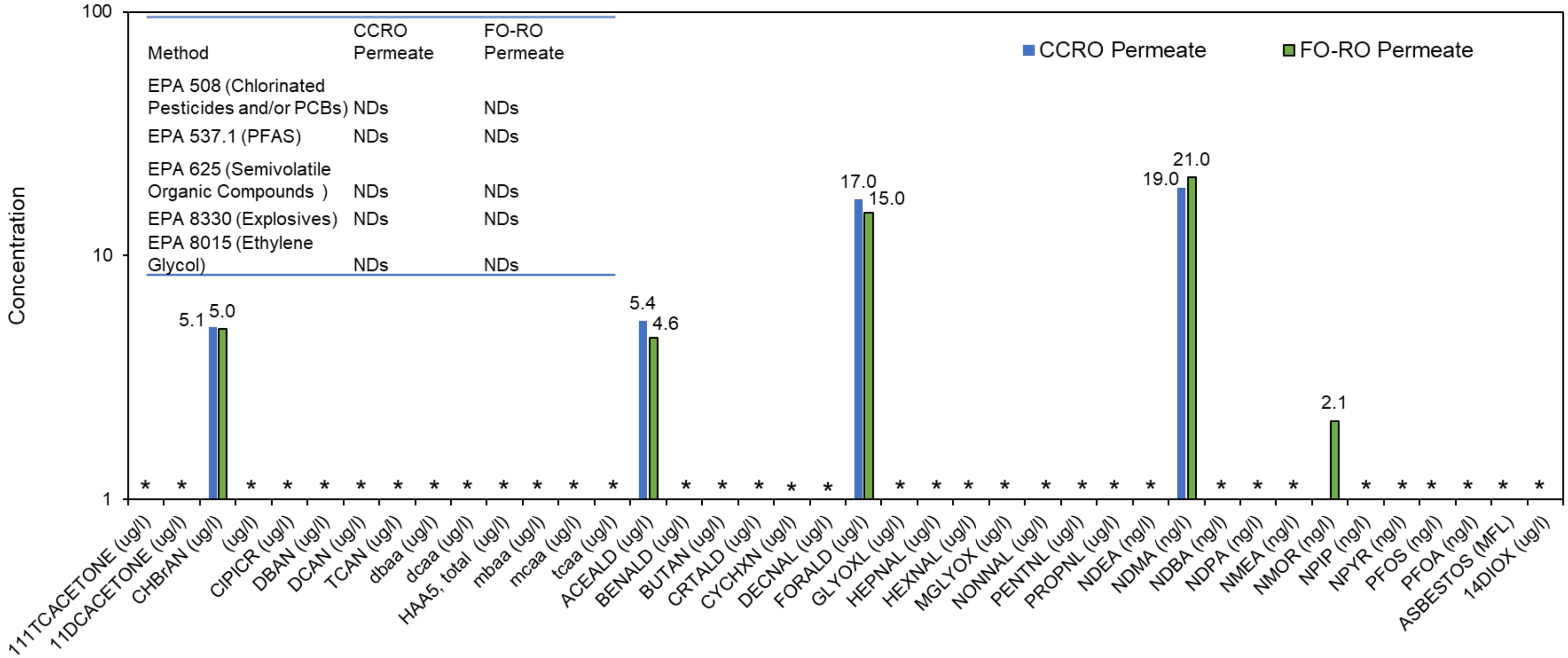

Figure H-4. Concentrations of organic compounds in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 2/21/2019 at OCWD. Methods: EPA 537.1 (PFAS), EPA 8015 (Ethylene Glycol), EPA 625 (SVOCs & Priority Pollutants), EPA 508 (Organochlorine Pesticides & PCBs), EPA 551.1 (Haloacetonitrile DBPs), EPA 556 (Aldehydes), EPA 552.2 (HAA5), Nitrosoamines-1625M, 8330A explosives residues, 1,4-dioxane, and Asbestos. * Indicates ND in sample (below reported detection limit).

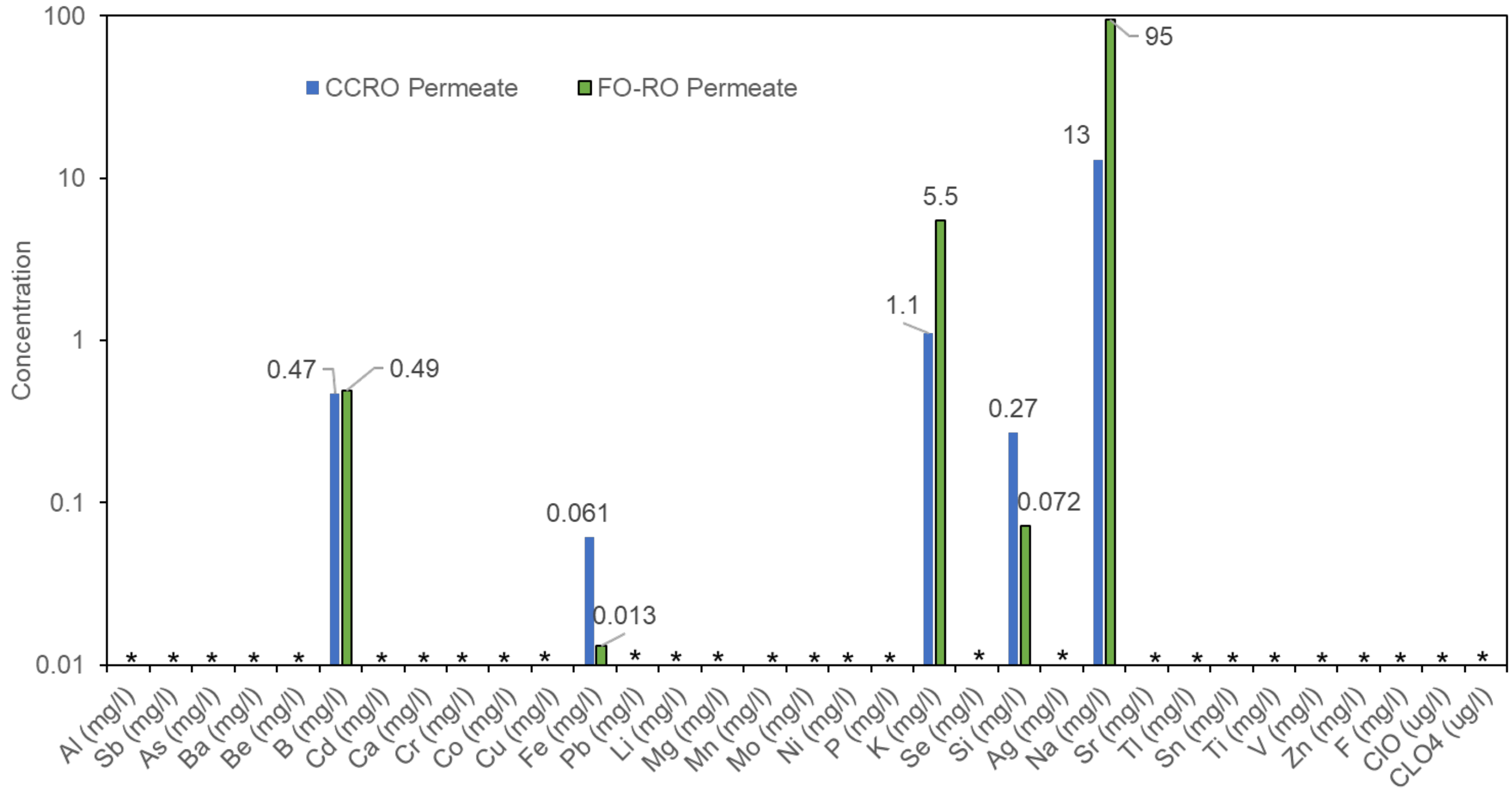

Figure H-5. Concentrations of inorganic in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 2/21/2019 at OCWD. Methods: Metals X200.7 and X200.8. * Indicates ND in sample (below reported detection limit).

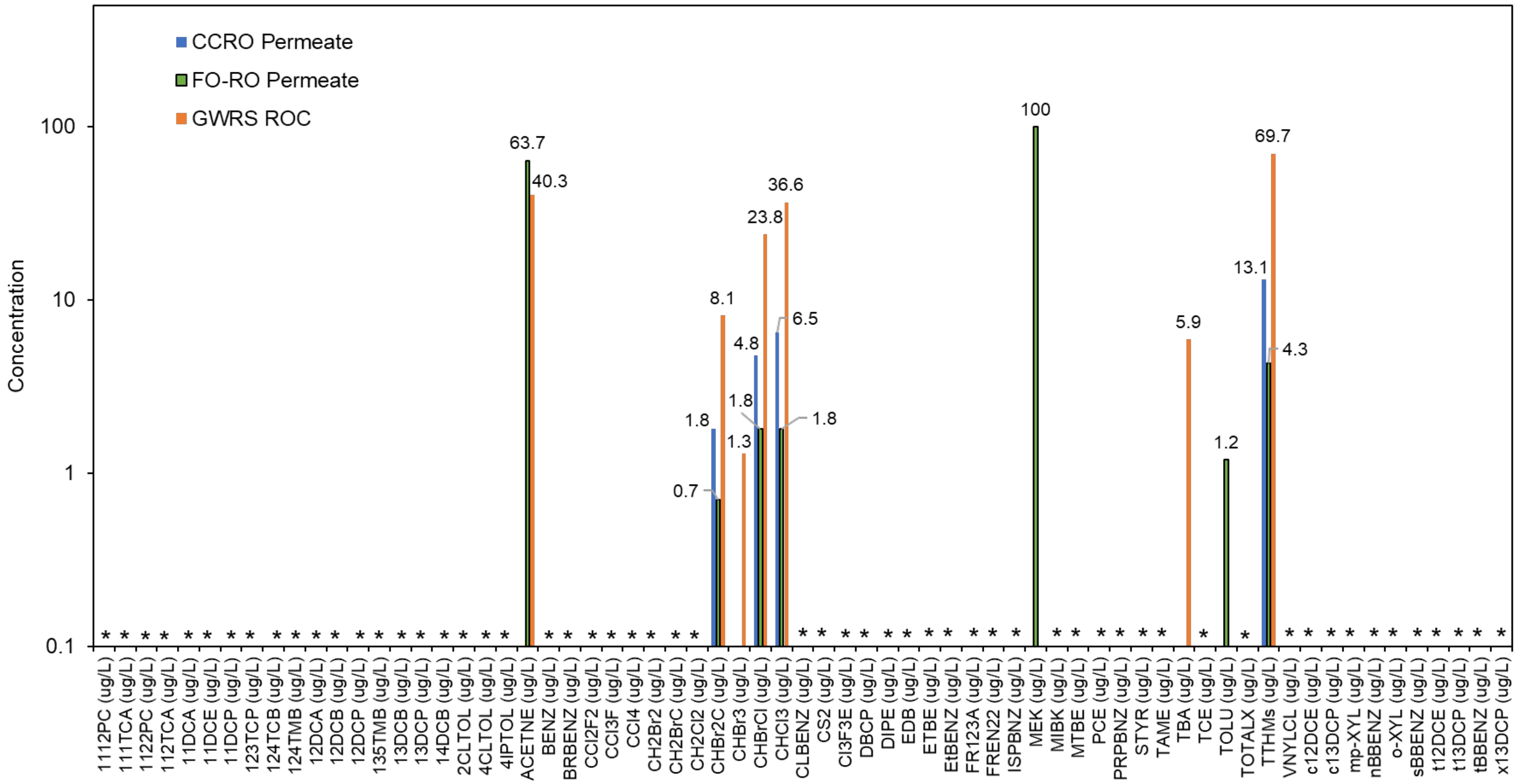

Figure H-6. Concentrations of EPA Method 524.2 (VOCs) compounds in GWRS ROC (feed), CCRO permeate, and FO-RO permeate. Based on water quality samples collected on 4/15/2019. * Indicates ND in sample (below reported detection limit).

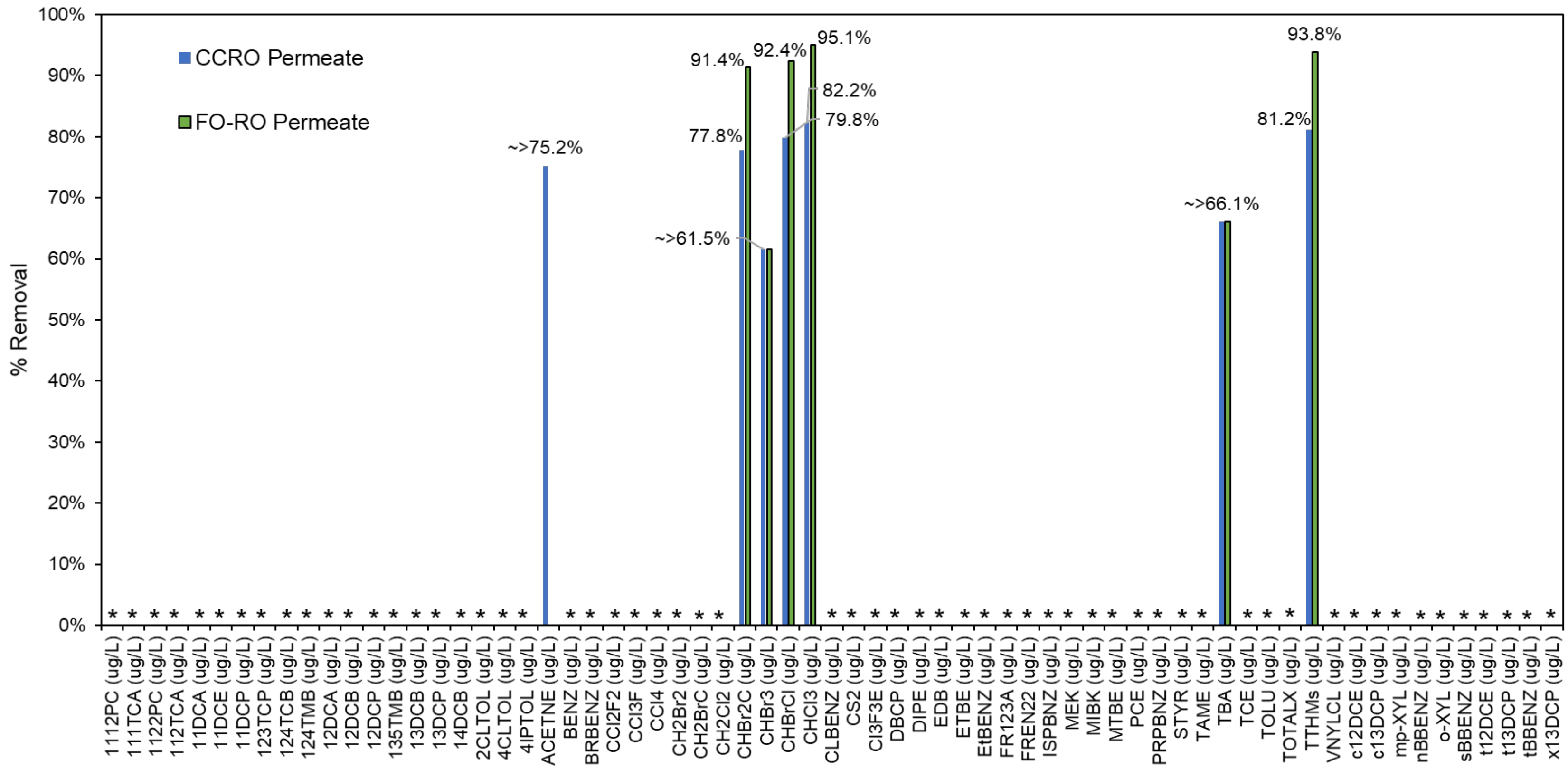

Figure H-7. Estimated percentage (%) removal of EPA Method 524.2 (VOCs) compounds of the CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water. Based on water quality samples collected on 4/15/2019. * Indicates ND in feed sample (below reported detection limit), ~> indicates ND in permeate sample, and RDL was used to estimate a % removal value.

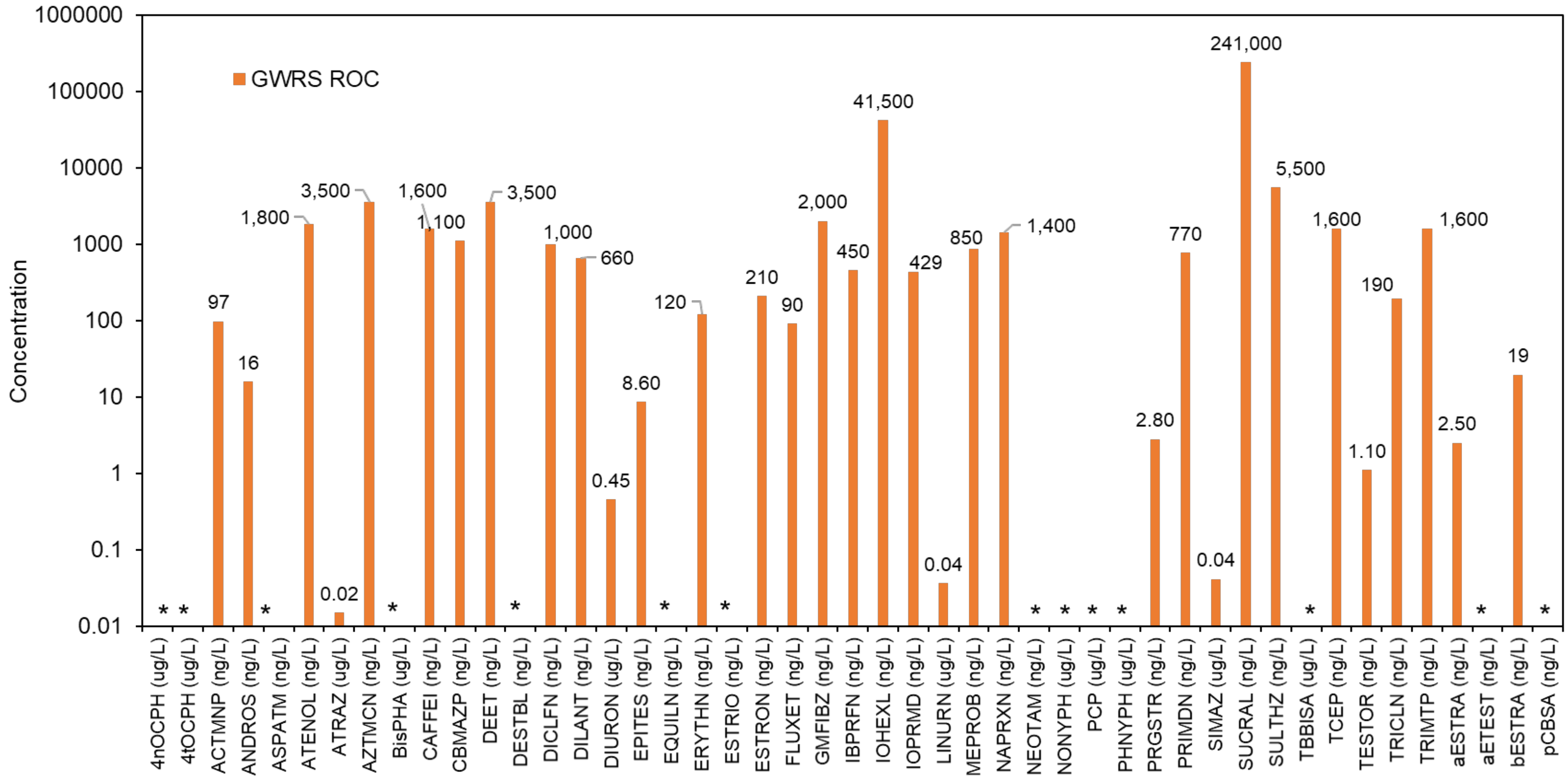

Figure H-8. Concentrations of CECs in samples of GWRS ROC (feed), CCRO, and FO-RO pilot system. Based on water quality samples collected on 4/15/2019. * Indicates ND in sample (below reported detection limit).

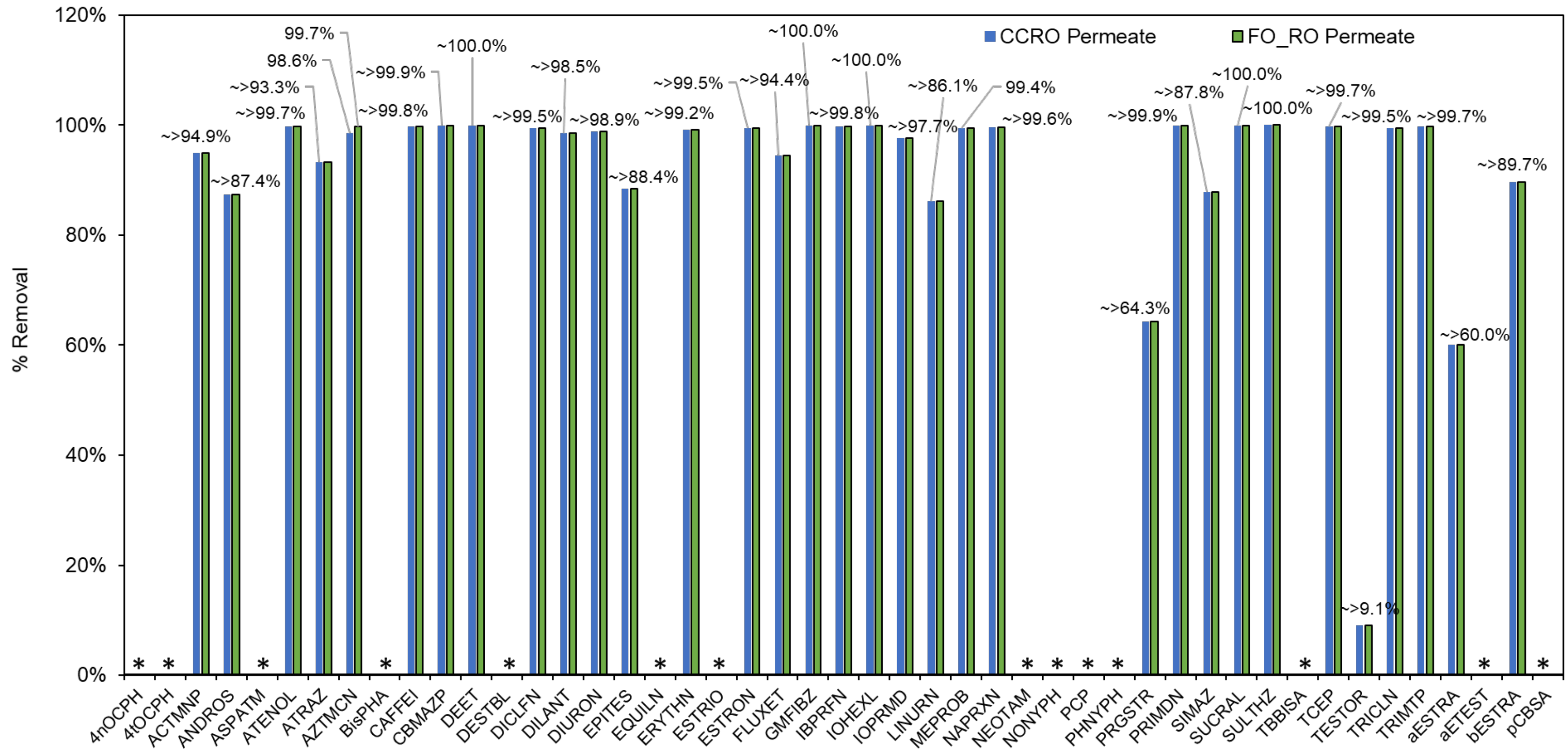

Figure H-9. Estimated percent (%) removal of CECs of the CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water. Based on water quality samples collected on 4/15/2019. * Indicates ND in feed sample (below reported detection limit), ~> indicates ND in permeate sample, and RDL was used to estimate a % removal value.

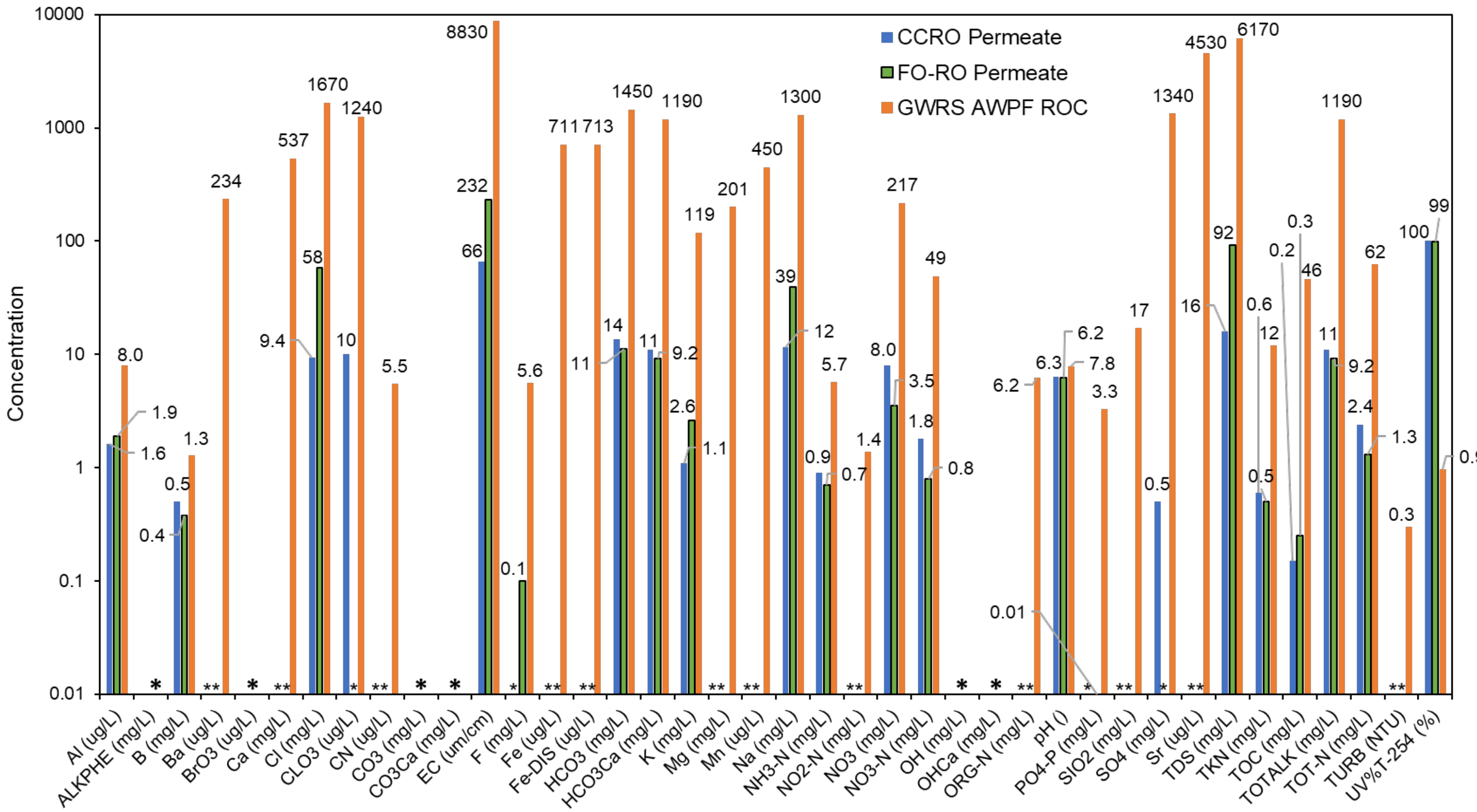

Figure H-10. Values for a list of inorganic species; concentration and physical properties of GWRS ROC (feed) and permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 4/15/2019. * Indicates ND in both CCRO and FO-RO permeate samples (below reported detection limit).

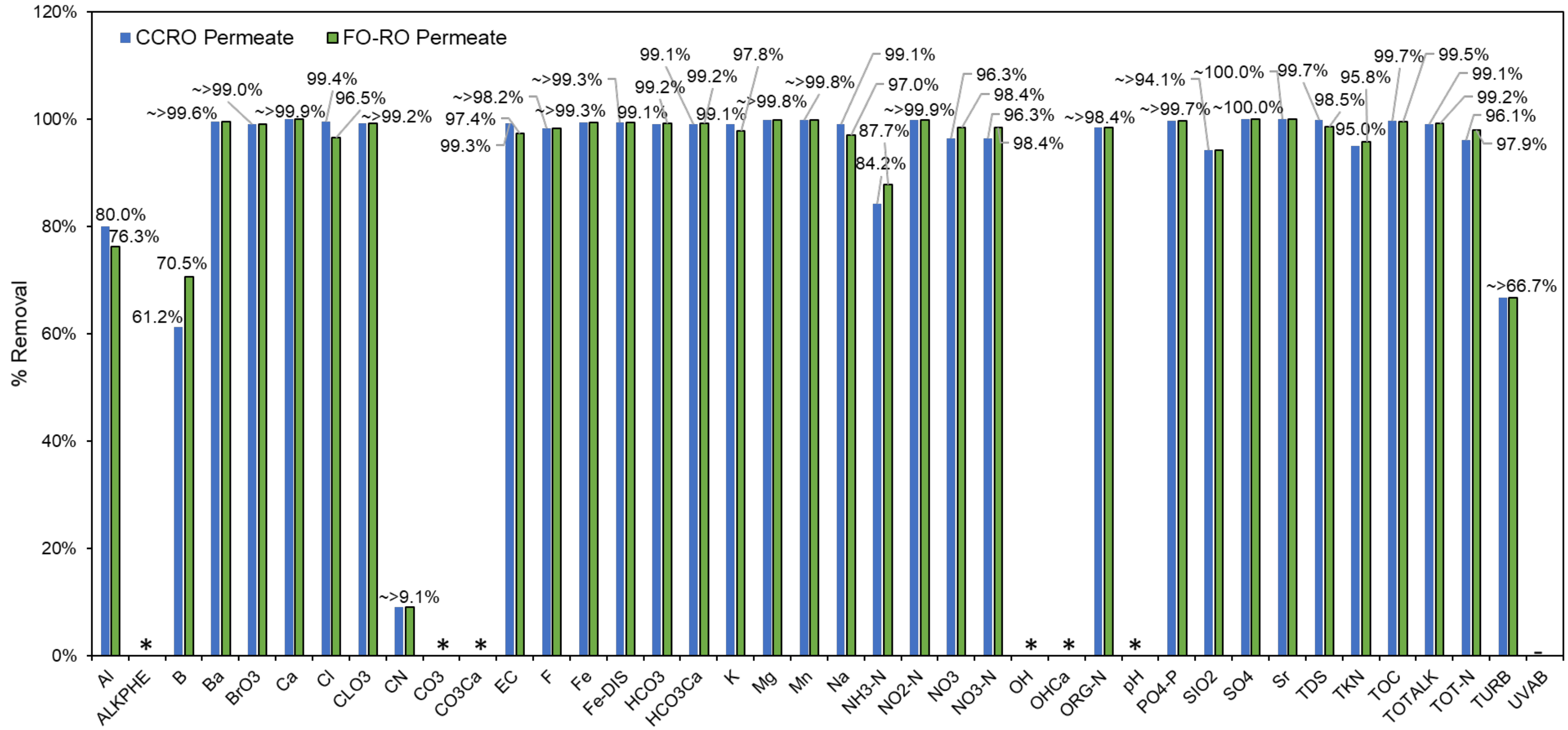

Figure H-11. Estimated percent (%) removal of a list of inorganic species; concentration and physical properties of the CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water. Based on water quality samples collected on 4/15/2019. * Indicates ND in feed sample (below reported detection limit), ~> indicates ND in permeate sample, and RDL was used to estimate a % removal value.

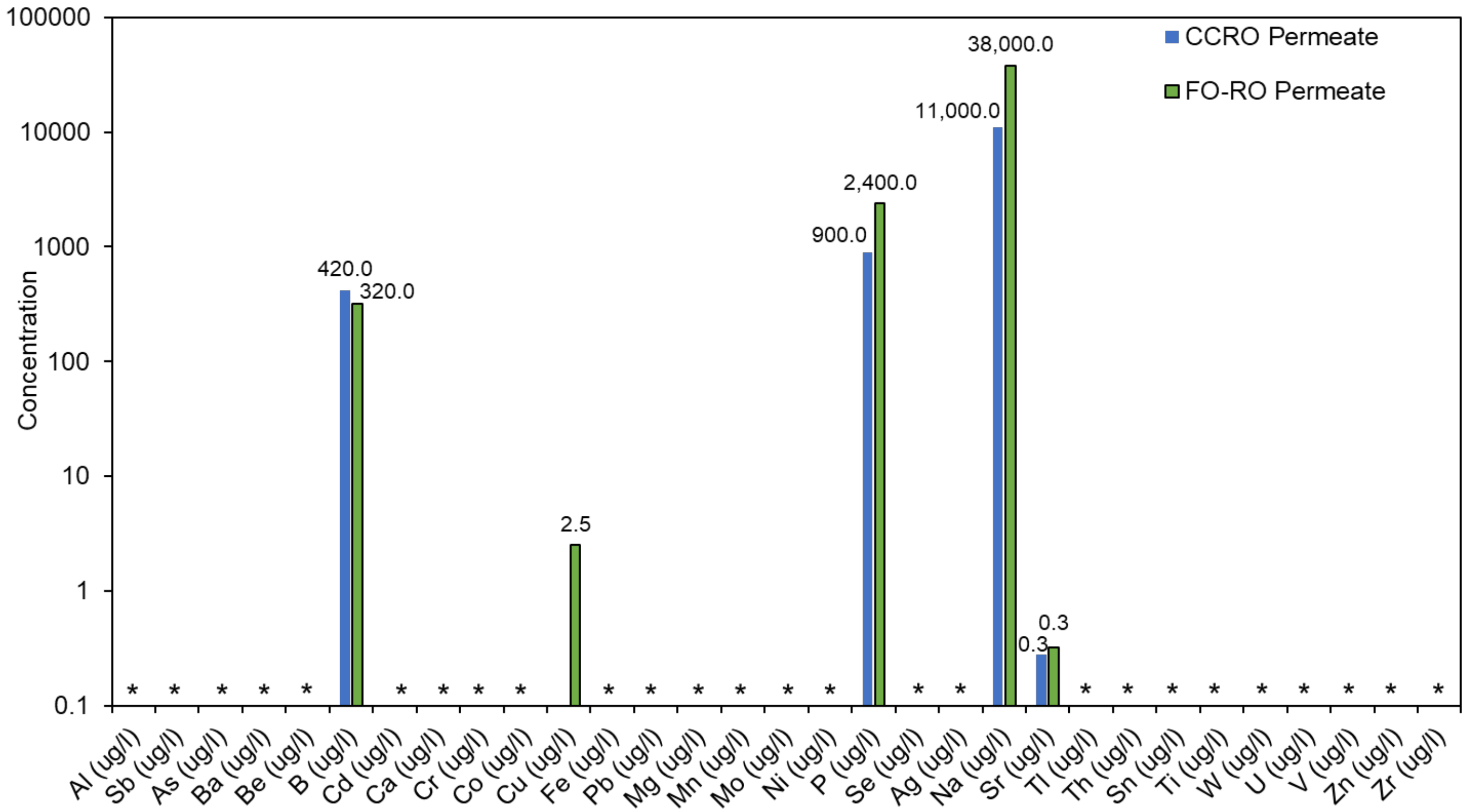

Figure H-12. Concentrations of inorganics in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 4/15/2019 at OCWD. Methods: Metals X200.7 and X200.8. * Indicates ND in both CCRO and FO-RO permeate samples (below reported detection limit).

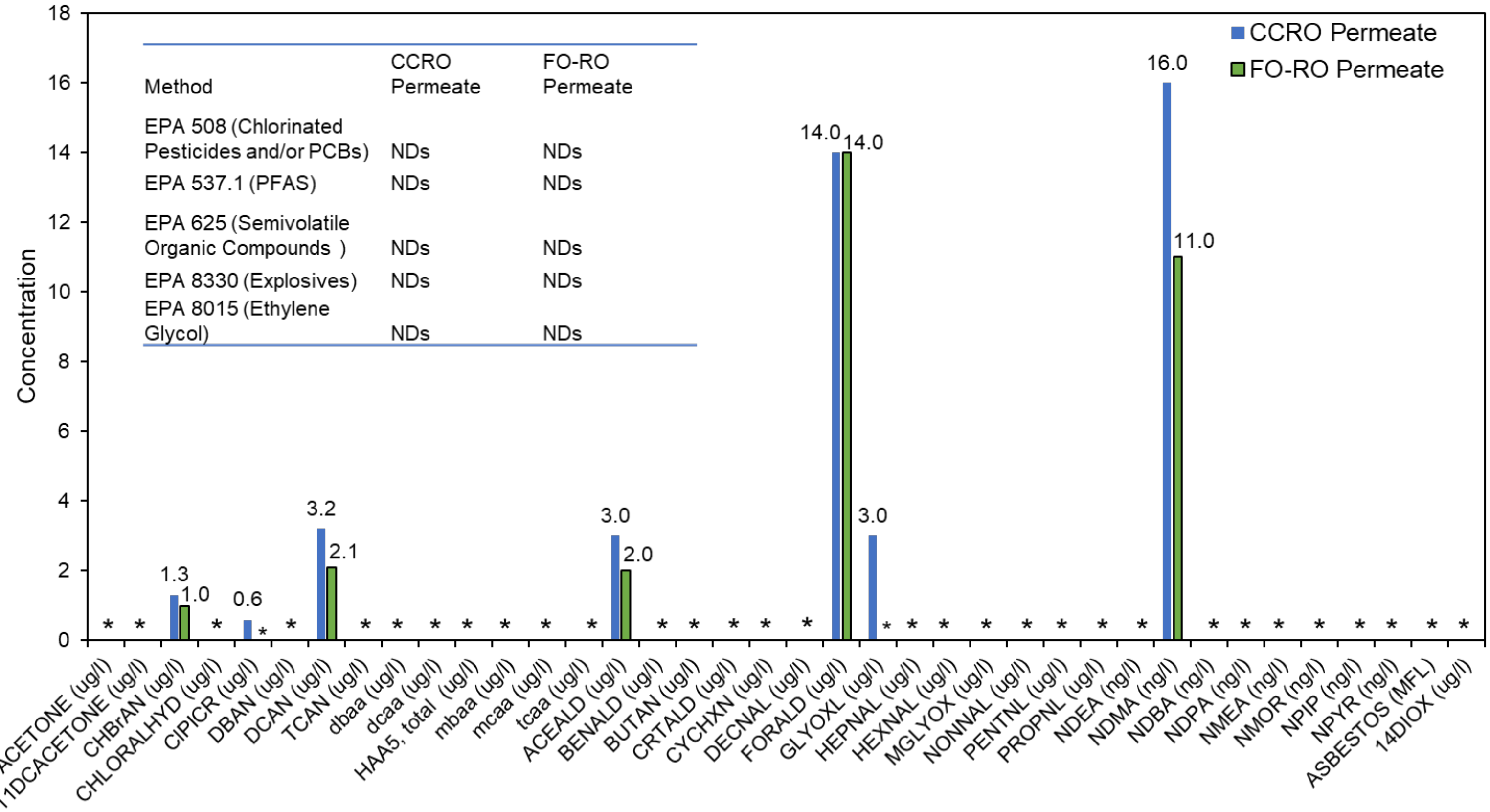

Figure H-13. Concentrations of organic compounds in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 4/15/2019 at OCWD. Methods: EPA 537.1 (PFAS), EPA 8015 (Ethylene Glycol), EPA 625 (SVOCs & Priority Pollutants), EPA 508 (Organochlorine Pesticides & PCBs), EPA 551.1 (Haloacetonitrile DBPs), EPA 556 (Aldehydes), EPA 552.2 (HAA5), Nitrosoamines-1625M, 8330A explosives residues, 1,4-dioxane, and Asbestos. * Indicates ND in both CCRO and FO-RO permeate samples (below reported detection limit). * Indicates ND in one of the permeate samples.

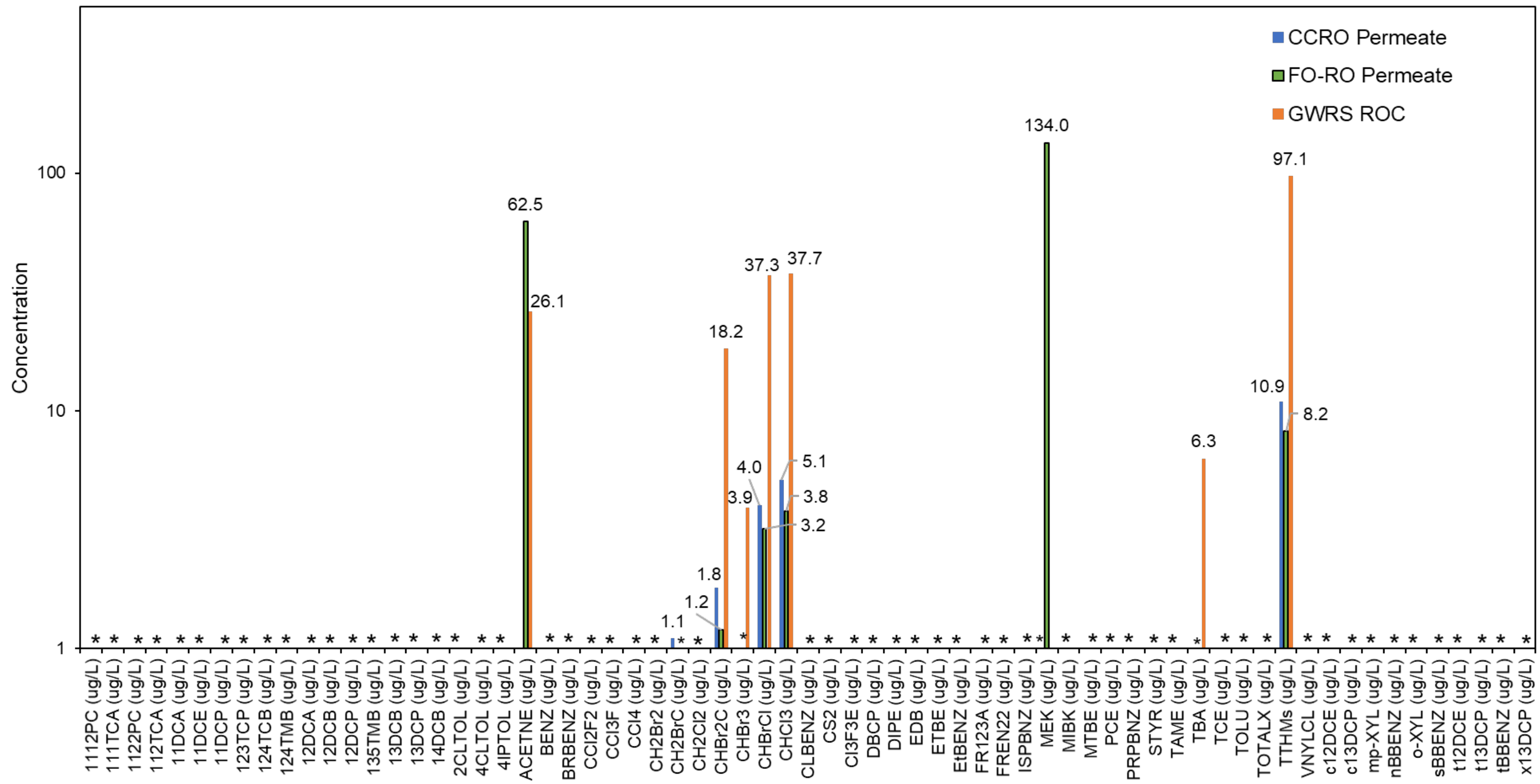

Figure H-14. Concentrations of EPA Method 524.2 (VOCs) compounds in GWRS ROC (feed), CCRO permeate, and FO-RO permeate. Based on water quality samples collected on 6/25/2019. * Indicates ND in sample (below reported detection limit).

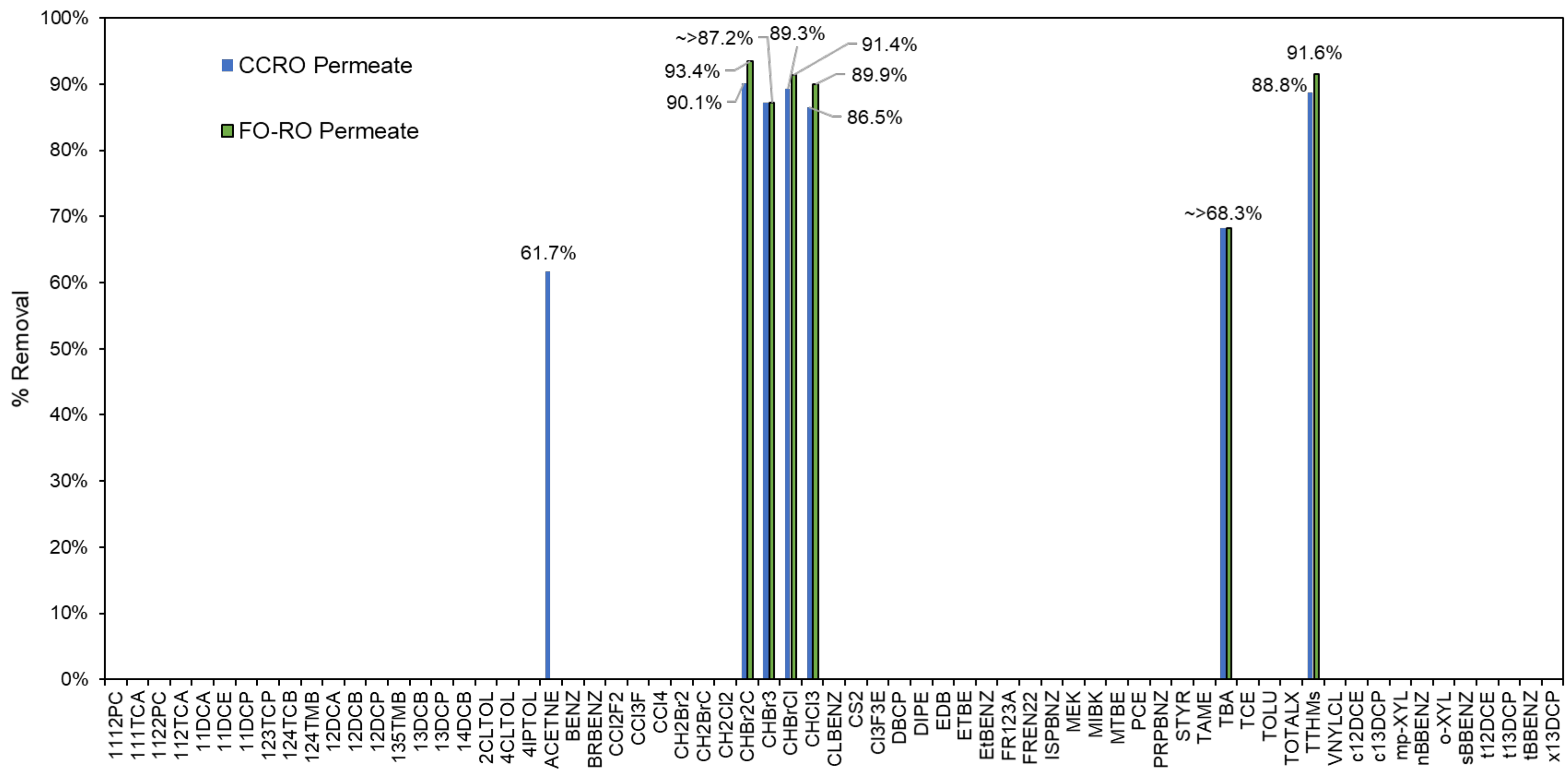

Figure H-15. Estimated percent (%) removal of EPA Method 524.2 (VOCs) compounds of the CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water. Based on water quality samples collected on 6/25/2019. * Indicates ND in feed sample (below reported detection limit), "~>" indicates ND in permeate sample, and RDL value was used to estimate a % removal value.

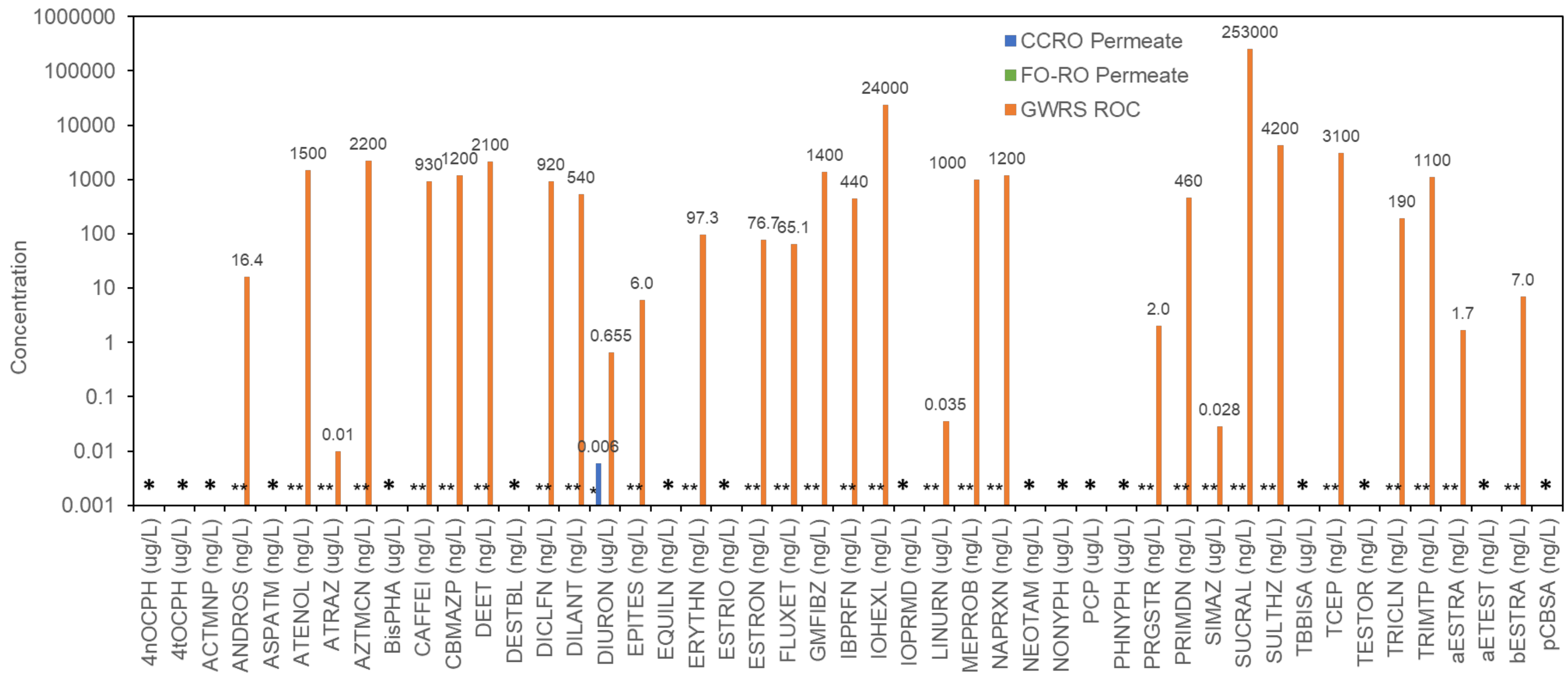

Figure H-16. Concentrations of CECs in samples of GWRS ROC (feed), CCRO and FO-RO pilot system. Based on water quality samples collected on 6/25/2019. * Indicates ND in sample (below reported detection limit).

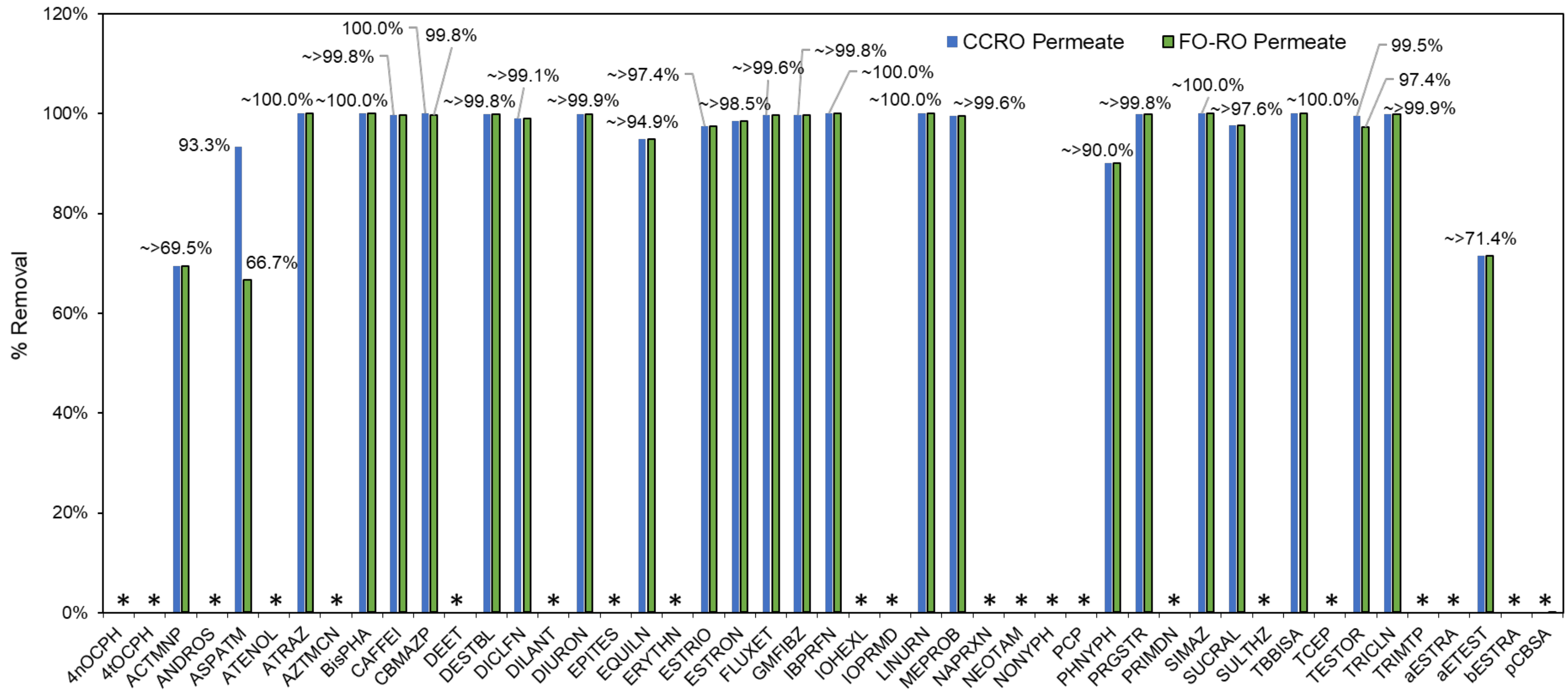

Figure H-17. Estimated percent (%) removal of CECs of the CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water. Based on water quality samples collected on 6/25/2019. * Indicates ND in feed sample (below reported detection limit), ~> indicates ND in permeate sample, and RDL was used to estimate a % removal value.

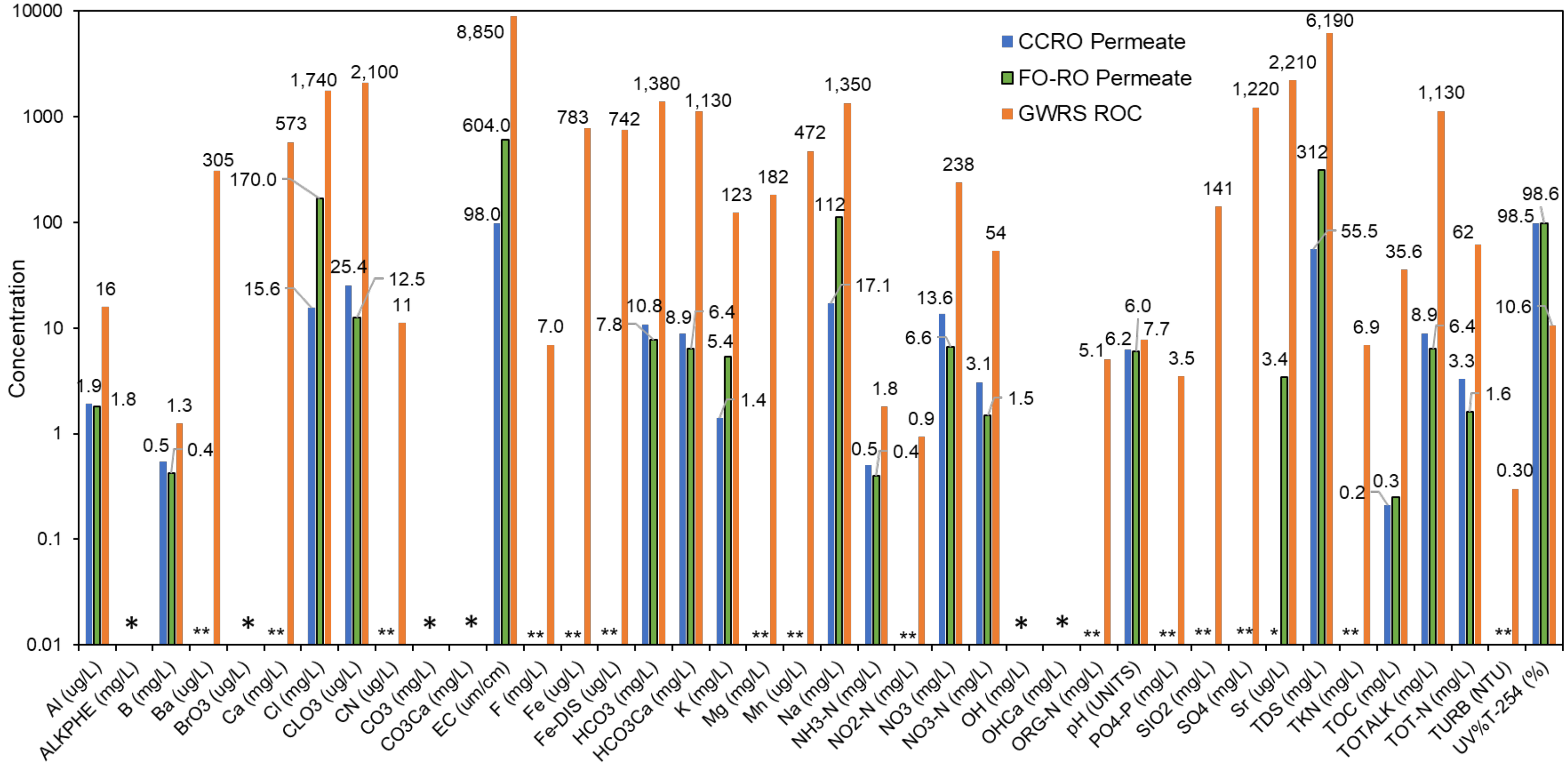

Figure H-18. Values for a list of inorganic species; concentration and physical properties of GWRS ROC (feed) and permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 6/25/2019. * Indicates NDs in both CCRO and FO-RO permeate samples (below reported detection limit).

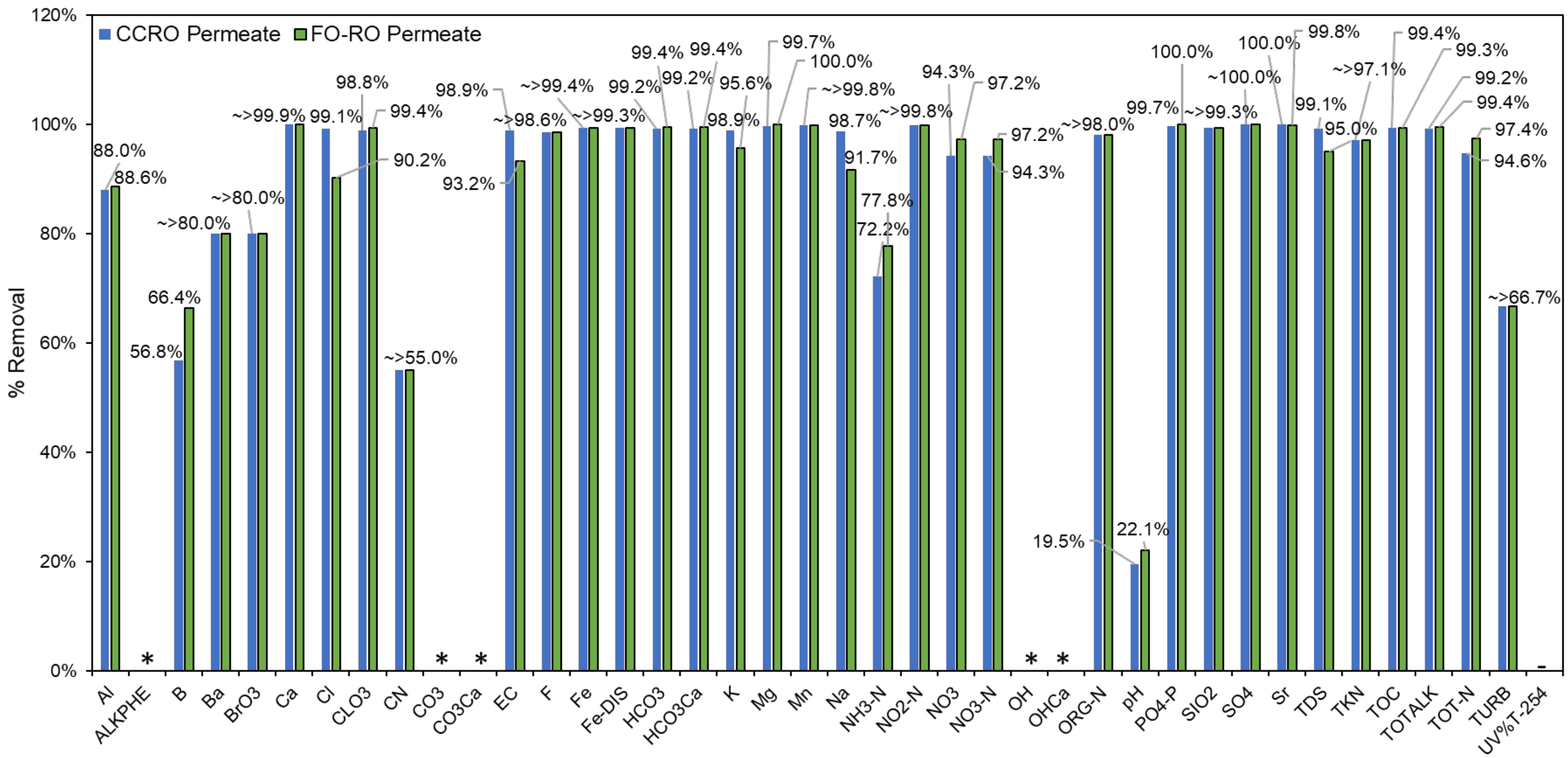

Figure H-19. Estimated percent (%) removal of a list of inorganic species; concentration and physical properties of the CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water. Based on water quality samples collected on 6/25/2019. * Indicates ND in feed sample (below reported detection limit), ~> indicates ND in permeate sample, and RDL was used to estimate a % removal value.

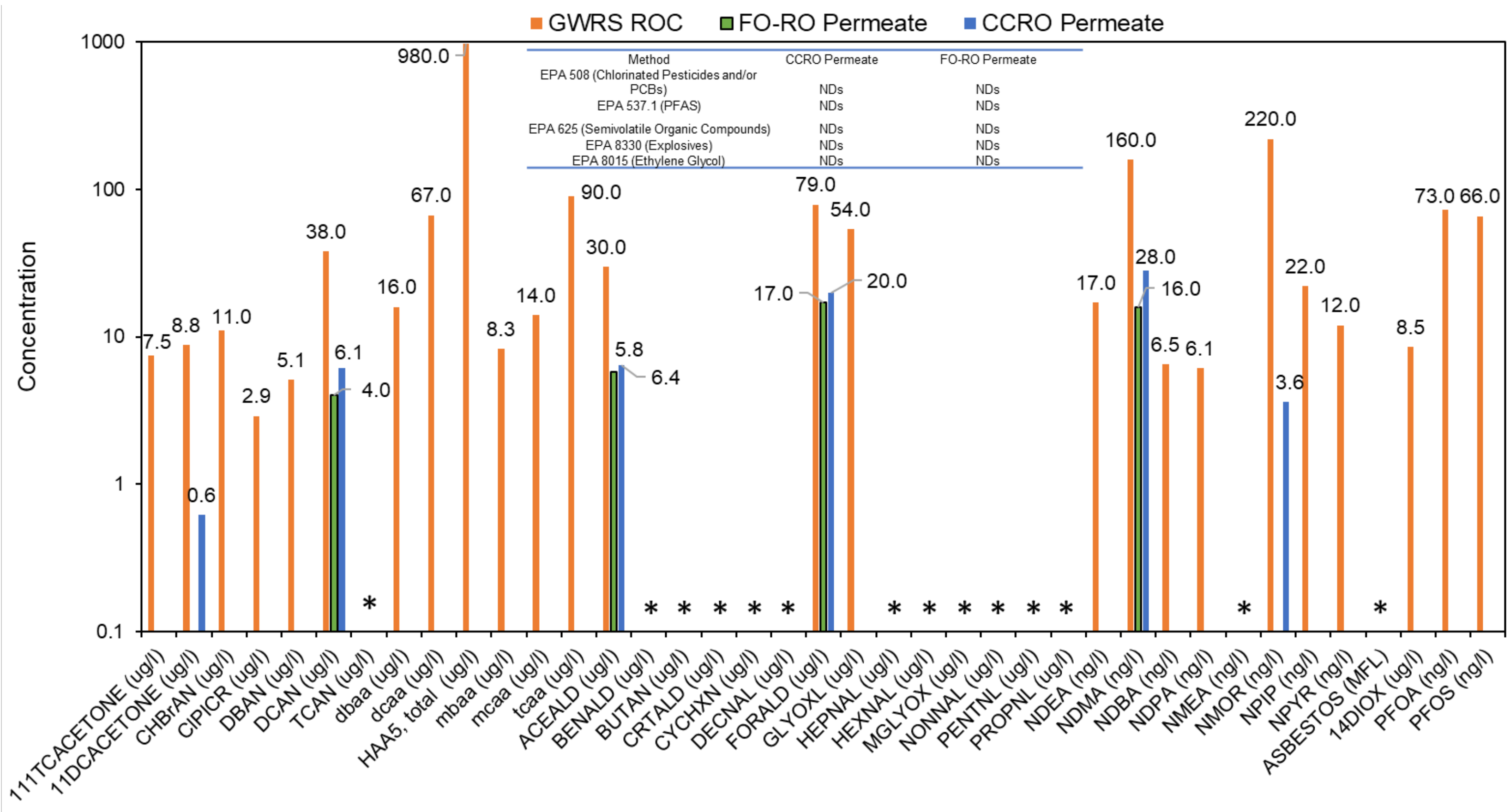

Figure H-20. Concentrations of organic compounds in samples of GWRS AWPF ROC, CCRO ,and FO-RO pilot permeate. Based on water quality samples collected on 6/25/2019 at OCWD. Methods: EPA 537.1 (PFAS), EPA 8015 (Ethylene Glycol), EPA 625 (SVOCs & Priority Pollutants), EPA 508 (Organochlorine Pesticides & PCBs), EPA 551.1 (Haloacetonitrile DBPs), EPA 556 (Aldehydes), EPA 552.2 (HAA5), Nitrosoamines-1625M, 8330A explosives residues, 1,4-dioxane, and Asbestos. * Indicates NDs in both CCRO and FO-RO permeate samples (below reported detection limit).

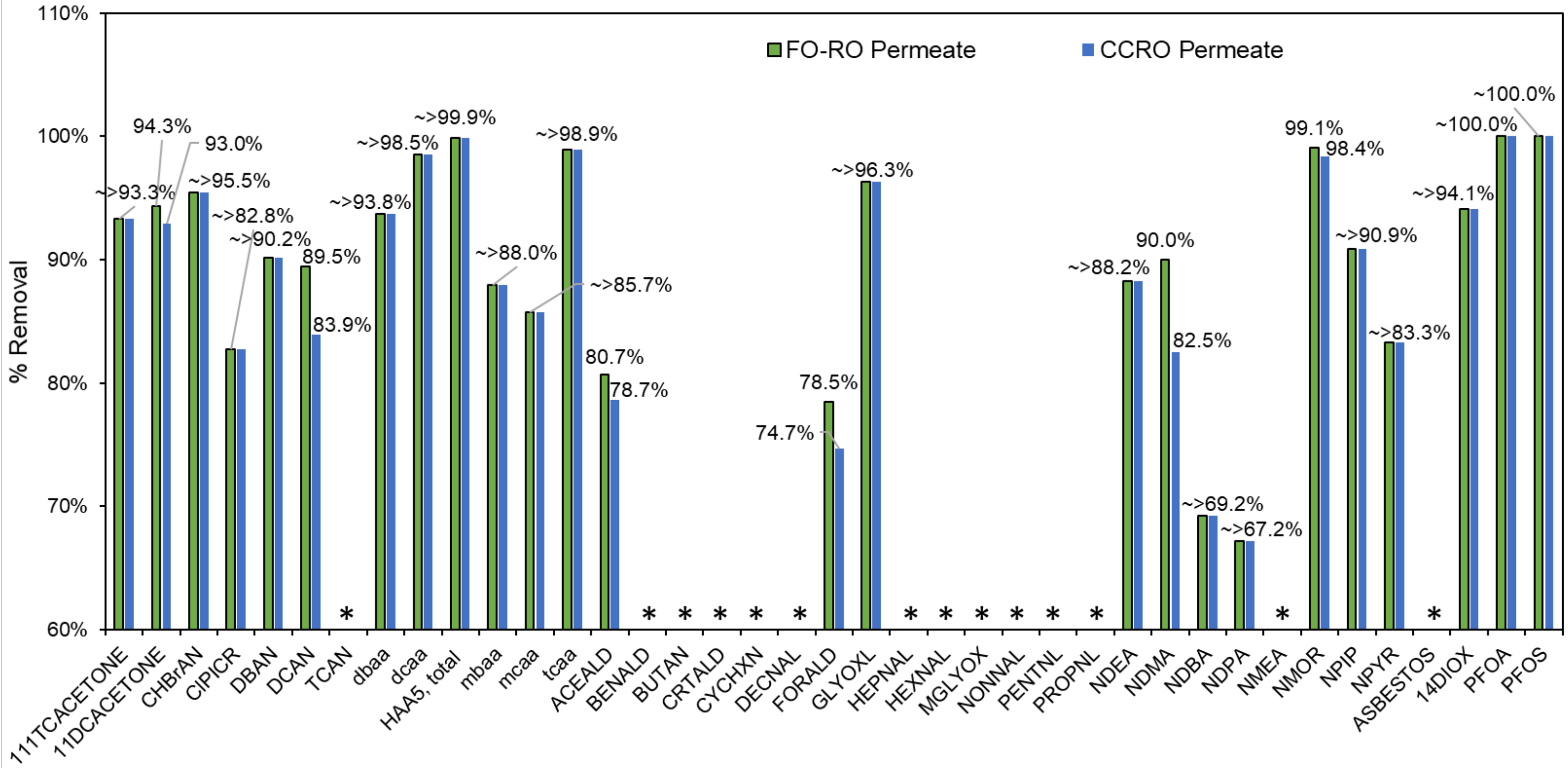

Figure H-21. Estimated percent (%) removal of organic compounds in permeate samples of CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water pilot permeate. Based on water quality samples collected on 6/25/2019. * Indicates ND in feed sample (below reported detection limit), "~>" indicates ND in permeate sample, and RDL value was used to estimate a % removal value.

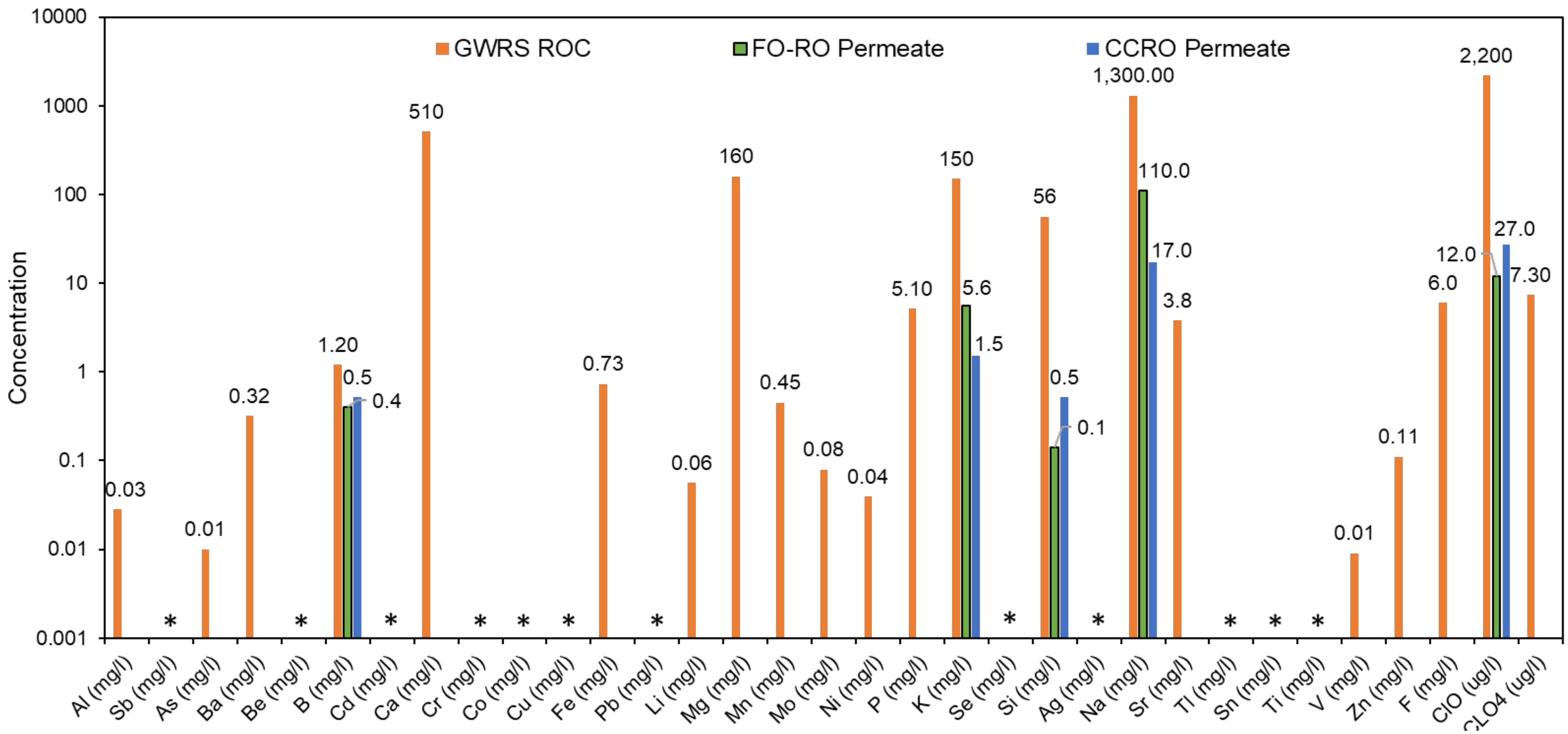

Figure H-22. Concentrations of inorganics in GWRS AWPF ROC sample and permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 6/25/2019 at OCWD. Methods: Metals X200.7 and X200.8. * Indicates ND in both CCRO and FO-RO permeate samples (below reported detection limit).

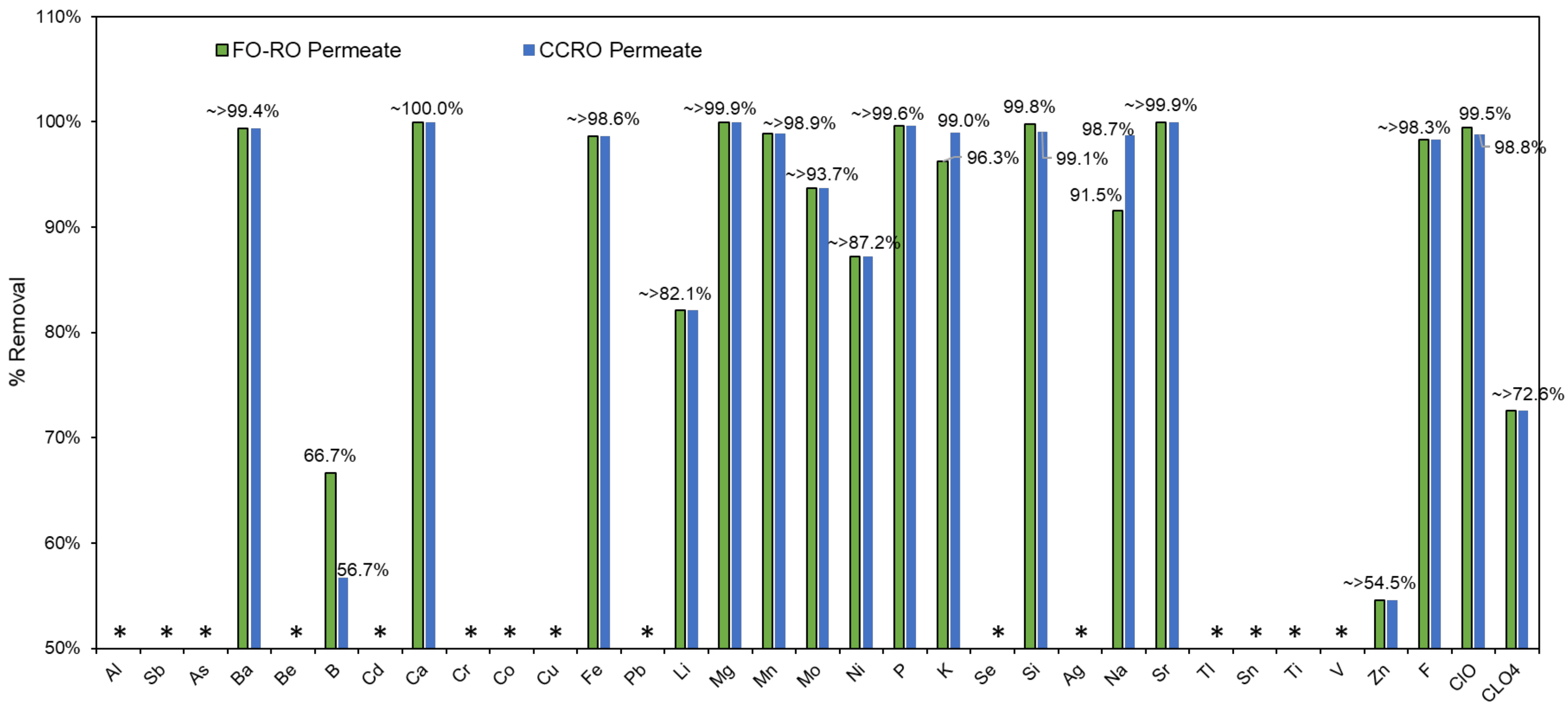

Figure H-23. Estimated percent (%) removal of inorganic in permeate samples of CCRO and FO-RO pilot at OCWD treating GWRS AWPF ROC water pilot permeate. Based on water quality samples collected on 6/25/2019. Methods: Metals X200.7 and X200.8. * Indicates ND in feed sample (below reported detection limit), "~>" indicates ND in permeate sample, and RDL value was used to estimate a % removal value.

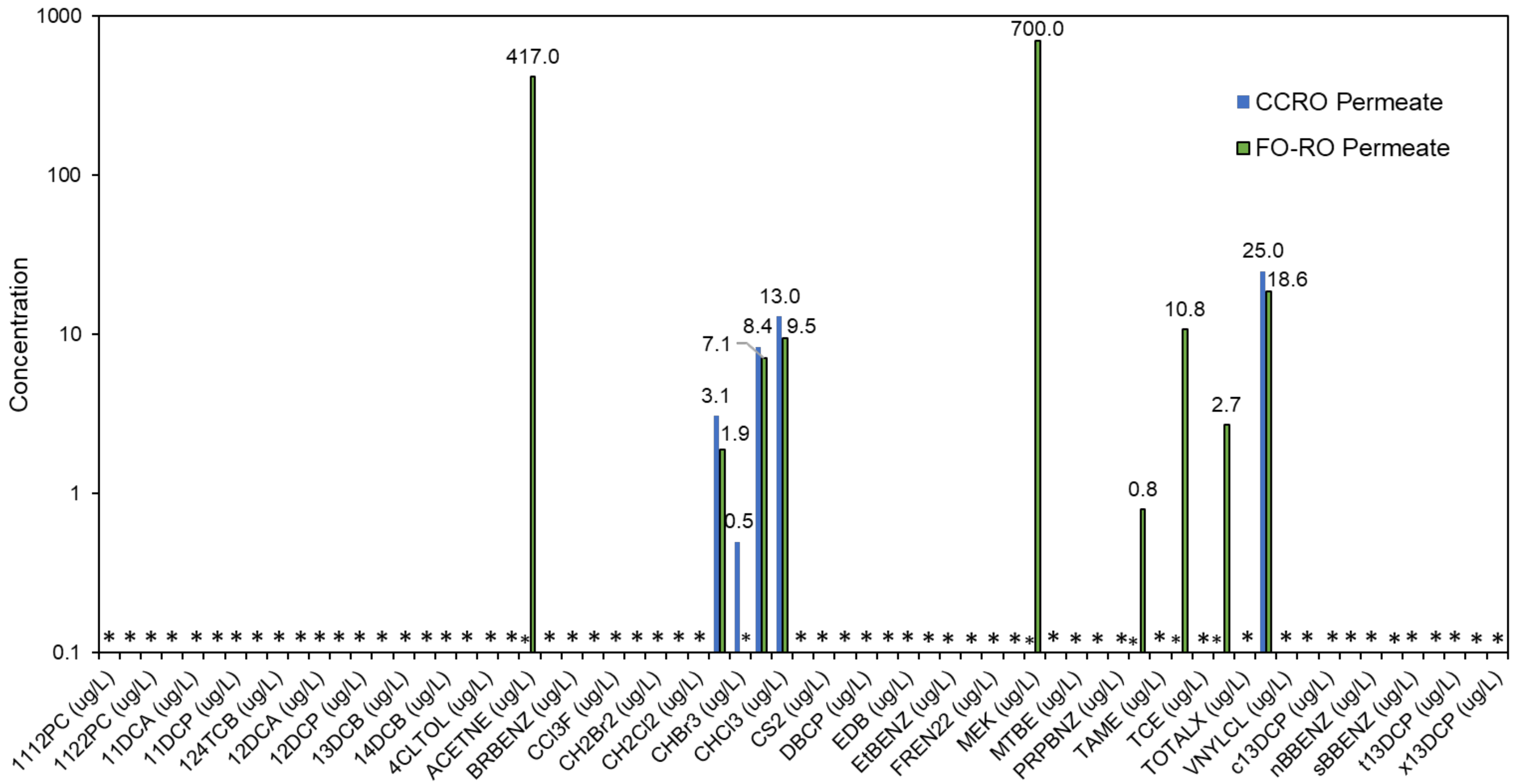

Figure H-24. Concentrations of EPA Method 524.2 (VOCs) compounds in CCRO permeate and FO-RO permeate. Based on water quality samples collected on 9/25/2019. * Indicates ND in sample (below reported detection limit).

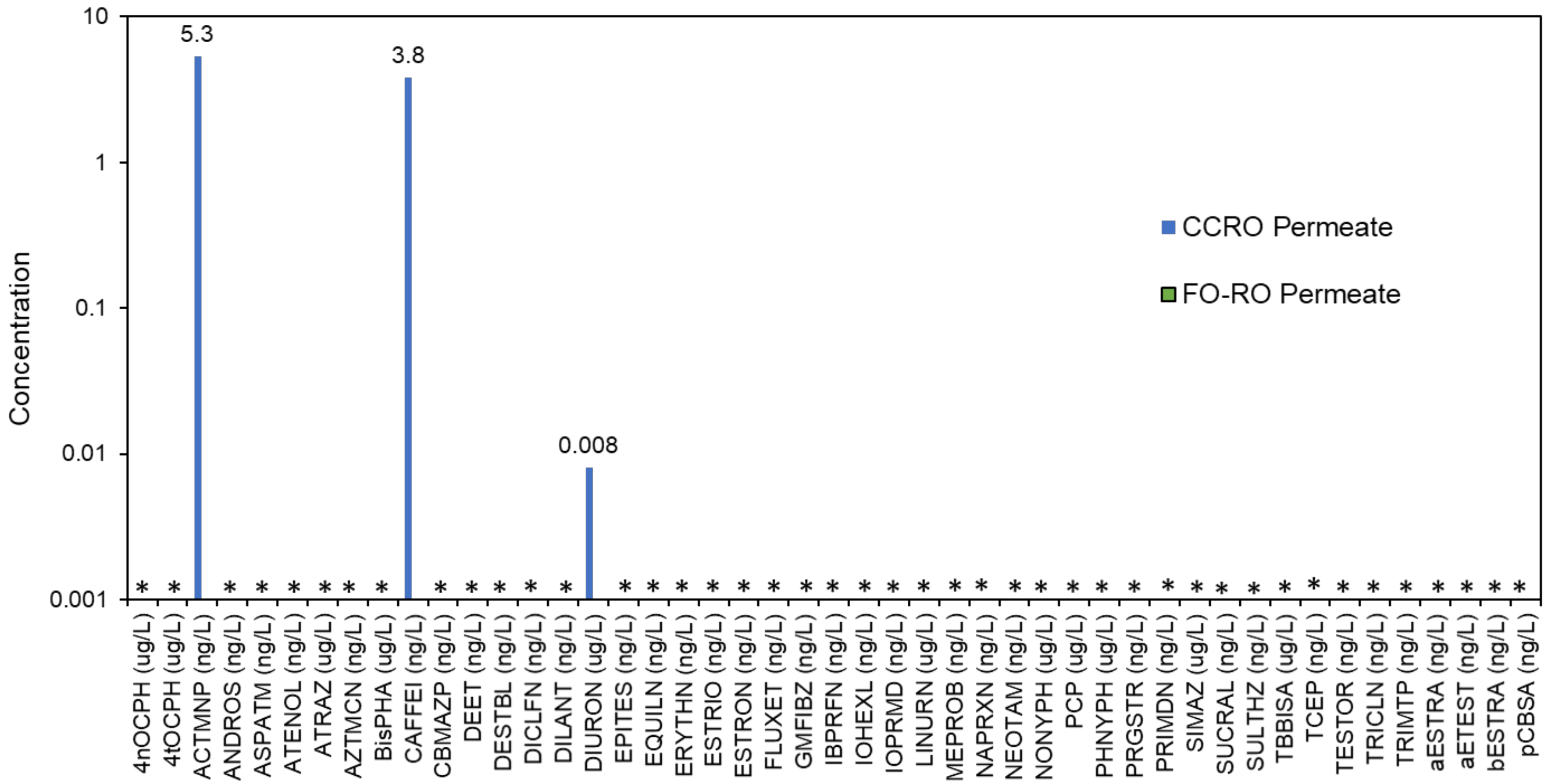

Figure H-25. Concentrations of CECs in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 9/25/2019. * Indicates ND in sample (below reported detection limit).

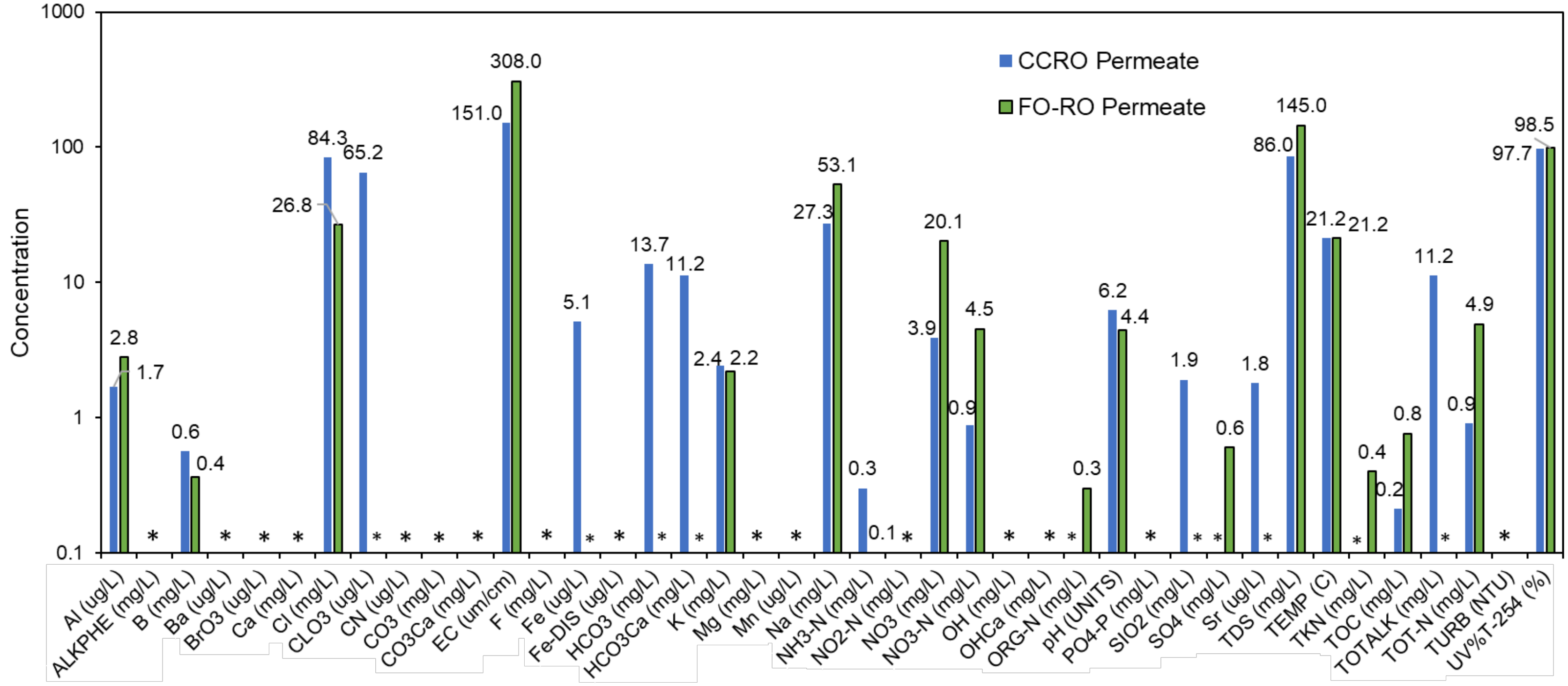

Figure H-26. Values for a list of inorganic species; concentration and physical properties of permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 9/25/2019. * Indicates ND in sample (below reported detection limit).

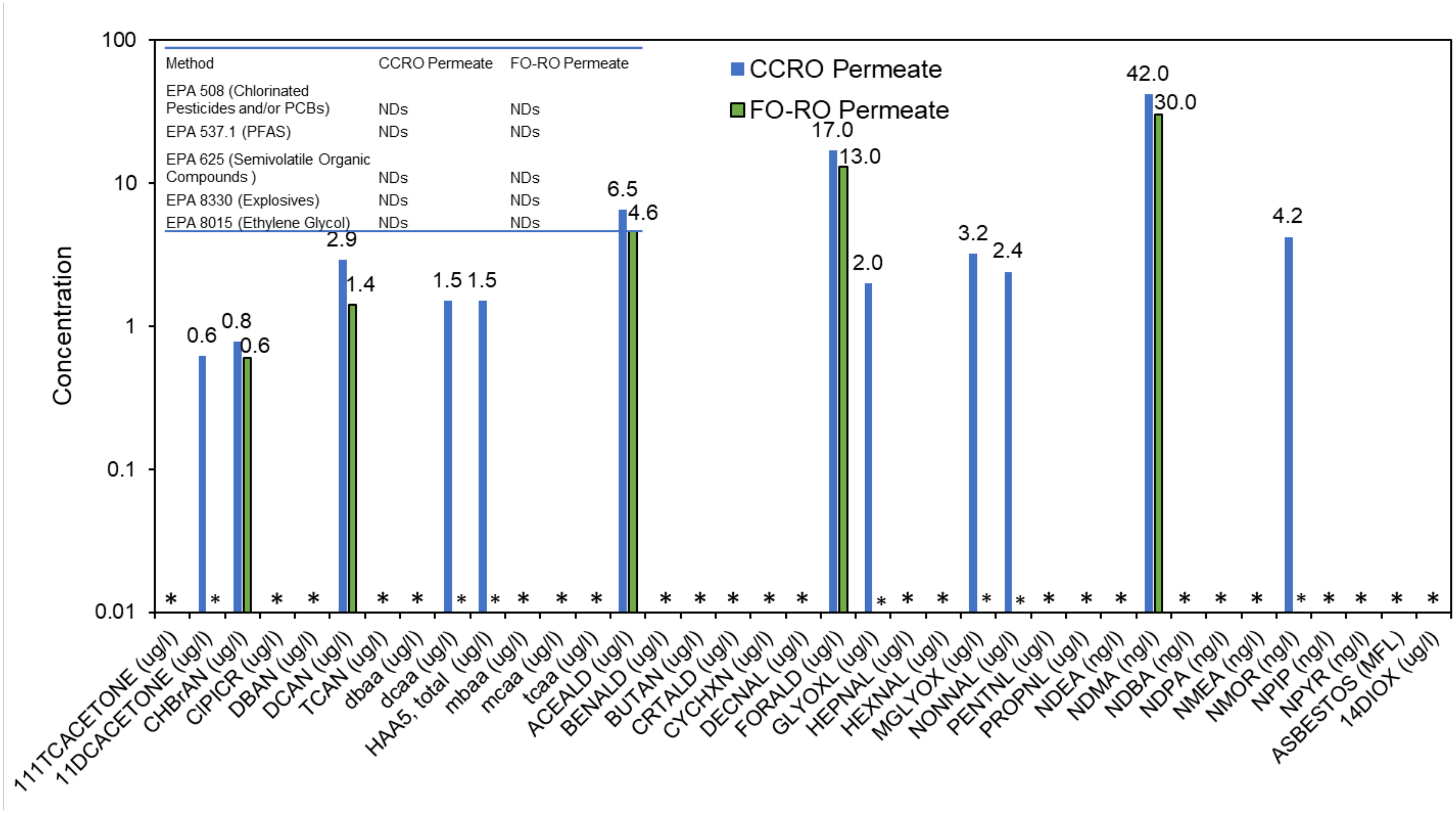

Figure H-27. Concentrations of organic compounds in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 9/25/2019 at OCWD. Methods: EPA 537.1 (PFAS), EPA 8015 (Ethylene Glycol), EPA 625 (SVOCs & Priority Pollutants), EPA 508 (Organochlorine Pesticides & PCBs), EPA 551.1 (Haloacetonitrile DBPs), EPA 556 (Aldehydes), EPA 552.2 (HAA5), Nitrosoamines-1625M, 8330A explosives residues, 1,4-dioxane, and Asbestos. * Indicates ND in sample (below reported detection limit).

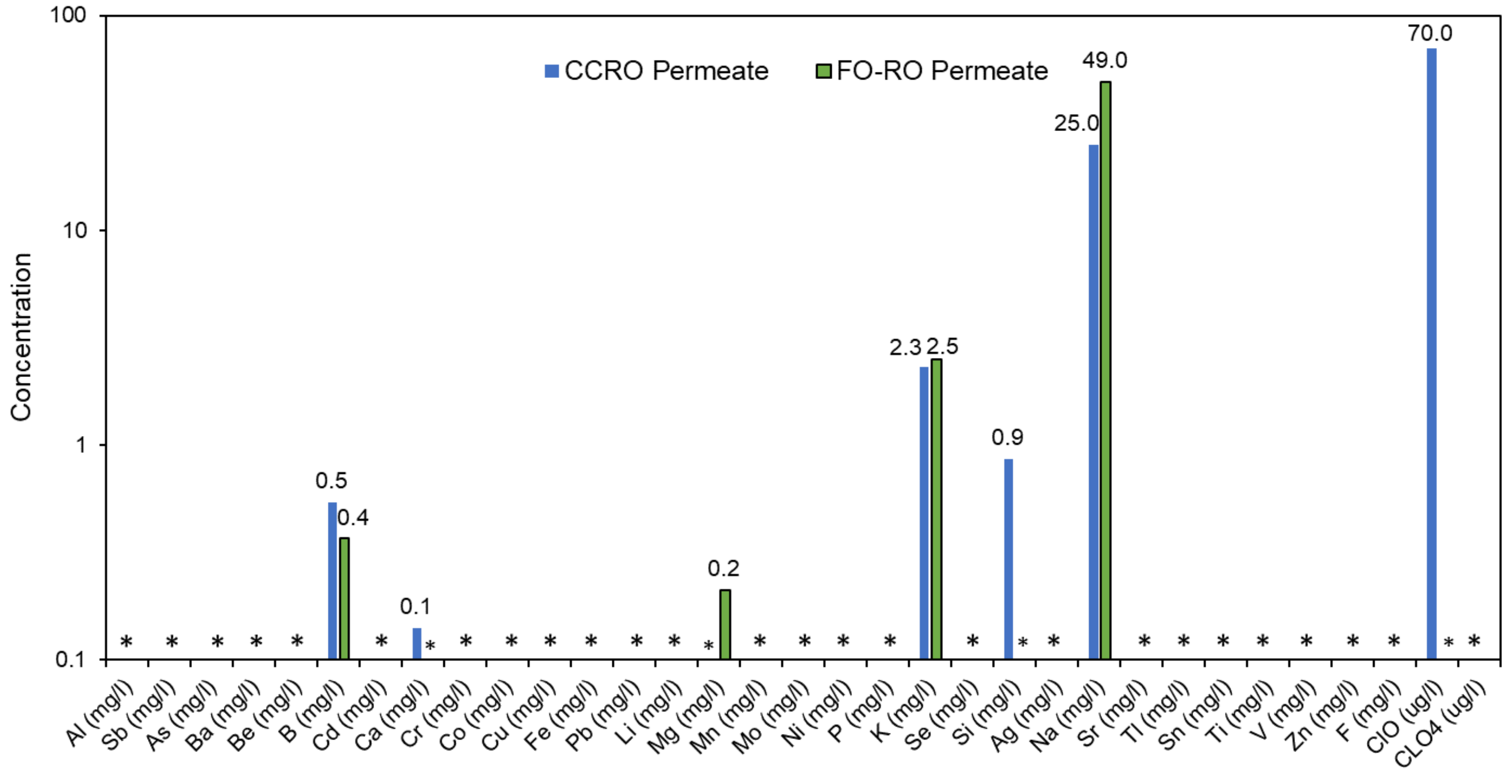

Figure H-28. Concentrations of inorganics in permeate samples of CCRO and FO-RO pilot system. Based on water quality samples collected on 9/25/2019 at OCWD. Methods: Metals X200.7 and X200.8. * Indicates ND in sample (below reported detection limit).

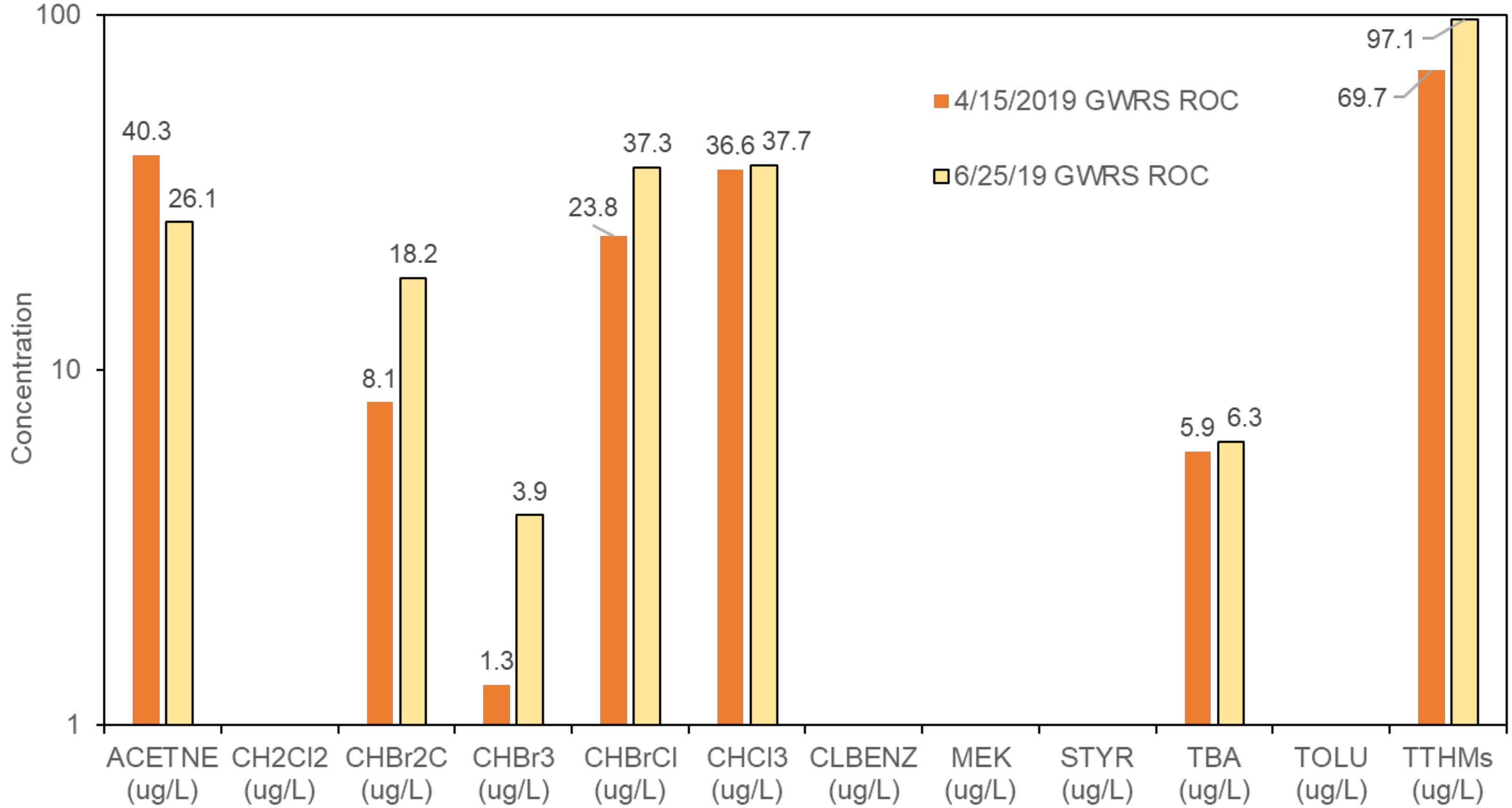

Figure H-29. Concentrations of EPA Method 524.2 (VOCs) compounds in GWRS AWPF ROC samples. Based on water quality samples collected in 4/15/2019 and 6/25/2019. * Indicates ND in sample (below reported detection limit).

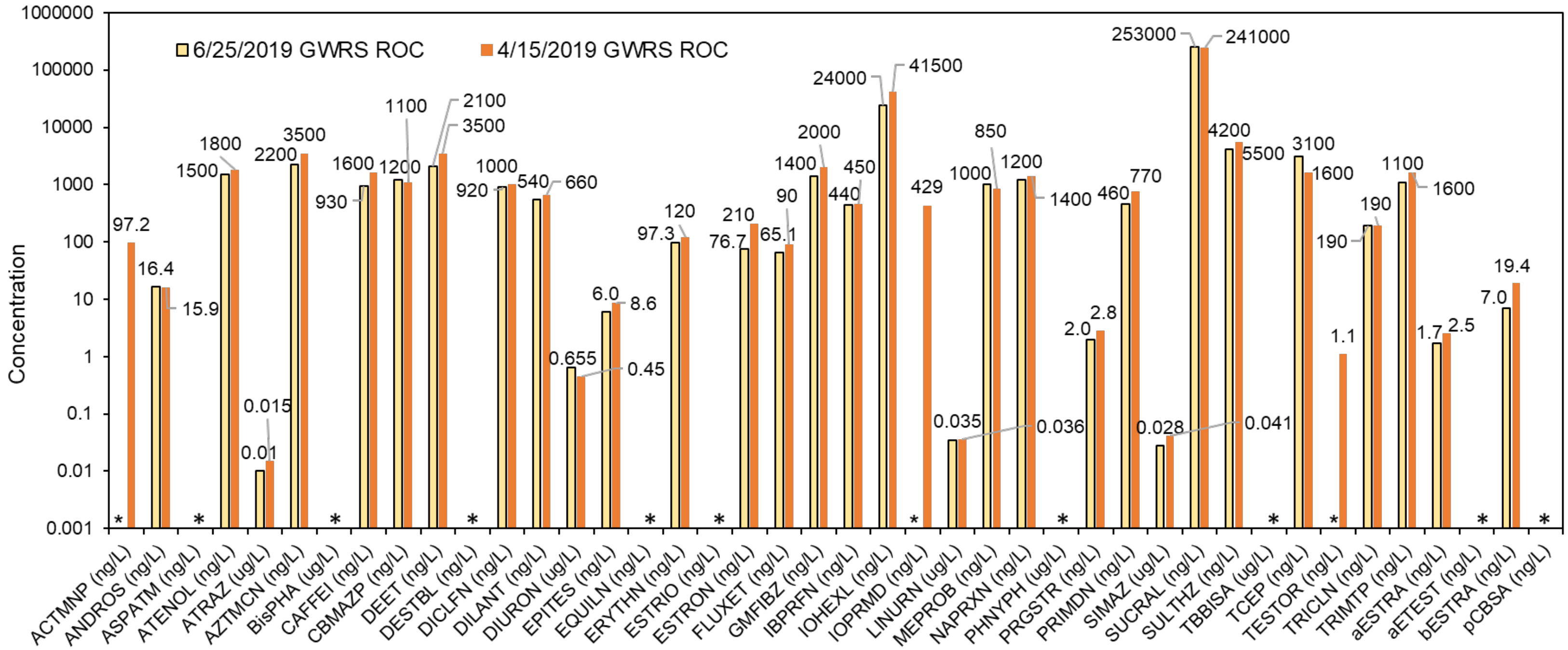

Figure H-30. Concentrations of CECs in GWRS AWPF ROC samples. Based on water quality samples collected in 4/15/2019 and 6/25/2019. * Indicates ND in sample (below reported detection limit).

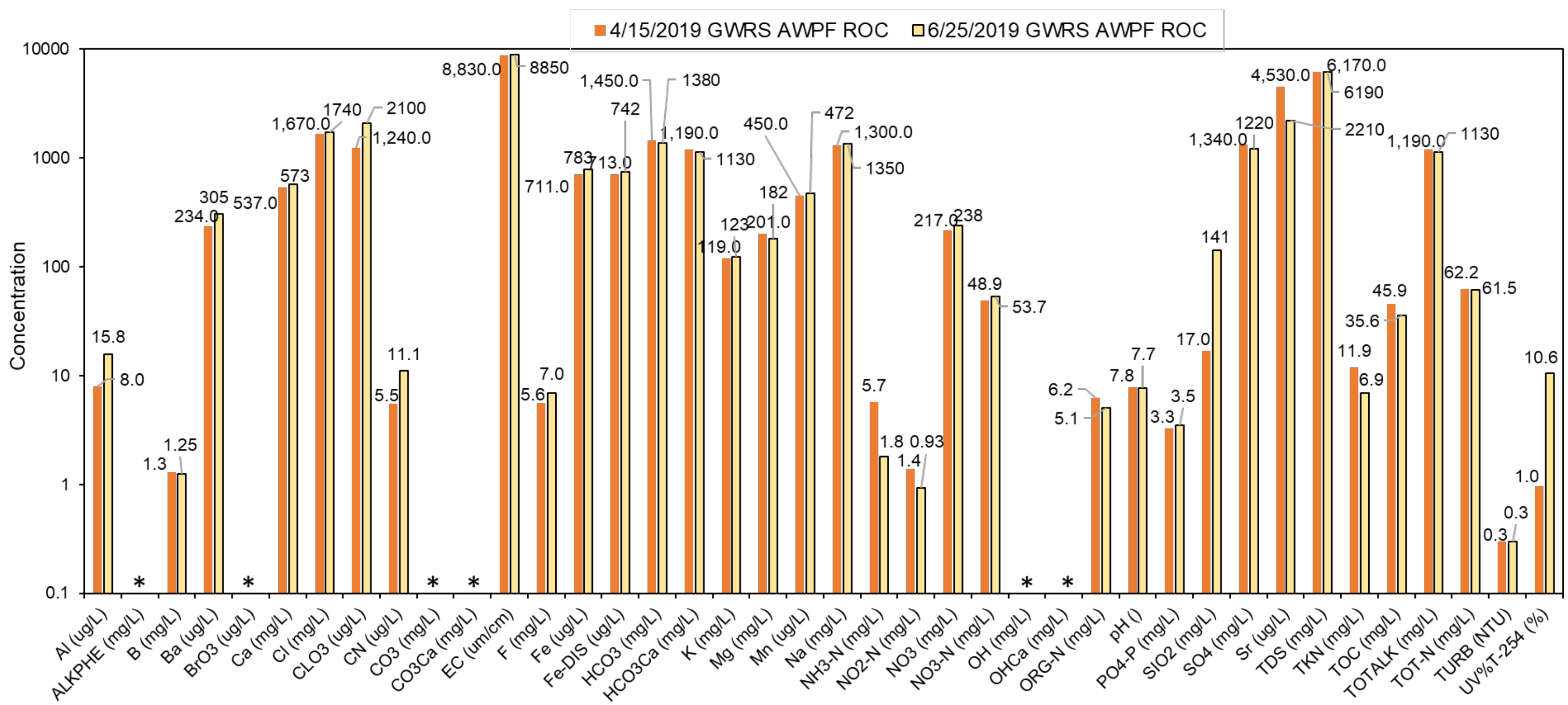

Figure H-31. Values of a list of inorganic species; concentration and physical properties of GWRS ROC (feed) in GWRS AWPF ROC samples. Based on water quality samples collected in 4/15/2019 and 6/25/2019. * Indicates ND in sample (below reported detection limit).

Appendix I

Excitation Emission Matrices

Figures I-1 through I-3 and Tables I-1 and I-2 present information on experimental excitation emission matrices for AWPF ROC, CCRO permeate, and FO-RO permeate for the June 25, 2019 water sampling.

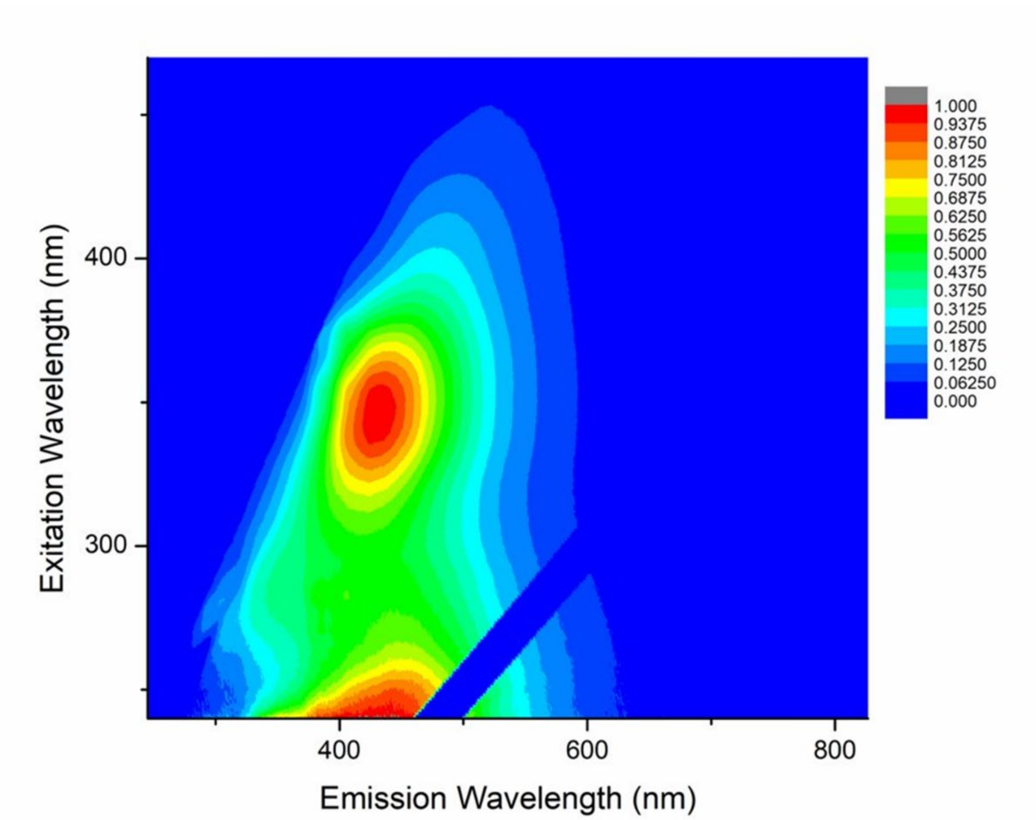

Figure I-1. Excitation emission matrices for AWPF ROC (June 25, 2019 sampling data)

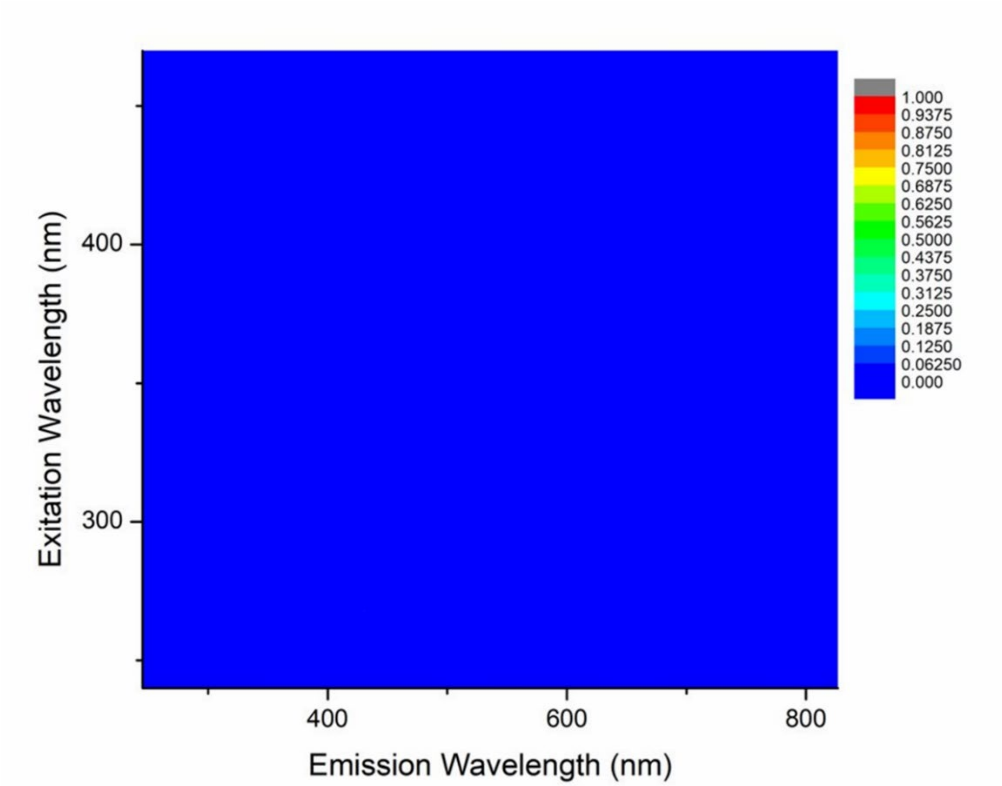

Figure I-2. Excitation emission matrices for CCRO ROP (June 25, 2019 sampling data)

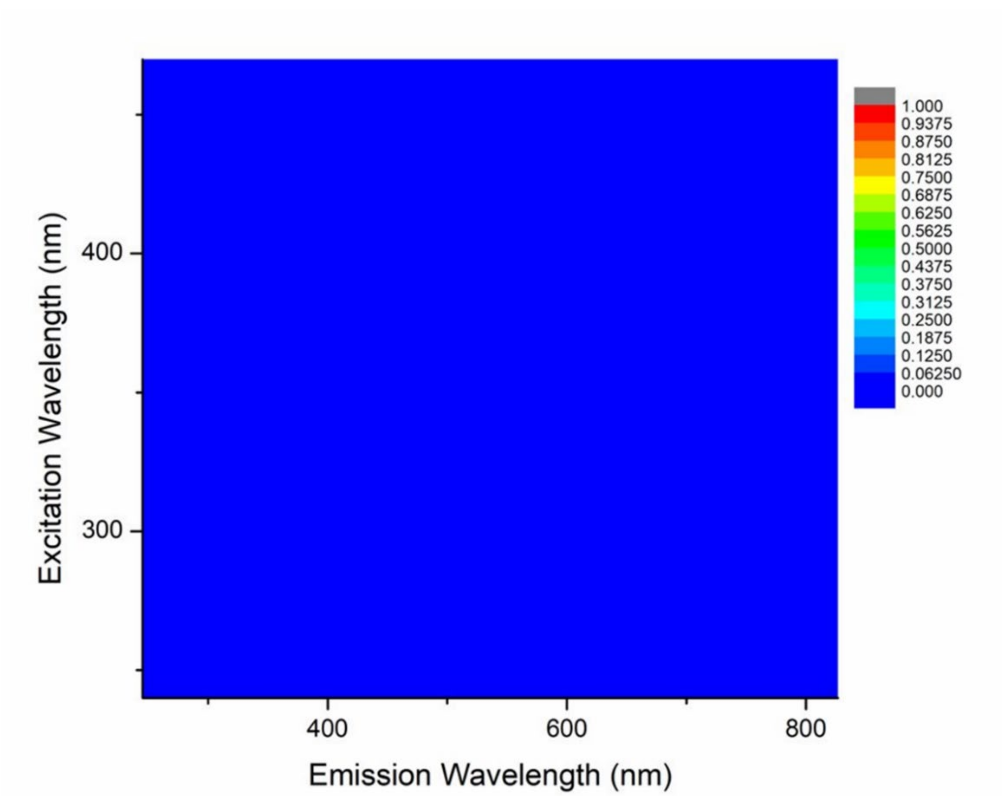

Figure I-3. Excitation emission matrices for FO-RO ROP (June 25, 2019 sampling data)

Table I-1. Summary of fluorescence peaks (June 25, 2019 sampling data)

Peak	Ex. (nm)	Em. (nm)	AWPF ROC (AFU[1])	CCRO ROP (AFU[1])	FO-RO ROP (AFU[1])
Proteins	280	331	2.032	0.0031	0.002
Humics	342	436	2.578	0.0025	0
A	260	450	2.912	-0.0004	-0.001
C	330	450	2.2	0.003	0.001
M	270-290	330-350	2.118	0.0029	0.002
T	275	340	2.167	0.004	0.004

[1]AFU = Arbitrary fluorescence units based on normalization to Raman peak area

Table I-2. Summary of regional fluorescence intensities (June 25, 2019 sampling data)

Region	ROC (AFU)	CCRO ROP (AFU)	FO-RO ROP (AFU)
Total	137061	111	63
Region I[1]	57203	63	38
Region II[2]	50543	26	15
Region III[3]	29315	21	10

.[1] $EX_{240-300}/Em_{280-390}$ Soluble microbial products and proteins

[2.] $EX_{240-300}/Em_{390-580}$ Fulvic-like acid compounds

[3.] $EX_{300-470}/Em_{317-580}$ Humic-like acid compounds

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Appendix J

Supplemental Information for the Microbial Tasks

Methodology for buffering of MS coliphage for die-off assessment

Samples taken from the CCRO pilot unit were carefully split into two bottles, one unbuffered fraction and another buffered fraction to be sent for analysis by the MSU laboratory. Buffered solutions were supplemented with a potassium phosphate and magnesium chloride solution. Upon arrival, MSU staff divided each buffered and unbuffered grab sample to measure native and spiked MS coliphage at various time intervals while stored at 4°C to mimic sample delivery. Measurements were taken at the 0-, 6-, and 24-hour marks, where 0 represents the time of spiked MS addition, using EPA Method 1602.

To prepare the buffering agent, a solution of 0.1 M MgCl2 and 0.18 M KH2PO4, pH = 7.2 was first prepared separately in glass bottles by sterile filtration. A 1:4 vol/vol working solution of KH2PO4:MgCl2 was premixed in a sterile 50 mL falcon tube immediately prior to addition to each grab sample. After grab sample collection, and upon confirming that all total residual chlorine (chloramines) had been quenched with 50 mg/L sodium thiosulfate, 1.0 mL of the 1:4 KH2PO4:MgCl2 solution was added to a 400 mL grab sample in 500 µl increments until an electrical conductivity of 300 µS was recorded. At this stage, samples were preserved between 2 and 10°C and shipped to MSU for analysis.

Methodology for MS challenge Test

Three MS coliphage seeding events were completed to evaluate the performance of the CCRO and FO-RO pilot units. To prepare each MS seeding event, a spiked solution was prepared by mixing concentrated MS coliphage (1011 PFU/mL), supplied by IEH-BioVir Laboratories, into a 400-gallon or 250-gallon feed tank for CCRO and FO-RO, respectively. Upon mixing, the target concentration of 108 PFU/mL was set to reliably observe up to an 8-log removal of MS coliphage using EPA Method 1602, which has a limit of detection of 0.1 PFU/ml.

To prepare each pilot unit for the challenge test, valves that feed GWRS RO concentrate into each pilot feed tank were closed. This prevented undesirable dilution of MS coliphage during mixing. With the pilot on standby, MS coliphage concentrate was then mixed into each feed tank with a PVC plunger as a mixing tool for approximately 20 minutes prior to pilot start-up. For seeding events 2 and 3, mixing MS coliphage within the tank continued throughout the sample collection period.

Since the addition of MS coliphage concentrate required each pilot unit to remain on standby during the mixing step, the sampling procedure varied slightly depending on the initiation sequence of each pilot unit. Grab samples from the FO-RO pilot unit were taken after an initial equilibration period of the two-membrane system and draw solution, approximately 40 minutes after startup. Samples from the CCRO pilot unit were taken after an initial startup sequence and after the completion of one full cycle. For all sampling locations (Figure 11), duplicate samples were collected. All grab samples were immediately dechlorinated with 50 mg/L of sodium thiosulfate to avoid MS coliphage degradation due to chlorination.

Appendix K

Additional Details for UV-AOP Experiments

Both UV-AOP pilot tests were conducted in batch mode. RO permeate (240 gal) from the FO-RO unit was collected over an extended period of time (~14 hours) due to the slow rate that the small pilot produced product water. As a result, permeate from the FO-RO unit sat for an extended period before the experiment was started. Enough CCRO permeate from the larger pilot unit could be generated in 1 to 2 hours. However, under both conditions, monochloramine in the RO permeate (near pH 6) disproportionated to dichloramine, which is favored to form below pH 6. This shift in speciation to dichloramine was evident based on the measured total chlorine and monochloramine in the CCRO and FO-RO permeates (Table K-1). Monochloramine only accounted for 26 percent of the total chlorine in the CCRO permeate and 14 percent of the total chlorine in FO permeate. Both concentrations of monochloramine were far less than the 60 to 70 percent normally measured in RO permeate from the AWPF.

Operation of the pilot UV reactor to emulate the performance of the full-scale UV reactors, i.e., a flow rate of 6 gpm with 3 mg/L H_2O_2, typically results in the loss of 60 percent of the total chlorine from the permeate. However, only 37 percent and 30 percent of the total chlorine in the CCRO and FO permeate, respectively, was consumed across the reactor under these conditions. These results were a direct reflection of the above-described chloramine speciation. Dichloramine ($\varepsilon_{254\ nm,\ NHCl2}$ = 136 $M^{-1}cm^{-1}$) absorbs significantly less light at 254 nm than monochloramine ($\varepsilon_{254\ nm,\ NH2Cl}$ = 371 $M^{-1}cm^{-1}$; Zhang et al. 2019). While the quantum yield of $NHCl_2$ (0.75) photolysis is greater than for NH_2Cl (0.35), it did not significantly impact the loss of total chlorine across the UV/H_2O_2 AOP under conditions of the two studies.

Table K-1. Pilot CCRO and FO-RO permeate (pilot UV-AOP feed water) and pilot UV-AOP product water quality

Pilot Test Date	Sample	Total Cl_2 (ng/L)[1]	NH_2Cl (mg/L)	H_2O_2 (mg/L)	UVT (@254 nm)
June 24, 2019	CCRO UVF	1.6	0.49 (30%)[2]	3.0	98.5
	CCRO UVP	0.9	0.23 (26%)	2.7	99.4
	CCRO % Consumed Across UV-AOP	44%	53%	12%	--
	FO UVF	1.5	0.26 (17%)	3.0	99.0
	FO UVP	1.0	0.15 (15%)	2.8	100
	FO % Consumed Across UV-AOP	33%	42%	6%	--
	CCRO UVF	1.3	0.15 (12%)[2]	3.0	98.7

Pilot Test Date	Sample	Total Cl_2 (ng/L)[1]	NH_2Cl (mg/L)	H_2O_2 (mg/L)	UVT (@254 nm)
August 26, 2019	CCRO UVP	1.0	0.10 (10%)	2.7	99.2
	CCRO % Consumed Across UV-AOP	23%	33%	12%	--
	FO UVF	1.3	0.29 (22%)	2.8	98.7
	FO UVP	1.0	0.16 (16%)	2.7	99.1
	FO % Consumed Across UV-AOP	23%	45%	4%	--

[1]Corrected concentration for 10% H2O2 contribution to result.

[2]Percentage monochloramine of total chlorine.

Appendix L

Schematics and Flow Rate Estimation for Hypothetical 10-MGD and 20-MGD FO-RO and CCRO System Design

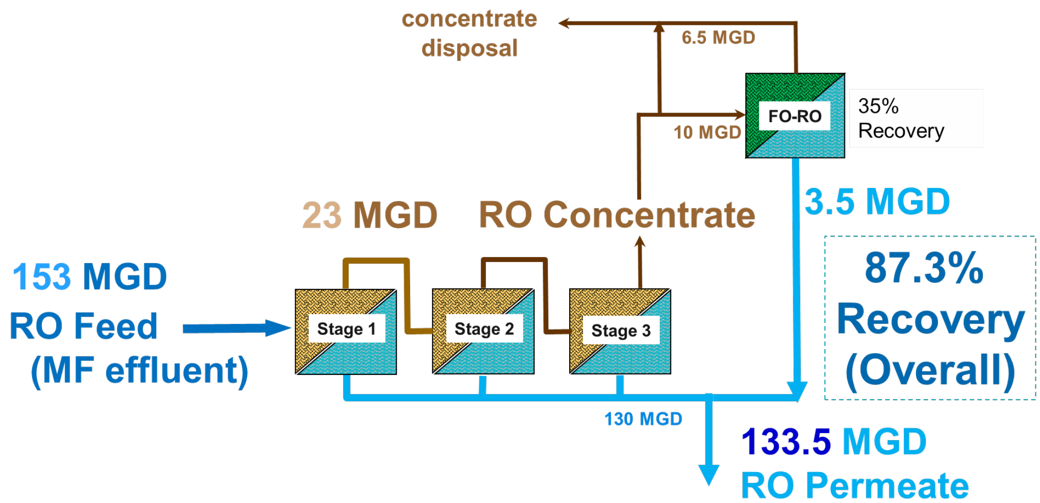

Figure L-1. Hypothetical full-scale 10-mgd FO-RO design

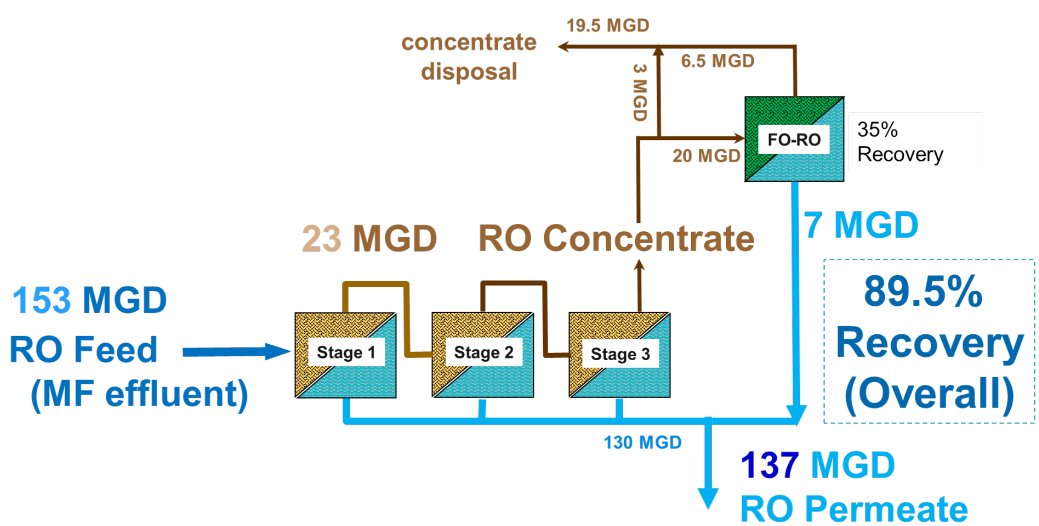

Figure L-2. Hypothetical full-scale 20-mgd FO-RO design

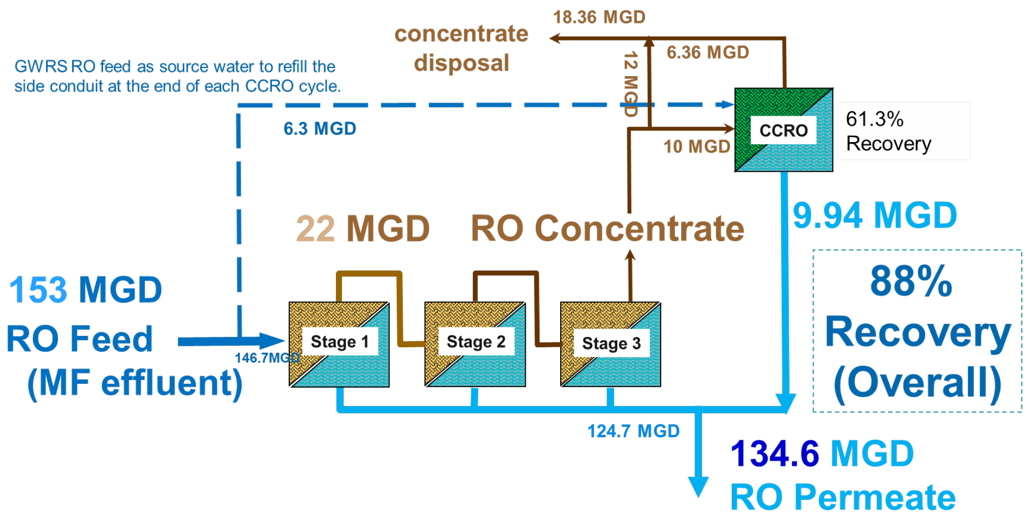

Figure L-3. Hypothetical full-scale 10-mgd CCRO design

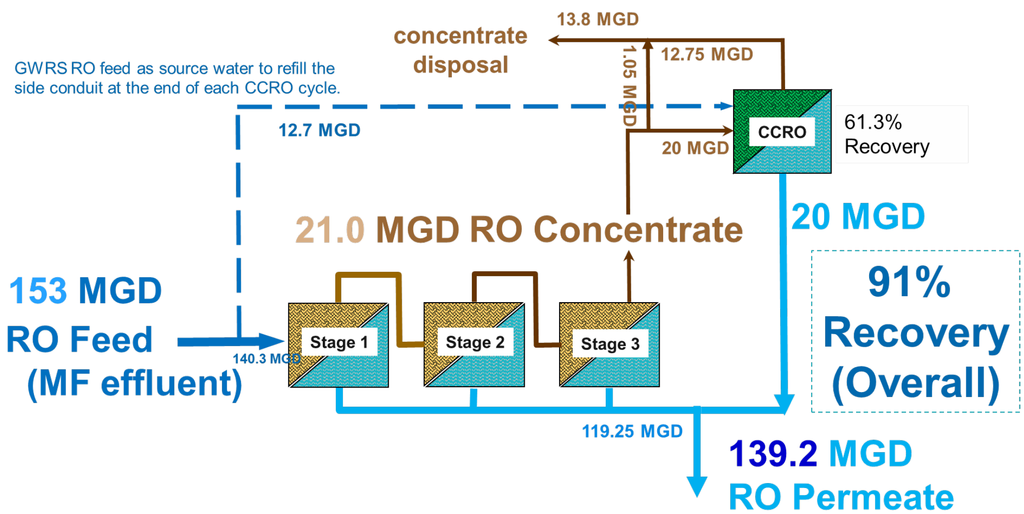

Figure L-4. Hypothetical full-scale 20-mgd CCRO design

Appendix M

Preliminary Cost and Footprint Evaluation of Two Concentrate Treatment Technologies for the Groundwater Replenishment System (Carollo Report)

Orange County Water District

PRELIMINARY COST AND FOOTPRINT EVALUATION OF TWO CONCENTRATE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

FINAL | December 2019

Orange County Water District

PRELIMINARY COST AND FOOTPRINT EVALUATION OF TWO CONCENTRATE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

FINAL | December 2019

Carollo Project No. 11266A.00

REGISTERED PROFESSIONAL ENGINEER
GRAHAM J.G. JUBY
No. 67217
CIVIL
STATE OF CALIFORNIA

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Abbreviations

AACE	Association for the Advancement of Cost Engineering
AF	acre foot
AFY	acre-feet per year
AOP	advanced oxidation process
Carollo	Carollo Engineers, Inc.
CCRO	closed circuit reverse osmosis
CIP	clean-in-place
CP	circulation pump
DS	draw solution
FO	forward osmosis
FRP	fiberglass reinforced plastic
FS	feed solution
ft	feet
GWRS	Groundwater Replenishment System
hp	horsepower
HPP	high-pressure pump
µg/L	micrograms per liter
MF	microfiltration
mgd	million gallons per day
mg/L	milligrams per liter
NaCl	salt
O&M	operation and maintenance
OCSD	Orange County Sanitation District
OCWD	Orange County Water District
PFD	process flow diagram
PFO	Porifera forward osmosis
PRO	primary reverse osmosis
psi	pounds per square inch
RO	reverse osmosis
ROC	reverse osmosis concentrate
SC	side conduit
SWRO	seawater reverse osmosis
USBR	US Bureau of Reclamation
UV	ultraviolet
VFD	variable frequency drive

Section 1

PRELIMINARY COST AND FOOTPRINT EVALUATION OF TWO CONCENTRATE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

1.1 Introduction

The Orange County Water District (OCWD) Groundwater Replenishment System (GWRS) initiated the Final Expansion Project in September 2016. The Final Expansion Project is the build-out capacity of the GWRS facility that treats secondary effluent from Orange County Sanitation District (OCSD) to drinking water standards for groundwater replenishment into the seawater intrusion barrier and in north and central Orange County.

The current GWRS facility produces 100 million gallons per day (mgd) of advanced treated water. The build-out treatment capacity increases water production to a total of 130 mgd. When expanded to its full capacity of 130 mgd, concentrate flow from GWRS' existing 3-stage, 85 percent recovery reverse osmosis (RO) system will increase from 17 mgd to 23 mgd.

OCWD received funding from the US Bureau of Reclamation (USBR) to pilot test two different RO concentrate treatment methods: Closed Circuit RO (CCRO) technology and forward osmosis (FO). The objective of the pilot study is to determine the feasibility of recovering 50 to 60 percent of the feed water (GWRS concentrate) as product to be blended with permeate from the primary GWRS RO process, upstream of the ultraviolet (UV)/advanced oxidation process (AOP). This would increase the overall recovery rate and therefore the daily recharge water production rate of GWRS would increase above 130 mgd.

1.2 Purpose

The purpose of this report is to estimate the cost and footprint for the two treatment alternatives for recovery of a portion of the RO concentrate and increase GWRS purified water production. The report includes a description and planning level capital and operation and maintenance (O&M) cost estimates of the two treatment systems. Cost estimates are focused on a comparison of the concentrate treatment technologies only. There would be additional capital and O&M costs associated with downstream treatment in the UV/AOP system, post-stabilization and for final pumping, which have not been included here. In addition, preliminary plant layouts were developed, to determine space requirements for the alternatives.

1.3 Basis of Cost Estimate and Methodology

Planning level capital, O&M, and life-cycle costs for 10- and 20-mgd systems were developed for the two treatment alternatives. Capital costs were estimated for the internal plant pumping and pipeline requirements. Estimated costs are presented in the following sections and detailed cost estimates can be found in Appendix A.

1.3.1 Cost Estimate Classification

All project costs associated with the two alternative systems have been prepared as Class 5 cost estimates, in accordance with the Association for the Advancement of Cost Engineering (AACE) International's definitions of the five "class estimates" in AACE International Recommended Practice No. 18R-97. The expected accuracy of any estimate included herein is 50 percent over the estimate to 30 percent under the estimate.

1.3.2 Cost Assumptions

1.3.2.1 Capital Cost Assumptions

Capital costs consist of all items that will be constructed/purchased for the evaluated alternatives. The direct cost of each process area was based on the following:

- Vendor-quoted information. The cost of major equipment for the CCRO system was obtained from Desalitech. FO system cost estimates were obtained from Porifera.
- Historical costs from other Carollo Engineers, Inc. (Carollo) projects or scale-up or scale-down of similar sized projects.

For most projects, depending on applicability, general factors are added to the direct costs derived from the information listed above. These factors include the following:

1. **General Site Work, Electrical, and Instrumentation:** These costs were estimated as percentages of the subtotal equipment cost. Typical percentage are 7, 10, and 8 percent, respectively, for general site work, electrical, and instrumentation.
2. **Project Contingency:** An amount added to the construction cost estimate to cover the cost of undefined project elements, to reduce risk of underestimation. The contingency usually ranges from 0 to 30 percent, depending on the level of development of the design and the potential project risks for unknown factors. A contingency of 30 percent of the total direct cost was used in this case, due to the planning nature of the evaluation and also due to the intended application of the process to treat RO concentrate.
3. **General Conditions:** Includes cost of mobilization/demobilization, bonds and insurance, contractor temporary project facilities and supervisory personnel, testing, start-up, and other constraints. Calculated as 10 percent of the total direct cost plus contingency.
4. **General Contractor Overhead and Profit:** Refers to general contractor’s home office overhead and profit. It was estimated to be 15 percent of the subtotal of above costs.
5. **Sales Tax:** Estimated at 7.75 percent on materials, based on material cost equaling 50 percent of the total direct cost and contingency.
6. **Engineering, Management, and Legal:** Encompasses engineering, planning, design and construction oversight costs, legal fees, and administration expenses to oversee the project from planning through construction. For this project, a factor of 30 percent of the total construction cost was used, including all above items.

1.3.2.2 O&M Cost Assumptions

O&M costs include the labor, power cost, chemicals, membrane replacement, and an allowance for on-going maintenance needs. O&M cost estimates were based on the following:

- Historical costs from recent Carollo projects.

- Pilot study experience for chemical usage.
- Electrical power usage based on conceptual design criteria and pressure estimates from the pilot study.
- Average electrical power cost of $0.085/kWh.
- Labor cost estimates from OCWD.
- Information from OCWD regarding pilot plant cleaning frequency and chemical use.

The cost estimates were generally based on applying the above information to flow diagrams for main process systems that have been developed for each alternative. O&M cost estimates for UV/AOP treatment, post treatment stabilization and final pumping were not included

1.4 Treatment Alternatives

In this report, the RO concentrate recovery facility was evaluated at two capacities: a system capable of treating either 10 mgd or 20 mgd of GWRS RO concentrate. Thus, 10 or 20 mgd refers to the RO concentrate feed volume to the treatment system (not the permeate/production from the treatment system). These two capacities were selected for the purpose of this planning-level cost estimate recognizing that after GWRS Final Expansion, GWRS will produce approximately 23 mgd of RO concentrate; however, a RO concentrate recovery facility would not necessarily be sized to treat the maximum flows and would instead be based on a production target.

1.4.1 Identification of Alternatives

The two treatment alternatives evaluated for recovering additional water from the GWRS RO concentrate were:

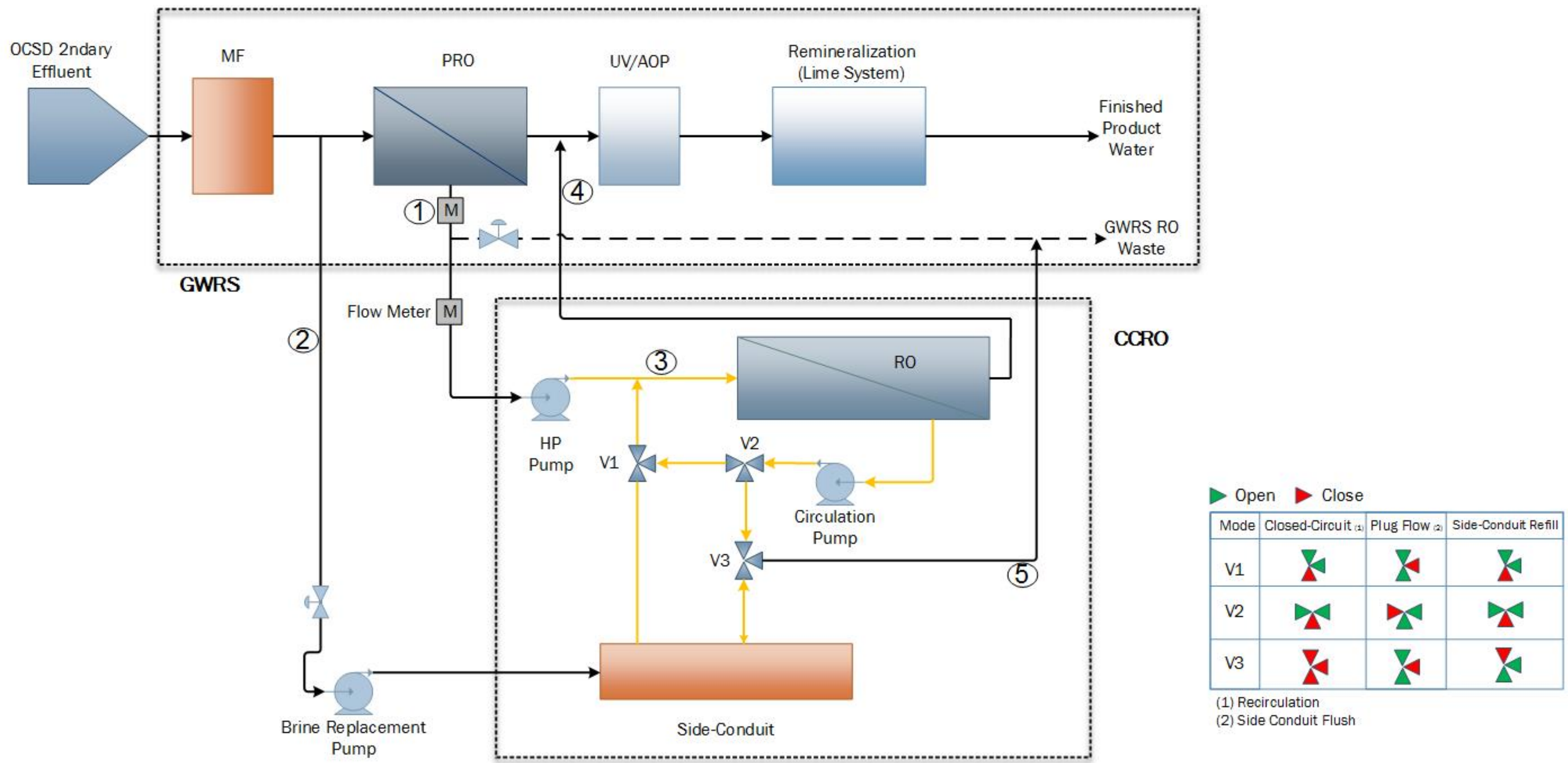
1. **CCRO:** Based on the pilot testing, Desalitech is proposing multiple 1-mgd trains for the 10- and 20-mgd alternatives to treat GWRS RO concentrate. The proposed CCRO system would be designed to treat the Primary RO (PRO) concentrate, while the Side Conduit (SC) will be filled with primary RO feed.
2. **FO:** The FO system offered by Porifera Forward Osmosis (PFO) was also based on the pilot testing. It would include FO membrane stacks that would receive the GWRS RO concentrate, as well as a conventional sea-water-type RO system to recover FO permeate that is drawn into a high salinity sodium chloride solution. The 20-mgd configuration would basically be a duplication of the 10-mgd configuration.

Each treatment approach is discussed in more detail in the sections that follow, including estimates of site footprint requirements for facilities to treat both 10 and 20 mgd of GWRS RO concentrate, and capital and operating cost estimates for each.

1.5 CCRO

1.5.1 Process Description for CCRO

The CCRO process flow diagram (PFD) for a 1-mgd module configuration is illustrated on Figure 1. Ten and twenty modules would operate in parallel to reach the desired treatment capacity of 10 and 20 mgd, respectively. A high-pressure pump (HPP) draws suction from the primary RO concentrate stream and feeds a closed loop comprised of a single-stage of membranes and a circulation pump (CP). Permeate is produced at a rate equal to flow rate of the HPP. The CP has been sized to allow for 65 gpm of cross flow per pressure vessel (therefore, the circulation pump flow rate is equal to 65 gpm x the number pressure vessels). When a desired recovery level is reached, brine is displaced with feed water from a hydrostatically



Capacity	10 MGD					20 MGD				
Stream Number	1	2	3	4	5	1	2	3	4	5
Description	Primary RO Concentrate (ROC)	CCRO Side-Conduit Fill	CCRO Feed	CCRO Total Permate	CCRO Concentrate	Primary RO Concentrate (ROC)	CCRO Side-Conduit Fill	CCRO Feed	CCRO Total Permate	CCRO Concentrate
Flow Rate (mgd)	17-23	6.3	10	10	8.5	17-23	12.7	20	20	17
Flow Rate (gpm)	11,806-15,972	4375	6,944.44	6,944.44	5,902.78	11,806-15,972	8819	13,888.9	13,888.89	11,805.56
Pressure (psi)	15-20	46	220	0.8	95	15-20	46	220	0.8	95
Conductivity (ms/cm)	9 to 12	2.5	9 to 12	0.07	16.5	9 to 12	2.5	9 to 12	0.07	16.5

Figure 1 CCRO Treatment Process Diagram for a 1-mgd Module Configuration

pre-pressurized side conduit (SC). The exchange of brine and feed water is executed without stopping the HPP, the CP, or the production of permeate. The initial membrane feed pressure of each CCRO sequence is just above the osmotic pressure of the feed water and the maximum pressure is just above the osmotic pressure of the final brine.

During the "recirculation" mode, valves V1, V2, and V3 would be in the positions shown on Figure 1. All concentrate produced by the RO membranes would be recycled and there would be no waste stream; and the side conduit would be isolated. During the next part of the cycle, "side conduit flush", V1 would switch to allow flow to enter from the side conduit. V2 and V3 would also adjust positions so that the concentrate stream is now directed into the side conduit to displace the solution that was there. Once the side conduit is filled with concentrate, the valves would switch again. V1 and V2 would return to their normal operating positions and V3 would switch to allow the contents of the side conduit to be directed to waste. This would be achieved by microfiltration (MF) effluent (RO feed water) being pumped into the side conduit, ready for the next cycle.

Based on the results of pilot testing conducted by OCWD, the cycle time for the CCRO system would be about 10 minutes. This would include about 9 minutes for "recirculation" mode, followed by 1 minute for "side conduit flush" mode. For the purposes of this evaluation it was assumed that these times would apply to the full scale systems. During the 10 minute cycle, permeate production would continue uninterrupted. At the completion of the side conduit flush, the side conduit would be refilled with MF effluent (RO feed water), as mentioned above.

Preliminary design criteria for the full scale CCRO systems are shown in Table 1. There are two factors used to determine the recovery of the CCRO system. The apparent recovery is the ratio of the permeate volume to the total volume, where the total volume is the CCRO permeate volume plus the waste stream volume, or the permeate volume plus the side-conduit feed flowrate

$$Apparent\ Recovery\ (\%) = \frac{\text{CCRO Permeate Flow}}{\text{CCRO Permeate Flow} + \text{CCRO Concentrate Flow}}\, x\ 100$$

As shown in Table 1, the apparent recovery is 61.3 percent. The true recovery takes into account that a certain volume of RO Feed is bypassed to the CCRO system. So, for the 10-mgd example, the equations below show the calculation:

$$True\ Recovery\ (\%) = \frac{\text{CCRO Permeate Flow}}{\text{RO Concentrate Flow} + \text{Side Conduit Flow}}\, x\ 100$$

$$True\ Recovery\ (\%) = \frac{10\ \text{mgd}}{23\ \text{mgd} + 6.3\ \text{mgd}}\, x\ 100$$

$$True\ Recovery\ (\%) = 34.1\ \%$$

The GWRS Overall Recovery calculates the recovery of the entire GWRS system downstream of the MF process. In this case, the calculation for the 10-mgd example would be:

$$GWRS\ Overall\ Recovery\ (\%) = \frac{\text{Total RO and CCRO Permeate Flow}}{\text{MF Effluent Flow}}\, x\ 100$$

$$GWRS\ Overall\ Recovery\ (\%) = \frac{124.7\ \text{mgd} + 10\ \text{mgd}}{153\ \text{mgd}}\, x\ 100$$

$$GWRS\ Overall\ Recovery\ (\%) = 88.0\ \%$$

Table 1 Preliminary Design Criteria for CCRO System

Description	Value
CCRO System Module	
CCRO Skid Capacity, mgd	1.0
Number of primary pressure vessels	80
Number of 8 x 40 inch elements	400
Number of side conduit pressure vessels	40
Permeate Flux, gfd	6.4
One pass Recovery, %	8.1
Side Conduit Volume, gal	2,796
CCRO Cycle	
Total Cycle Time, min	6.4
Recirculation Mode, % cycle time/min	90/9
Side Conduit Flush Mode, % cycle time/min	10/1
Max Side Conduit Fill Time, min	5
High-Pressure Pump	
Flow Rate @ 200 - 300 pounds per square inch (psi), gpm	694
Recirculation Pump (one of six)	
Flow Rate @ 200 - 300 psi, gpm	867
Common Brine Replacement Pump(1)	
Flow Rate @ 30 psi, gpm (10 mgd system)	1,677
Flow Rate @ 30 psi, gpm (20 mgd system)	3,354
CCRO Recovery (based on 10-minute cycle time)	
Apparent Recovery, %	61.3
True (Net) Recovery(2), % (10 mgd; 20 mgd)	34.1; 56.0
GWRS Overall recovery, % (10 mgd; 20 mgd)	88.0; 91.0

Notes:
(1) The common brine replacement pump would provide side conduit refill capacity for all CCRO skids. It was assumed that up to 30 percent of the skids would be refilling simultaneously, based on a 10 minute total cycle time, and that the side conduit would need to fill within 5 minutes to allow for uninterrupted cycles.
(2) Actual or net recovery accounts for loss of GWRS primary RO system production due to a portion of the feed stream used for side conduit filling. This is the net amount of available RO concentrate recovered as "new" water.

Based on the results of piloting at OCWD, the CCRO system is expected to achieve an apparent recovery of 61.3 percent, as shown by the values in Table 1 and in the table of Figure 1. This would increase the overall recovery of GWRS from 85 percent to 88.0 percent, for the 10-mgd system, and produce an additional 4.7 mgd (5,260 acre-feet per year (AFY)) of recharge water. For the 20-mgd alternative, the overall recovery would increase to 91.0 percent and production would increase by 9.3 mgd (10,400 AFY).

1.5.2 Site Layout of Alternatives for CCRO

Conceptual site layouts were developed for CCRO facilities for 10- and 20-mgd primary RO concentrate feed flow rate options. The site layouts are preliminary and show the general footprints of unit operations on the project site. To develop the site layouts, the footprints of each process were estimated using rule of thumb parameters, vendor quotes, and previous projects. An aerial photograph of the existing site and facilities is presented on Figure 2.

Figure 2 Existing Site Layout

1.5.2.1 Treatment Alternative 1A – 10-mgd CCRO

The CCRO system would require the construction of facilities as previously described. Primary RO concentrate (ROC) is the required feed to the CCRO system, and to keep the facilities in reasonable proximity to each other, the CCRO treatment process could be located in the southwest corner of the facility near the primary RO building, that could provide the feed connection. A conceptual site layout for treatment Alternative 1A is shown on Figure 3 and Figure 4. As indicated, this alternative treatment train consists of ten 1-mgd CCRO skids, a common clean-in-place (CIP) skid, and an electrical room for the variable frequency drive (VFD) panels. The footprints are shown for a capacity of 10 mgd. The site layout indicates sufficient space at the location selected for the facility. The space between each CCRO skid was assumed to be 10 feet (ft) based on 40-inch RO elements. The proposed location of the new CCRO system building is shown on OCSD property. Negotiations with OCSD for use of this area would need to take place prior to any future project.

For the electrical building footprint, 6-pulse VFDs were assumed for the 25-, 40-, and 75-horsepower (hp) CCRO pumps. The VFD footprint required for each 1-mgd CCRO skid is 27 (ft^2) and 4 ft clear work space was assumed between each sets of VFDs.

A preliminary estimate of the pipeline systems that would be needed to convey the CCRO feed, SC refill, CCRO permeate, and CCRO brine stream were made. A conceptual yard piping layout for Alternative 1A is shown on Figure 5.

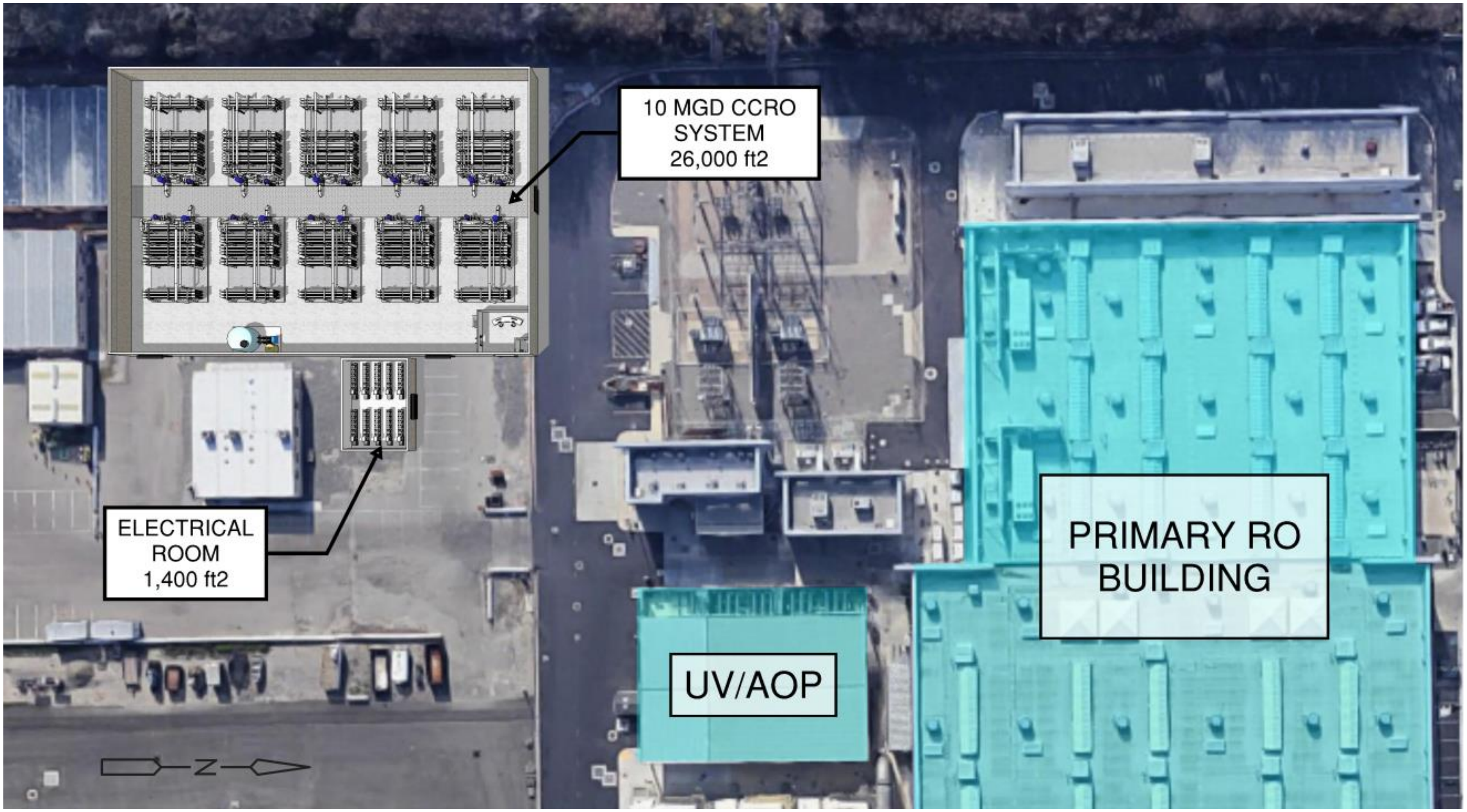


Figure 3 Alternative 1A Site Layout

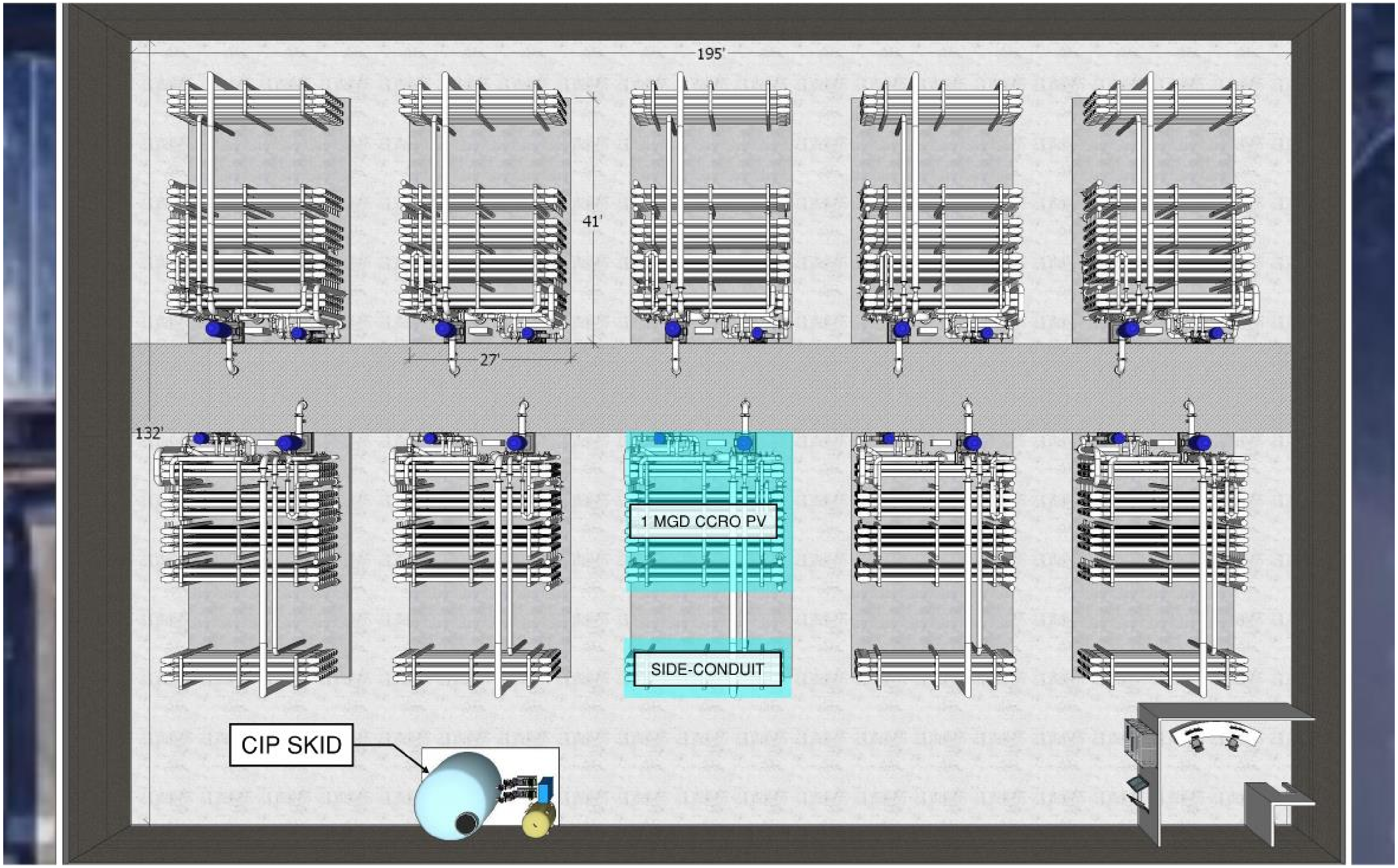


Figure 4 10-mgd CCRO System with Common CIP Skid

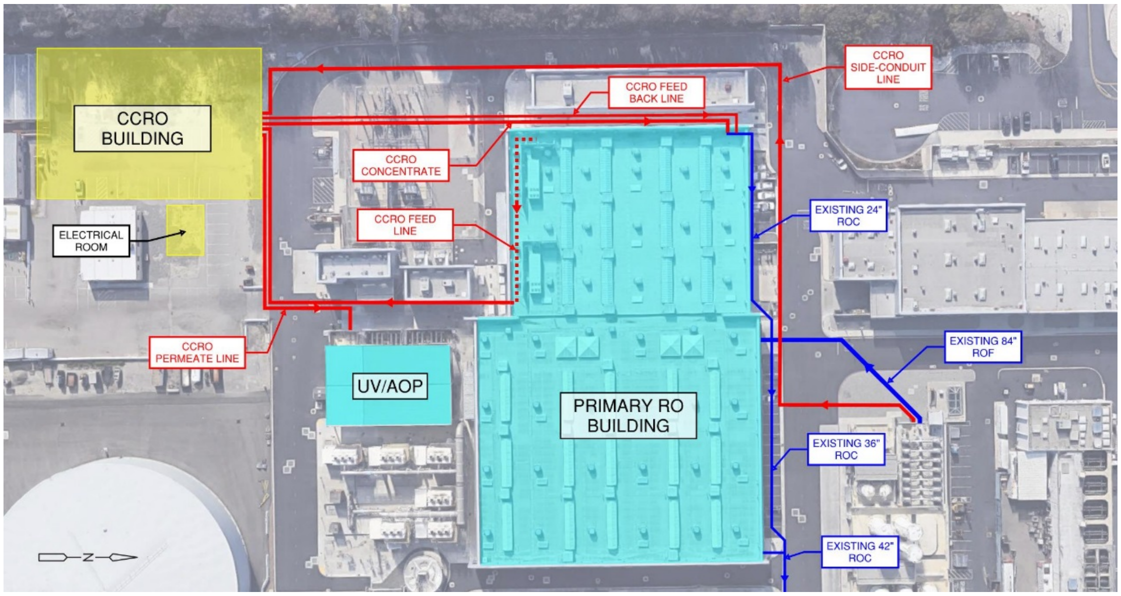


Figure 5 10-mgd CCRO Yard Piping

The pipeline material and preliminary estimates of the pipeline sizes are shown in Table 2. This information was used in the cost estimate.

Table 2 Pipeline Specification for 10-mgd CCRO

Pipeline	Size (inch)	Flow (mgd)	Material
CCRO Feed	24	10	HDPE
CCRO Permeate	24	10	HDPE
CCRO Concentrate	24	8.5	HDPE
Side-Conduit	24	8.5	HDPE

1.5.2.2 Treatment Alternative 1B – 20 mgd CCRO

Alternative 1B is similar to Alternative 1A except for the system capacity. In Alternative 1A, the treatment system included 10 CCRO skids in service; however for 20 mgd, 10 more CCRO skids would be required. A conceptual site layout for Treatment Alternative 1B is presented on Figure 6. As shown, the 20-mgd CCRO could be located in the southwest corner of the facility.

The pipeline materials and preliminary pipeline sizes are presented in Table 3. This information was used in the cost estimate.

Table 3 Pipeline Specification for 20-mgd CCRO

Pipeline	Size (inch)	Flow (mgd)	Material
CCRO Feed	36	20	HDPE
CCRO Permeate	36	20	HDPE
CCRO Concentrate	32	17	HDPE
Side-Conduit	32	17	HDPE

The electrical building was sized using the same assumptions used for Alternative 1A.

Alternative 1B would consist of twenty 1-mgd CCRO skids and a common electrical building. A conceptual yard piping layout for Alternative 1B is shown on Figure 7.

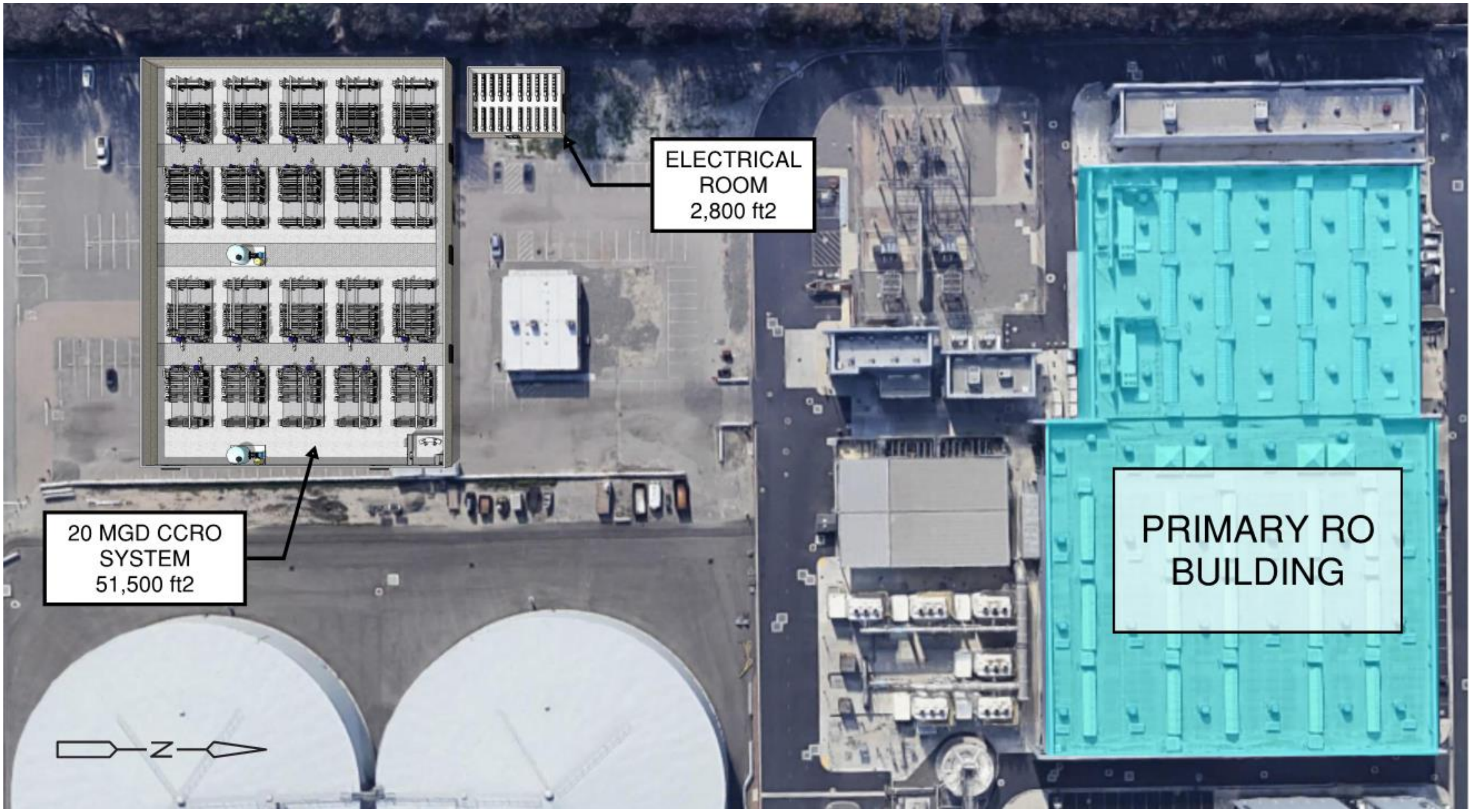


Figure 6 Alternative 1B Site Layout

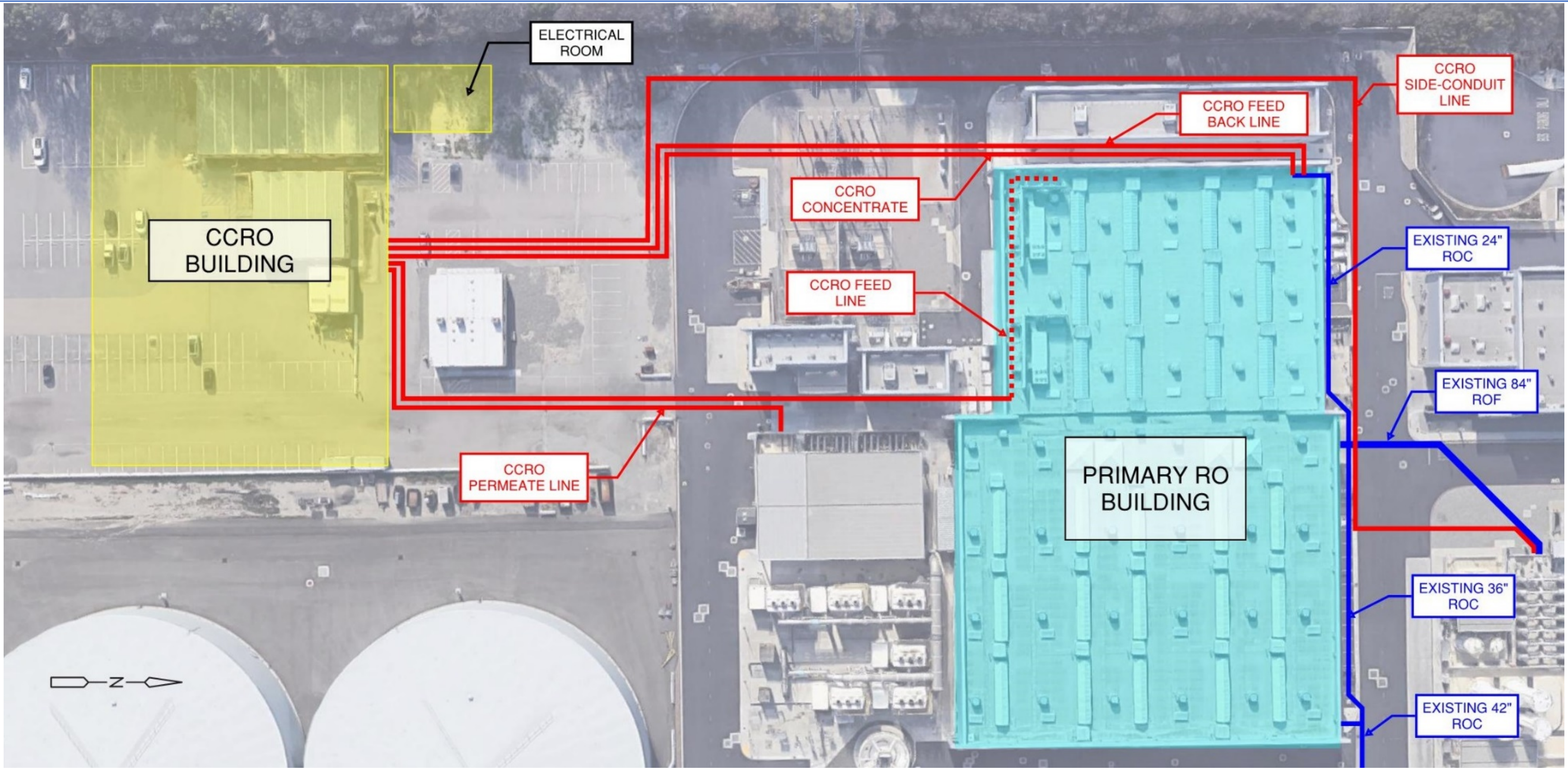


Figure 7 20-mgd CCRO Yard Piping

1.5.3 Capital Cost Estimate for CCRO

Preliminary project cost estimates were developed for the two alternatives based on the information presented above. Since each alternative has a different overall permeate flow rate, feed water flow requirements vary for each treatment train. Table 4 summarizes the alternative cost comparison. Appendix A includes detailed cost estimates. Costs are presented in 2019 dollars without escalation.

Table 4 CCRO Capital Cost Estimate for Treatment of 10 and 20 mgd of GWRS ROC

Description	Alternative 1A 10 mgd CCRO	Alternative 1B 20 mgd CCRO
Equipment(1)	$13,185,000	$26,370,000
Building/Structure(2)	$4,110,000	$8,145,000
Equipment Installation(3)	$6,500,000	$13,000,000
Site Work(4)	$1,354,000	$2,800,900
Subtotal - Direct Cost	$25,149,000	$50,315,900
Allowance for Electrical and Instrumentation(5)	$4,527,000	$9,057,000
Total Construction Cost(6)	**$50,297,000**	**$92,911,000**
Total Project Cost(7)	**$65,387,000**	**$120,785,000**
Project Unit Cost ($/AF)(8)	**809**	**756**

Notes:
(1) Equipment costs were provided by Desalitech.
(2) Based on footprint needs and $150 per ft^2 building cost estimate.
(3) Assumed to be 50 percent of equipment cost based on modular nature of equipment.
(4) Including grading, paving, yard pipes, and assumed to be 3 percent and 2 percent of equipment cost as CCRO piping and general site work respectively.
(5) Assumed to be 10 percent and 8 percent of equipment cost for electrical (including VFDs and wiring) and instrumentation for CCRO modules, respectively.
(6) Includes 30 percent contingency, contractor general conditions, and contractor overhead and profit.
(7) Includes a 30 percent allowance for engineering, construction management and legal costs. Totals may not sum due to rounding
(8) Calculated assuming a 30-year loan period at a fixed annual interest rate of 5 percent, and production of "new" product water: 5,260 AFY for 10 mgd system, and 10,400 AFY for 20 mgd system.

As shown in Table 4, the majority of the cost for the CCRO system would be for the supply and installation of the RO equipment.

1.5.4 O&M Cost Estimate for CCRO

Preliminary O&M cost estimates were developed for the each alternative. The O&M costs discussed in this report include operating a 10- and 20-mgd CCRO treatment system and are based on the findings of OCWD's pilot study. The O&M cost estimates include power, labor, chemicals, membrane replacement, and an allowance for equipment replacement costs. The O&M cost estimates are summarized in Table 5. Appendix B includes detailed cost estimates.

Table 5 CCRO O&M Cost Estimate for 10 and 20 mgd

Description	Alternative 1A 10 mgd CCRO	Alternative 1B 20 mgd CCRO
Annual Power Cost(1)	$712,800	$1,444,600
Annual Chemical Cost(2)	$558,200	$1,116,400
Annual Labor Cost(3)	$442,600	$442,600
Membranes Replacement Cost(4)	$376,000	$752,000

Description	Alternative 1A 10 mgd CCRO	Alternative 1B 20 mgd CCRO
Mechanical Maintenance and Miscellaneous(5)	$52,000	$92,000
Total Annual O&M Cost	$2,141,600	$3,847,600
Unit O&M Cost ($/AF)(6)	407	370

Notes:
(1) $0.085 kW/h is assumed as a unit price.
(2) Based on pilot testing and includes, high pH CIP.
(3) Assumes four full-time equivalent staff.
(4) Assumes a 5-year membrane lifetime.
(5) Assumes a 20-year useful life-time for major mechanical and electrical equipment, excluding membranes.
(6) Based on 5,260 and 10,400 AFY new water production for the 10 and 20 mgd systems, respectively.

1.5.5 Combined Unit Cost of "New" Water

Based on the unit capital and O&M costs presented in Tables 4 and 5, the combined cost of new water produced by a CCRO system is expected to range between $1,126 per acre foot (AF) to $1,216 per AF, for a system treating 20- and 10-mgd of RO concentrate, respectively. Again, for clarity, this cost excludes any costs associated with upsizing the downstream process to accommodate the additional flow

1.6 FO

1.6.1 Process Description for FO

FO is an emerging membrane technology with a range of possible water treatment applications. Almost no external hydraulic pressure is required to run the process. Potential FO applications are a function of the respective feed and draw solutions selected, and the water quality objectives. In FO, water is extracted from a lower osmotic pressure feed solution (FS), in this case the GWRS RO concentrate, into a higher osmotic pressure draw solution (DS), in this case a high-strength sodium chloride solution; the process is driven by the osmotic pressure difference between the two aqueous solutions on the opposite sides of the semi-permeable FO membrane and results in concentration of the FS and dilution of the DS.

In the current study, as mentioned, sodium chloride was chosen as the draw solution and seawater RO (SWRO) was chosen for the regeneration of the draw solution because of its high efficiency and suitability to treat different types of draw solutions. Because some salt leakage occurs across semi-permeable membranes, a portion of the draw solution must be blown down periodically to retain its purity. Therefore, a sodium chloride brine solution is added to the draw solution periodically as make-up. High-pressure pumps are required for the RO system.

System apparent recovery based on pilot study data is 30 to 35 percent and RO recovery is 87.5 percent. The FO PFD is shown on Figure 8, and Table 6 shows preliminary design criteria. The apparent recovery is the ratio of the FO system permeate volume leaving the RO process, to the total volume, where the total volume is the FO system feed, as shown by the equation below:

$$Apparent\ Recovery\ (\%) = \frac{\text{FO System Permeate Flow}}{\text{FO System Feed Flow}} x\ 100$$

Table 6 Preliminary Design Criteria for the FO System

Description	Value
FO System	
Design flux, gfd	
Membrane sheet dimensions (l x w), feet	4 x 4
Membrane area per PFO-1500 stack, ft^2	16,000
Membrane stacks for 10 mgd, 20 mgd	70, 140
Operating Recovery, %	30-35
Maximum Feed Pressure, psi	20
FO Concentrate flow Rate, gpm (10 mgd; 20 mgd)	4,167; 8,333
FO Concentrate TDS, milligrams per liter (mg/L)	16,500 - 18,000
Draw Solution System	
Draw Solution	NaCl
Draw Solution Concentration, g/L	18 – 20
Blowdown Rate, % of permeate	2
Salt make-up, t/d (10 mgd; 20 mgd)	13; 26
Draw Solution RO System	
Draw Solution Feed Flow Rate, mgd (10 mgd; 20 mgd)	8; 16
Recovery, %	87.5
Flux, gfd	8.2
RO Feed Pressure, psi	500
RO Feed Pump, hp	500
FO Brine Boost Pump System	
Flow Rate @30 psi, mgd (10 mgd; 20 mgd)	6; 12
Pump, hp	25
FO Recovery	
Apparent Recovery, %	30-35
GWRS Overall recovery, % (10 mgd; 20 mgd)	87.3; 89.5

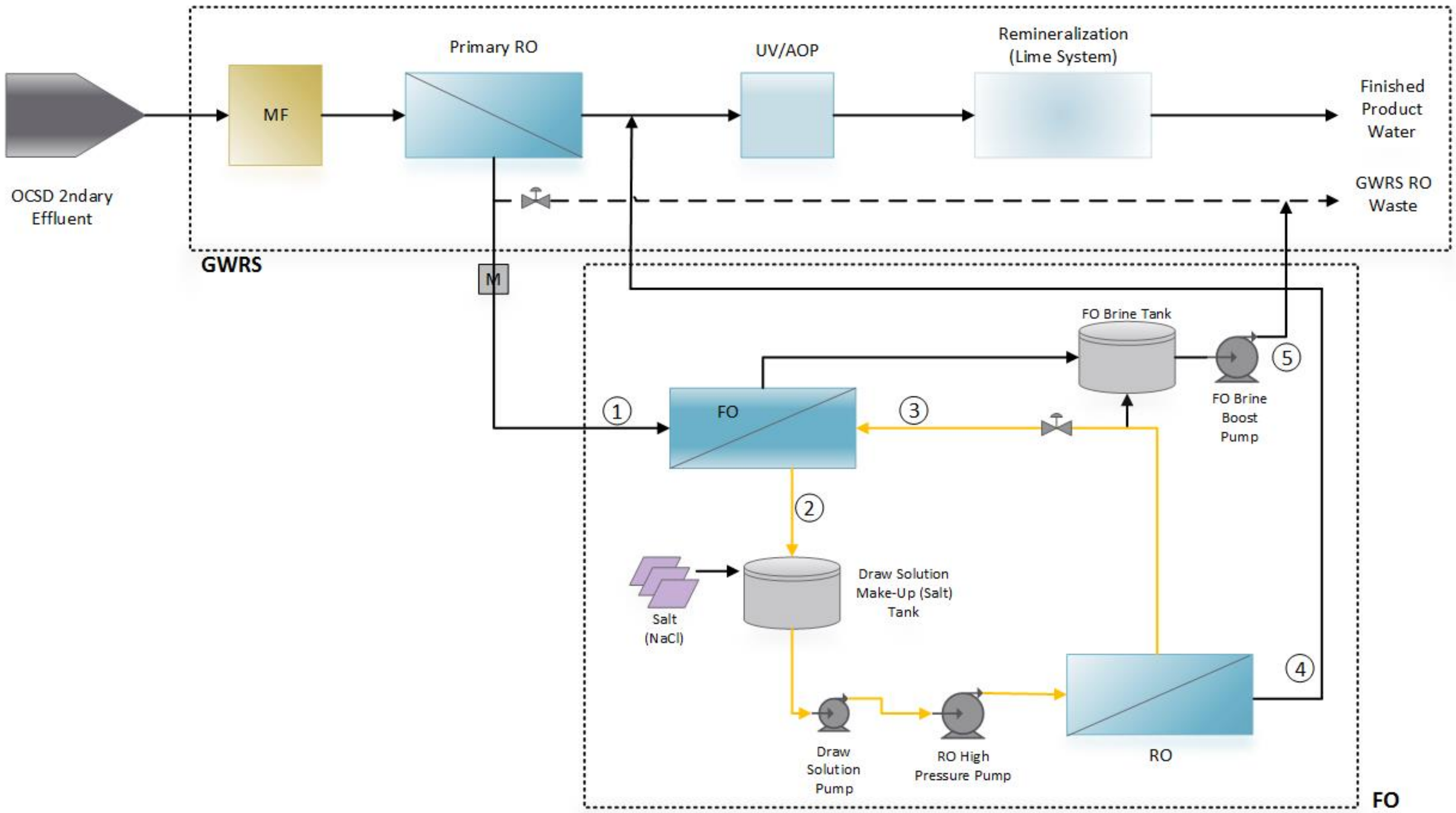
The FO system has a maximum operating pressure of 20 psi. Although the stacks do not result in much head loss, around 15 psi, the residual pressure would not be sufficient to convey the concentrate to the GWRS RO concentrate disposal point. Therefore, concentrate storage and transfer pumps would be required, as indicated on Figure 8.

1.6.2 Site Layout of Alternatives for FO

Conceptual site layouts were developed for the two different feed flow rates of 10 mgd and 20 mgd. The site layouts are preliminary and show the general footprint of each unit operation in a similar manner to those shown earlier for the CCRO treatment system.

1.6.2.1 Treatment Alternative 2A – 10-mgd FO

A conceptual site layout for Treatment Alternative 2A is presented on Figure 9. The primary ROC feed stream would be pumped from a primary RO building to the FO system. The residual pressure in the feed line to the FO membrane stacks would be sufficient to meet the head requirements, and a pressure reducing station may be need so as not to over pressurize the membrane stacks. As mentioned earlier, concentrate storage and transfer pumps will be needed to provide sufficient residual head downstream of the stacks to discharge the concentrate and RO blowdown to the ROC 24-inch pipeline.



Capacity	10 MGD					20 MGD				
Stream Number	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Description	FO Feed	FO Draw Out	FO Draw In	FO Total Permate	FO Reject	FO Feed	FO Draw Out	FO Draw In	FO Total Permate	FO Reject
Flow Rate (mgd)	10	8	4	3.5	6.5	20	16	8	7	13
Flow Rate (gpm)	6,944	5,556	2,778	2,431	4,514	13,889	11,111	5,556	4,861	9,028
Pressure (psi)	15-20	5	12	NA	5 to 20	15-20	5	12	NA	5 to 20
Conductivity (ms/cm)	9 to 12	27.5	30.5	0.35	27.5	9 to 12	27.5	30.5	0.35	27.5

Figure 8 FO PFD (based on assumed recovery of 35 percent)

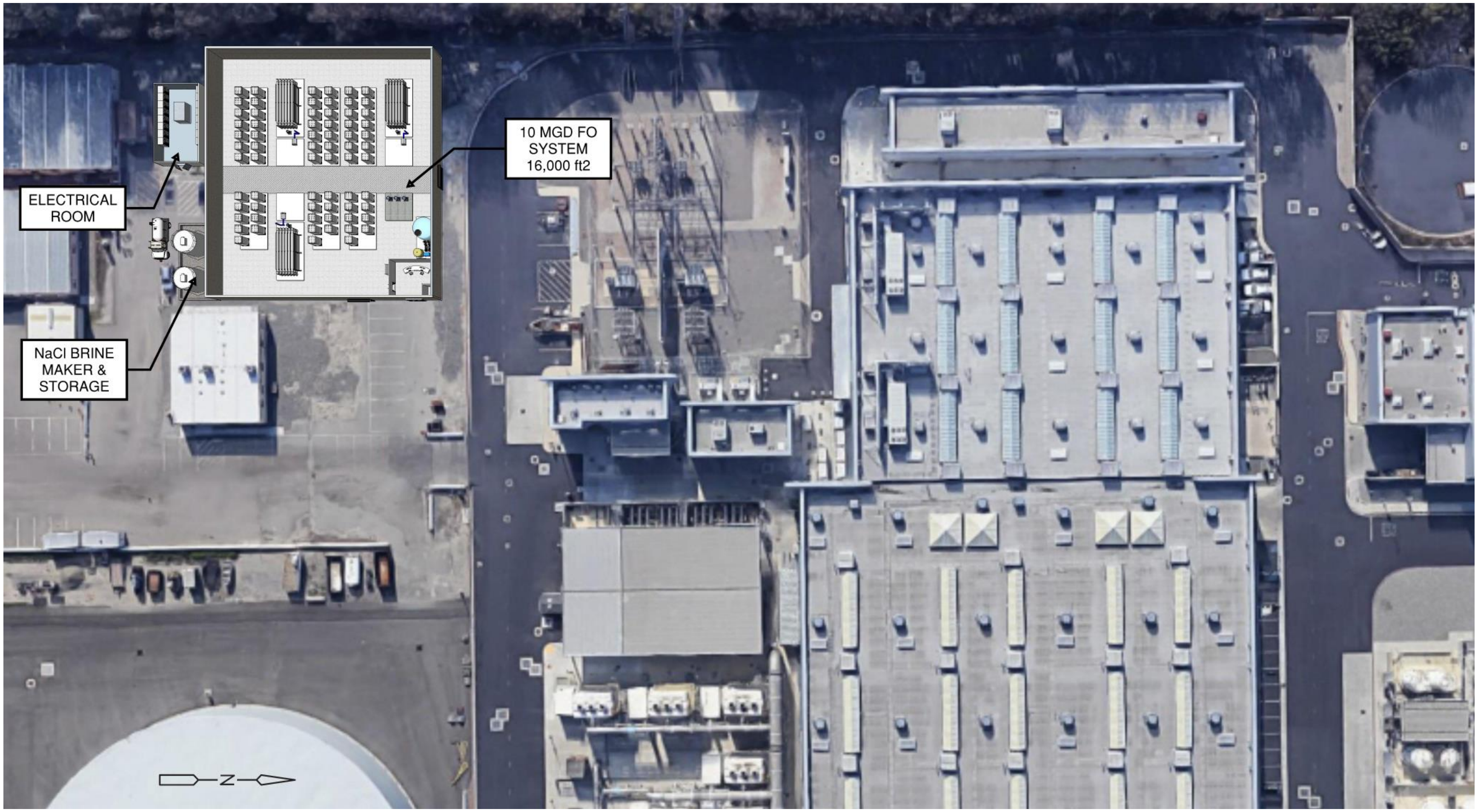


Figure 9 Alternative 2A Site Layout

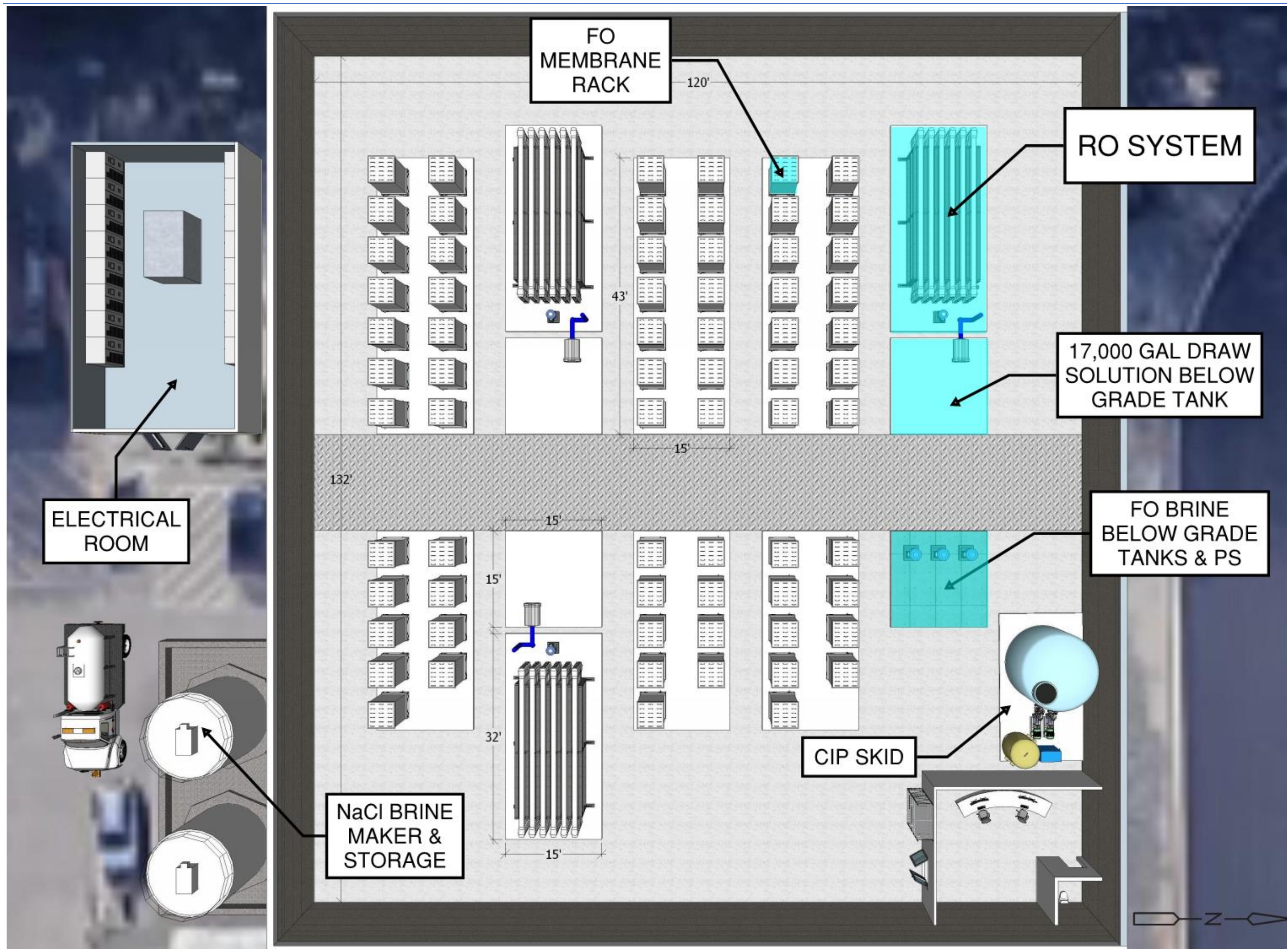


Figure 10 10-mgd FO System Layout

As shown on Figure 9, the FO treatment facility could be located in the southwest corner of the OCWD site and the electrical room and salt (NaCl) storage and a brine maker (two 30-ton fiberglass reinforced plastic (FRP) tanks) could be located next to the FO building. Figure 10 shows a larger image of the FO building with additional detail and some preliminary dimensions. The FO treatment system would consist of the FO membrane stacks, the RO skids, draw solution tank, RO CIP system, and pumping equipment. The footprints for the FO treatment system shown have a capacity of 10 mgd, which would require 16,000-ft^2 of membrane area per stack. For this treatment method, 70 PFO-1500 racks of FO membranes were assumed for calculation of FO system footprint (ft^2) based on information from the supplier and a flux of 3.5 gfd. As was the case for the CCRO example, negotiations with OCSD for use of this area would need to take place prior to any future project.

This alternative would result in the production of 3.5 mgd (3,920 AFY) of recovered water, based on the pilot results and an assumed constant apparent recovery value of 35 percent.

A conceptual pipeline arrangement to transport ROC, FO concentrate, and FO permeate for the FO system was developed and is shown on Figure 11.

The pipeline material and sizes for this alternative are stated in Table 7.

Table 7 Pipeline Specification for 10-mgd FO

Pipeline	Size (inch)	Flow (mgd)	Material
FO Feed	24	10	HDPE
FO Permeate	16	4	HDPE
FO Concentrate	20	6	HDPE

1.6.2.2 Treatment Alternative 2B – 20 mgd FO

This Alternative is similar to the 10 mgd system. The only difference is the surface area needed for the 20 mgd flow rate. For both alternatives (10 and 20 mgd) a membrane flux of 3.5 gfd was assumed for calculation of the footprint requirements. To produce 7.0 mgd (7,840 AFY) of product water (at 35 percent FO system recovery), 140 racks of the PFO-1500 type would be used, and the total membrane area would be 2,263,413 ft^2. Figure 12 shows the conceptual site layout for 20 mgd FO system.

The conceptual yard piping arrangement, pipe size, and material for 20 mgd FO system are shown on Figure 13 and in Table 8, respectively.

Table 8 Pipeline Specification for 20-mgd FO

Pipeline	Size (inch)	Flow (mgd)	Material
FO Feed	36	20	HDPE
FO Permeate	24	8	HDPE
FO Concentrate	28	12	HDPE

1.6.3 Capital Cost Estimate for FO

Preliminary project cost estimates were developed for the two alternatives based on capacity. Since each alternative has a different overall permeate flow rate, feed water flow requirements vary for each treatment train. Table 9 summarizes the alternative cost comparison. Appendix B includes detailed cost estimates. Costs are presented in 2019 dollars and are not escalated to future years.

Table 9 FO Capital Cost Estimate for 10 and 20 mgd

Description	Alternative 1A 10 mgd FO	Alternative 1B 20 mgd FO
Equipment(1)	$4,417,000	$8,678,000
Building/Structure(2)	$2,625,000	$3,920,500
Equipment Installation(3)	$2,208,500	$4,339,500
Site Work(4)	$567,200	$1,075,000
Subtotal – Direct Cost	$9,817,700	$18,012,900
Allowance for Electrical and Instrumentation(5)	$1,767,000	$3,242,000
Total Construction Cost(6)	**$19,636,000**	**$36,025,000**
Total Project Cost(7)	**$25,527,000**	**$46,833,000**
Project Unit Cost ($/AF) (8)	**424**	**389**

Notes:
(1) Equipment costs were provided by Porifera, this cost includes FO membrane stacks, brackish water RO system, CIP equipment, pumps and valves.
(2) Based on footprint needs and $150 per ft^2 building cost estimate.
(3) Assumed to be 50 percent of equipment cost based on modular nature of equipment.
(4) Consist of grading, paving, yard pipes, and assumed to be 5 percent and 2 percent of equipment cost as FO piping and general site work respectively.
(5) Assumed to be 15 percent and 8 percent of equipment cost for electrical includes VFDs and wiring and instrumentation for FO modules respectively.
(6) Includes 30 percent contingency, general contractor overhead and etc.
(7) Includes 30 percent allowance for engineering, construction management, legal and administration costs.
(8) Calculated assuming a 30-year loan period at a fixed annual interest rate of 5 percent, and production of "new" product water: 3,920 AFY for 10 mgd system, and 7,840 AFY for 20 mgd system.

1.6.4 O&M Cost Estimate for FO

Preliminary O&M cost estimates were developed for each alternative. The O&M costs discussed in this report are include operating a 10- and 20-mgd FO treatment system. The O&M cost estimates include power, labor, chemicals, membrane replacement, and replacement cost. The O&M cost estimates are summarized in Table 10. Appendix B includes detailed cost estimates.

Table 10 FO O&M Cost Estimate for 10 and 20 mgd

Description	Alternative 1A 10 mgd FO	Alternative 1B 20 mgd FO
Annual Power Cost(1)	$899,700	$1,795,100
Annual Chemical Cost(2)	$1,688,700	$3,377,400
Annual Labor Cost(3)	$442,600	$442,600
Membranes Replacement Cost(4)	$669,350	$1,338,700
Mechanical Maintenance and Miscellaneous(5)	$56,250	$85,750
Total Annual O&M Cost	$3,756,600	$7,039,550
O&M Unit Cost ($/AF) (6)	958	898

Notes:
(1) $0.085 kW/h is assumed as a unit price.
(2) Based on pilot testing and includes, high pH RO CIP and low pH RO CIP, salt, and high pH FO CIP. According to the pilot CIP result, $0.6 per m^2 is assumed for low pH CIP.
(3) Assumes four full time equivalent staff.
(4) Assumed 5 years' membranes lifetime for FO membranes and 7 years' lifetime for RO membranes.
(5) Assumed 20 years' useful time of major mechanical equipment and potable water cost and etc.
(6) Based on production of 3,920 and 7,840 AFY of new water for the 10 and 20 mgd systems, respectively.

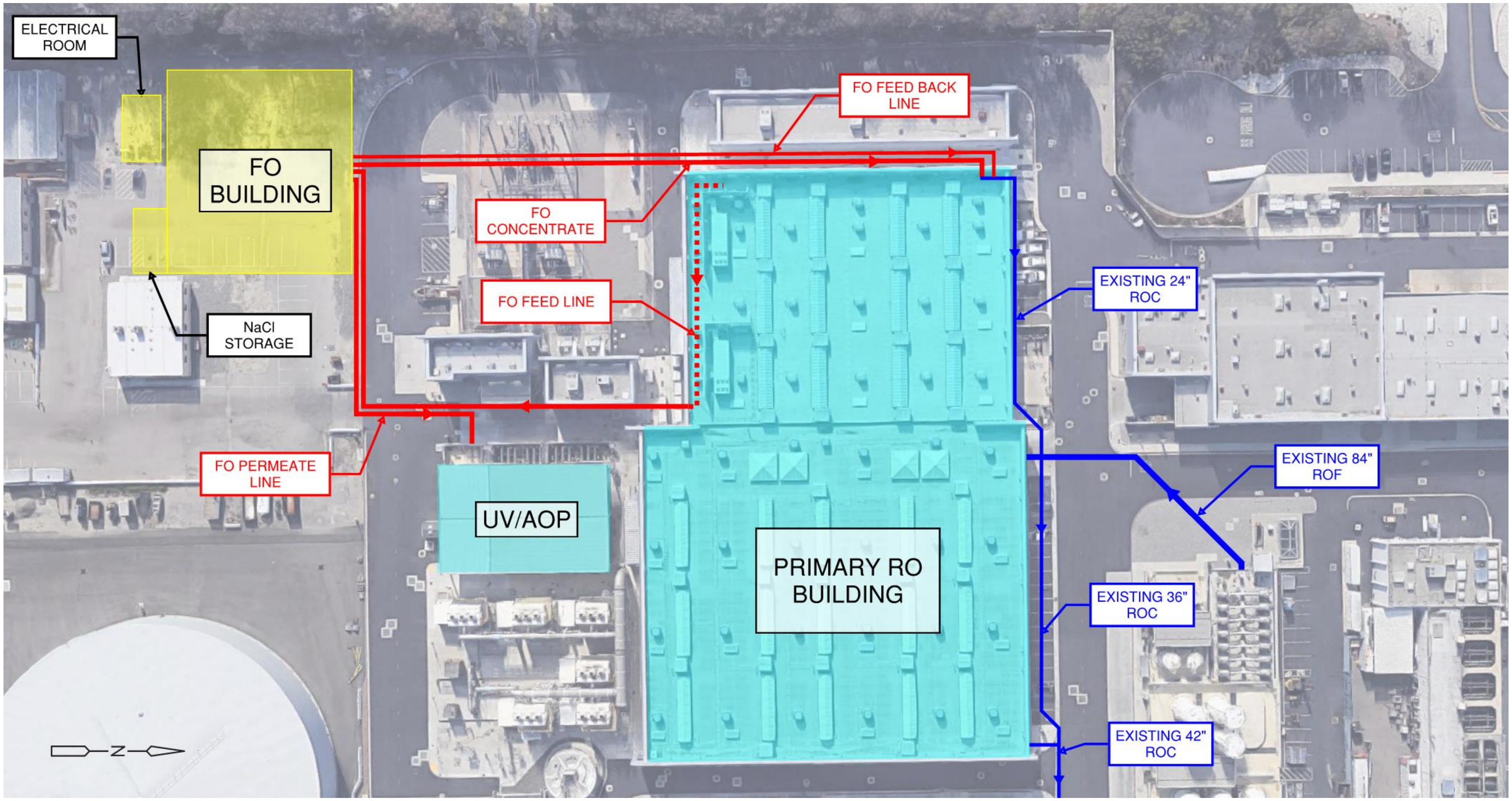


Figure 11 10-mgd FO Yard Piping

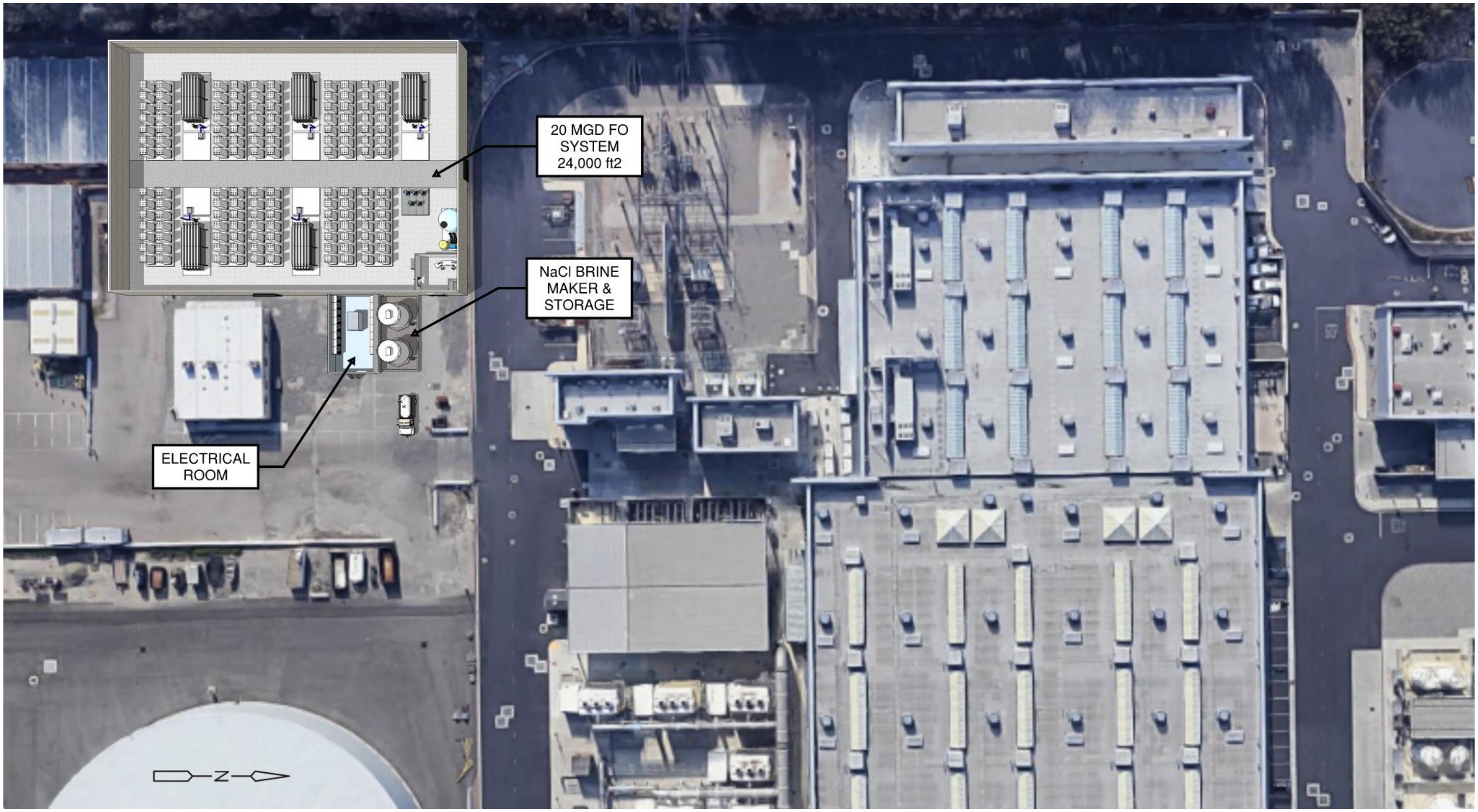


Figure 12 Alternative 2B Site Layout

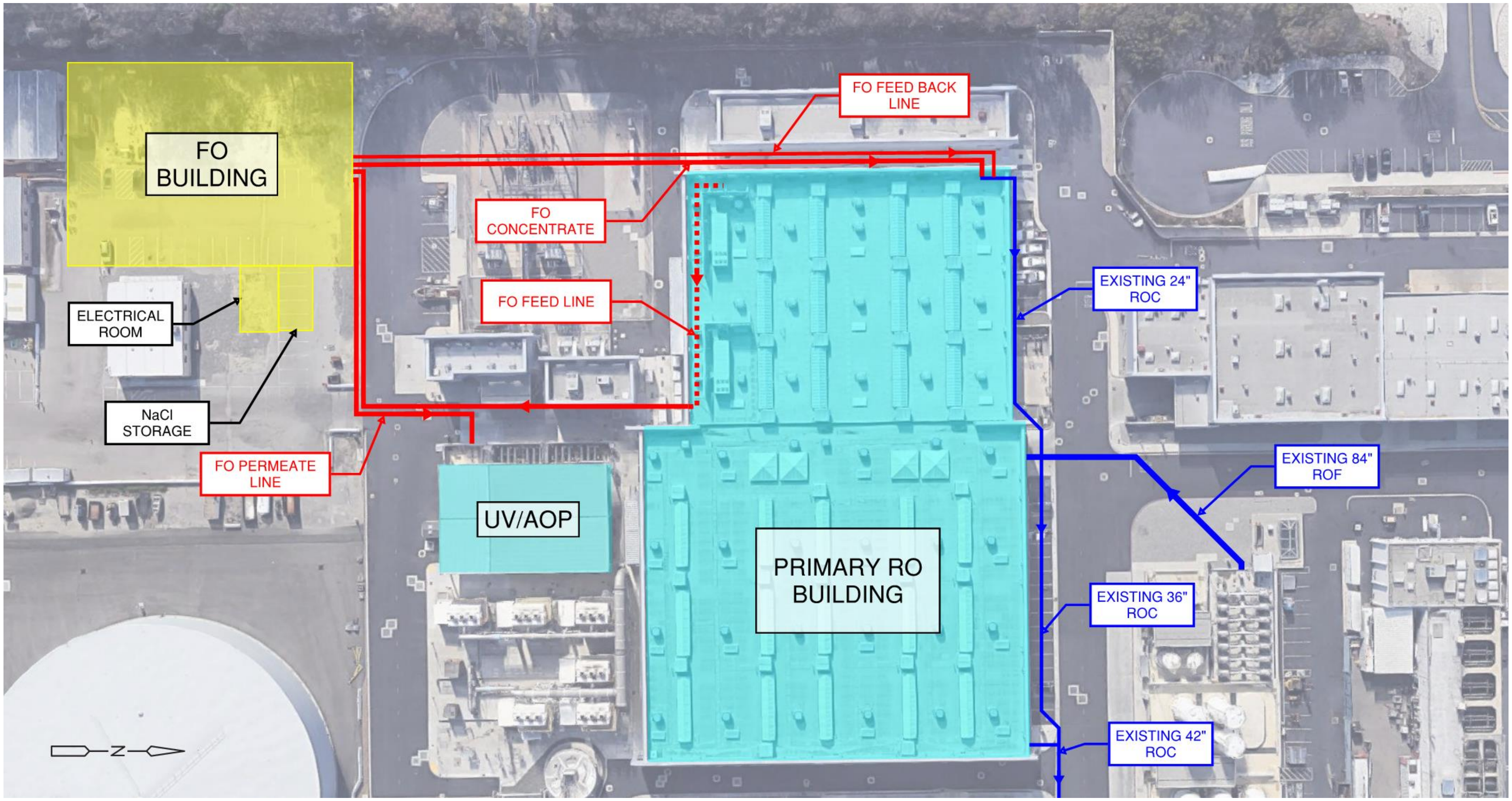


Figure 13 20-mgd FO Yard Piping

For the FO system some assumptions were based on the pilot study. To calculate the annual power cost for the RO high-pressure pump (300 hp), the FO brine boost pumps (30 hp), and the draw solution system pump (20 hp) the horsepower values shown for each were used. As shown in Table 10, the main O&M cost for FO system is related to the annual chemical costs. Based on the PFD provided by Porifera, ≤0.08 to ≤0.16 mgd of draw solution needs to be blow down in order to maintain the solution purity. Sodium chloride (NaCl) would be added to increase the TDS concentration in the draw solution tank. For the 10 and 20 mgd systems, 13 and 26 tons of salt would be needed per day, respectively.

The cleaning chemical cost is assumed to be $0.60 per square-meter using a high pH cleaning chemical (AWC C-227). Using the flux of 3.5 gfd, the FO membrane replacement cost per year is estimated to be $588,800. The additional cost shown for membrane replacement in Table 10 is for replacement of the RO membranes.

1.6.5 Combined Unit Cost of "New" Water

Based on the unit capital and O&M costs presented in Tables 9 and 10, the combined cost of new water produced by an FO system is expected to range between $1,287 per AF to $1,382 per AF, for a system treating 20 mgd and 10 mgd of RO concentrate, respectively. Again, for clarity, this cost excludes any costs associated with upsizing the downstream processes to accommodate the additional flow.

1.7 Summary and Conclusions

OCWD completed pilot testing of two novel RO concentrate treatment technologies, namely, CCRO and FO. The results of the pilot testing were used to carry out a preliminary evaluation of both technologies to treat 10 and 20 mgd of GWRS RO concentrate. Any recovered water from concentrate treatment would increase the overall recovery of the GWRS and produce more water for groundwater recharge.

The evaluation developed some preliminary design criteria for both technologies, made estimates of footprint requirements for the 10- and 20-mgd facilities, and prepared Class 5 planning level capital costs estimates and annual O&M cost estimates.

Based on the planning level evaluation, the following conclusions can be made:

1. From the information provided by the two vendors (Desalitech for the CCRO system, and Porifera for the FO system), and the assumptions used to establish the building dimensions, it should be possible to accommodate both technologies on the OCWD site at both 10- and 20-mgd treatment capacity, if additional land is made available from OCSD.
2. The Desalitech CCRO system is expected to recover more "new" water than the Porifera FO system; about 5,260 AFY and 10,400 AFY for the 10- and 20-mgd CCRO systems, respectively, compared with 3,920 AFY and 7,840 AFY for the 10- and 20-mgd FO systems.
3. Net recovery of the CCRO system ranged between 34.1 and 56.0 percent based on pilot testing, for the 10- and 20-mgd systems, respectively. The FO system was expected to achieve a recovery of 30 to 35 percent, again based on the pilot testing conducted by OCWD.

4. The CCRO system is expected to increase overall GWRS recovery from 85 percent, at the buildout capacity, to 88 percent and 91 percent for the 10- and 20-mgd systems, respectively. For the FO system, the overall GWRS recovery is expected to increase from 85 percent to 87.3 percent and 89.5 percent for the 10- and 20-mgd systems, respectively.
5. Based on equipment cost estimates received from the two vendors, the FO system would cost less than the CCRO system. However, the equipment cost estimate provided by Porifera is significantly lower than expected. So, it is likely that if an FO system were designed the capital cost would be higher, given that it includes two membrane systems - the FO membrane stacks and the conventional high-pressure RO system.
6. Based on O&M cost information provided by the vendors, electrical power cost estimates, and pilot plant chemical usage provided by OCWD, the CCRO system is expected to have the lowest annual O&M cost.
7. Overall, assuming that the capital cost is funded over a 30-year loan period at a fixed annual interest rate of 5 percent, the unit cost of new water produced by the two technologies is expected to be in the range of $1,126 per AF to $1,382 per AF, depending on the volume of RO concentrate that is treated, and the technology used. For the CCRO process, the total unit cost is expected to be between $1,126 and $1,216/AF for systems treating 20-mgd and 10-mgd of RO concentrate, respectively. For the FO process, the total unit cost range is expected to be similar but slightly higher at between $1,287 and $1,382/AF for systems treating 20-mgd and 10-mgd of RO concentrate, respectively. Treating a higher percentage of the RO concentrate will reduce the overall unit cost of the new water, as indicated. Despite the significantly lower capital cost estimate for the FO process, it is expected to have slightly higher total unit costs due to the higher relative O&M costs compared with the CCRO process. The total unit costs seem reasonable for treating RO concentrate bearing in mind that the final disposal cost for the concentrate is already in place and does not contribute any additional cost.
8. Note that should OCWD wish to implement a project such as described in this report, there would be additional capital (and O&M) expenditure related to expansion of the downstream processes such as UV/AOP, final product stabilization and final pumping, as a result of the "new water" produced. These costs have not been included here.

Appendix A

CCRO CAPITAL AND O&M COST ESTIMATES

Engineers...Working Wonders With Water®

ORANGE COUNTY WATER DISTRICT

GWRS Brine Recovery

TASK : PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

ESTIMATE PREPARATION DATE : 11/7/2019

JOB # : CCRO 10 MGD CAPEX

PREPARED BY : MFS

LOCATION : OCWD

REVIEWED BY : GJ

ITEM NO.	DESCRIPTION	QTY	UNIT	UNIT COST	SUBTOTAL	TOTAL
1	**Equipment**					
	ReFlex Max CCRO System Model No. R80-M (1 MGD Permeate) (1)	10	LS	$1,085,000	$10,850,000	
	Filmtec Membranes Model No. BW30XFLE-400 (1)	4000	EA	$470	$1,880,000	
	Completely Automated Clean-in-Place (CIP) (1)	1	EA	$150,000	$150,000	
	Start-up Services (membrane loading, cartridge filter install, startup, training, expenses) (1)	1	LS	$125,000	$125,000	
	Freight to Site (1)	1	LS	$100,000	$100,000	
	Side-Conduit Brine Replacement Pump (BRP) (1)	10	EA	$8,000	$80,000	
	Total					$13,185,000
2	**Building/Structure**					
	CCRO Building	26000	SF	$150	$3,900,000	
	Electrical Building	1400	SF	$150	$210,000	
	Total					$4,110,000
3	**Equipment Installation**					
	Installation (including unloading, concrete work, onsite assembly, interconnecting piping, electrical, switchgear, MCC, rental equipment, project management, etc.) (2)	1	LS	$6,500,000	$6,500,000	
	Total					$6,500,000
4	**Site Work - Grading, Paving, Yard Pipes**					
	24" Pipeline for 10 mgd CCRO Feed Line	1	LS	$165,000	$165,000	
	24" Pipeline for 10 mgd CCRO Permeate Line	1	LS	$82,000	$82,000	
	24" Pipeline for CCRO Concentrate Line	1	LS	$59,000	$59,000	
	24" Pipeline for Side-Conduit Line	1	LS	$125,000	$125,000	
	CCRO Piping	5	%		$659,250	
	General Site Work	2	%		$263,700	
	Total					$1,353,950
	ITEM NOS. 1-4 SUBTOTAL					**$25,148,950**
5	**Allowances**					
	Electrical	10	%		$2,514,895	
	Instrumentation Allowance	8	%		$2,011,916	
	Total					$4,527,000
	SUBTOTAL					**$29,675,950**

	Estimating Contingency	30	%			$8,903,000
	SUBTOTAL					**$38,578,950**
	General Conditions	10	%			$3,857,895
	SUBTOTAL					**$42,436,845**
	General Contractor Overhead & Profit	15	%			$6,365,527
	SUBTOTAL					**$48,802,372**
	Escalation	0	%			$0
	SUBTOTAL					**$48,802,372**
	Sales Tax on 50% of Subtotal Above	7.75	%			$1,495,000
	CONSTRUCTION COST SUBTOTAL					**$50,297,000**
	Engineering, Management, and Legal	30	%			$15,090,000
	PROJECT COST (April 2019 Dollars)					**$65,387,000**

(1) CCRO Equipment cost provided by Desalitech for 1 MGD skids.
(2) Installation cost provided by Desalitech for 10 MGD configuration.

The cost estimate herein is based on our perception of current conditions at the project location. This estimate reflects our professional opinion of accurate costs at this time and is subject to change as the project design matures. Carollo Engineers have no control over variances in the cost of labor, materials, equipment; nor services provided by others, contractor's means and methods of executing the work or of determining prices, competitive bidding or market conditions, practices or bidding strategies. Carollo Engineers cannot and does not warrant or guarantee that proposals, bids or actual construction costs will not vary from the costs presented as shown.

OPERATION AND MAINTENANCE COSTS
DETAILED PROJECT SUMMARY

Engineers...Working Wonders With Water®

Project: PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

Updated: 9/20/2019
Estimator: MFS
Project Status:

Job #: CCRO 10 MGD
Location: *OCWD*

Item No.		Description	Unit Qty.	Std. Unit	Unit Price	Total Annual Cost
A.	**ANNUAL POWER COSTS**					
	1	CCRO Pumping	8,334,085	kW-hr	0.0850	$708,397
	2	HVAC Systems	51,252	kW-hr	0.0850	$4,356
					ANNUAL POWER COST SUBTOTAL	***$712,800***
B.	**ANNUAL CHEMICAL COSTS**					
	1	AWC C-227 (organic cleaner)	100,000	lb	5.56	$556,000
	2	Caustic soda (50% wt) (for pH adjustment)	1,040	gal	2	$2,184
					ANNUAL CHEMICAL COST SUBTOTAL	***$558,200***
C.	**ANNUAL LABOR COSTS**					
	1	Supervisor	0.50	staff	147,600	$73,800
	2	Operators	2.00	staff	73,710	$147,420
	3	Mechanical	0.75	staff	147,600	$110,700
	4	Electrical/Instrumentation	0.75	staff	147,600	$110,700
					ANNUAL LABOR SUBTOTAL	***$442,600***
D.	**ANNUAL MISCELLANEOUS AND REPLACEMENT COSTS**					
	1	CCRO Pumping	1	LS	40,000	$40,000
	2	RO Membrane Replacement	1	LS	376,000	$376,000
	3	Potable Water, Gas, Communication	12	months	1,000	$12,000
					ANNUAL MISCELLANEOUS COST SUBTOTAL	***$428,000***
					ANNUAL COST SUBTOTAL	***$ 2,141,600***

Engineers...Working Wonders With Water®

ORANGE COUNTY WATER DISTRICT

GWRS Brine Recovery

TASK : PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

ESTIMATE PREPARATION DATE : 11/7/2019

JOB # : CCRO 20 MGD CAPEX

PREPARED BY : MFS

LOCATION : OCWD

REVIEWED BY : GJ

ITEM NO.	DESCRIPTION	QTY	UNIT	UNIT COST	SUBTOTAL	TOTAL
1	**Equipment**					
	ReFlex Max CCRO System Model No. R80-M (1 MGD Permeate) (1)	20	LS	$1,085,000	$21,700,000	
	Filmtec Membranes Model No. BW30XFLE-400 (1)	8000	EA	$470	$3,760,000	
	Completely Automated Clean-in-Place (CIP) (1)	2	EA	$150,000	$300,000	
	Start-up Services (membrane loading, cartridge filter install, startup, training, expenses) (1)	2	LS	$125,000	$250,000	
	Freight to Site (1)	2	LS	$100,000	$200,000	
	Side-Conduit Brine Replacement Pump (BRP) (1)	20	EA	$8,000	$160,000	
	Total					$26,370,000
2	**Building/Structure**					
	CCRO Building	51500	SF	$150	$7,725,000	
	Electrical Building	2800	SF	$150	$420,000	
	Total					$8,145,000
3	**Equipment Installation**					
	Installation (including unloading, concrete work, onsite assembly, interconnecting piping, electrical, switchgear, MCC, rental equipment, project management, etc.) (2)	2	LS	$6,500,000	$13,000,000	
	Total					$13,000,000
4	**Site Work - Grading, Paving, Yard Pipes**					
	36" Pipeline for 20 mgd CCRO Feed Line	1	LS	$390,000	$390,000	
	36" Pipeline for 20 mgd CCRO Permeate Line	1	LS	$136,000	$136,000	
	32" Pipeline for CCRO Concentrate Line	1	LS	$164,000	$164,000	
	32" Pipeline for Side-Conduit Line	1	LS	$265,000	$265,000	
	CCRO Piping	5	%		$1,318,500	
	General Site Work	2	%		$527,400	
	Total					$2,800,900
	ITEM NOS. 1-4 SUBTOTAL					**$50,315,900**
5	**Allowances**					
	Electrical	10	%		$5,031,590	
	Instrumentation Allowance	8	%		$4,025,272	
	Total					$9,057,000
	SUBTOTAL					**$59,372,900**
	Estimating Contingency	30	%			$17,812,000

	SUBTOTAL					**$77,184,900**
	General Conditions	10	%			$7,718,490
	SUBTOTAL					**$84,903,390**
	General Contractor Overhead & Profit	15	%			$12,735,509
	SUBTOTAL					**$89,920,409**
	Escalation	0	%			$0
	SUBTOTAL					**$89,920,409**
	Sales Tax on 50% of Subtotal Above	7.75	%			$2,991,000
	CONSTRUCTION COST SUBTOTAL					**$92,911,000**
	Engineering, Management, and Legal	30	%			$27,874,000
	PROJECT COST (April 2019 Dollars)					**$120,785,000**

(1) CCRO Equipment cost provided by Desalitech for 1 MGD skids.
(2) Installation cost provided by Desalitech for 20 MGD configuration.

The cost estimate herein is based on our perception of current conditions at the project location. This estimate reflects our professional opinion of accurate costs at this time and is subject to change as the project design matures. Carollo Engineers have no control over variances in the cost of labor, materials, equipment; nor services provided by others, contractor's means and methods of executing the work or of determining prices, competitive bidding or market conditions, practices or bidding strategies. Carollo Engineers cannot and does not warrant or guarantee that proposals, bids or actual construction costs will not vary from the costs presented as shown.

Carollo Engineers...Working Wonders With Water®

OPERATION AND MAINTENANCE COSTS
DETAILED PROJECT SUMMARY

Project: PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

Updated: 9/20/2019
Estimator: MFS
Project Status:

Job #: CCRO 20 MGD
Location: ***OCWD***

Item No.		Description	Unit Qty.	Std. Unit	Unit Price	Total Annual Cost
A.	**ANNUAL POWER COSTS**					
	1	Headworks	16,668,170	kW-hr	0.0850	$1,416,794
	3	HVAC Systems	326,622	kW-hr	0.0850	$27,763
			ANNUAL POWER COST SUBTOTAL			***$1,444,600***
B.	**ANNUAL CHEMICAL COSTS**					
	1	AWC C-227 (organic cleaner)	200,000	lb	5.56	$1,112,000
	2	Caustic soda (50% wt) (for pH adjustment)	2,080	gal	2	$4,368
			ANNUAL CHEMICAL COST SUBTOTAL			***$1,116,400***
C.	**ANNUAL LABOR COSTS**					
	1	Supervisor	0.50	staff	147,600	$73,800
	2	Operators	2.00	staff	73,710	$147,420
	3	Mechanical	0.75	staff	147,600	$110,700
	4	Electrical/Instrumentation	0.75	staff	147,600	$110,700
			ANNUAL LABOR SUBTOTAL			***$442,600***
D.	**ANNUAL MISCELLANEOUS AND REPLACEMENT COSTS**					
	1	Headworks	1	LS	80,000	$80,000
	3	Rotary Drum Screens	1	LS	752,000	$752,000
	4	Potable Water, Gas, Communication	12	months	1,000	$12,000
			ANNUAL MISCELLANEOUS COST SUBTOTAL			***$844,000***
			ANNUA COST SUBTOTAL			***$ 3,847,600***

Appendix B

FO CAPITAL AND O&M COST ESTIMATES

Engineers...Working Wonders With Water®

ORANGE COUNTY WATER DISTRICT

GWRS Brine Recovery

TASK : PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

ESTIMATE PREPARATION DATE : 11/7/2019

JOB # : FO 10 MGD CAPEX

PREPARED BY : MFS

LOCATION : OCWD

REVIEWED BY : GJ

TITLE :

ITEM NO.	DESCRIPTION	QTY	UNIT	UNIT COST	SUBTOTAL	TOTAL
1	**FO Equipment and Materials**					
	10 MGD FO System (PFO-1500 Module) (1)	1	LS	$4,000,000	$4,000,000	
	Brinemaker Tank (30 ton)	2	LS	$66,000	$132,000	
	Completely Automated Clean-in-Place (CIP)	1	EA	$150,000	$150,000	
	Brine Boost Pumps	3	EA	$25,000.00	$75,000	
	Draw Solution Pumps	3	EA	$20,000.00	$60,000	
	Total					$4,417,000
2	**Building/Structure**					
	FO Building	16000	SF	$150	$2,400,000	
	Draw Solution Concrete Tank (15x15x10)	2	LS	$30,000	$60,000	
	Electrical Building	1000	SF	$150	$150,000	
	Salt Storage Concrete Pad	1	LS	$15,000	$15,000	
	Total					$2,625,000
3	**Equipment Installation**					
	FO System Installation	50	%		$2,208,500	
	Total					$2,208,500
4	**Site Work - Grading, Paving, Yard Pipes**					
	24" Pipeline for 10 mgd FO Feed Line	1	LS	$165,000	$165,000	
	16" Pipeline for 4 mgdFO Permeate Line	1	LS	$53,000	$53,000	
	20" Pipeline for 6 mgd FO Concentrate Line	1	LS	$40,000	$40,000	
	FO Piping	5	%		$220,850	
	General Site Work	2	%		$88,340	
	Total					$567,200
	ITEM NOS. 1-4 SUBTOTAL					**$9,817,700**
5	**Allowances**					
	Electrical	10	%		$981,770	
	Instrumentation Allowance	8	%		$785,416	
	Total					$1,767,000
	SUBTOTAL					**$11,584,700**
	Estimating Contingency	30	%			$3,476,000
	SUBTOTAL					**$15,060,700**
	General Conditions	10	%			$1,506,070
	SUBTOTAL					**$16,566,770**

	General Contractor Overhead & Profit	15	%			$2,485,016
	SUBTOTAL					**$19,051,786**
	Escalation	0	%			$0
	SUBTOTAL					**$19,051,786**
	Sales Tax on 50% of Subtotal Above	7.75	%			$584,000
	CONSTRUCTION COST SUBTOTAL					**$19,636,000**
	Engineering, Management, and Legal	30	%			$5,891,000
	PROJECT COST (April 2019 Dollars)					**$25,527,000**

(1) FO Equipment cost provided by Porifera. Includes FO membranes, FO stacks, and RO equipment for draw solution processing.

The cost estimate herein is based on our perception of current conditions at the project location. This estimate reflects our professional opinion of accurate costs at this time and is subject to change as the project design matures. Carollo Engineers have no control over variances in the cost of labor, materials, equipment; nor services provided by others, contractor's means and methods of executing the work or of determining prices, competitive bidding or market conditions, practices or bidding strategies. Carollo Engineers cannot and does not warrant or guarantee that proposals, bids or actual construction costs will not vary from the costs presented as shown.

Engineers...Working Wonders With Water®

OPERATION AND MAINTENANCE COSTS
DETAILED PROJECT SUMMARY

Project:	PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM	**Updated:**	**11/1/2019**
		Estimator:	**MFS**
Job #:	FO 10 MGD	**Project Status:**	
Location:	***OCWD***		

Item No.		Description	Unit Qty.	Std. Unit	Unit Price	Total Annual Cost
A.	**ANNUAL POWER COSTS**					
	1	FO Pumping	10,533,557	kW-hr	0.0850	$895,352
	2	HVAC Systems	51,252	kW-hr	0.0850	$4,356
				ANNUAL POWER COST SUBTOTAL		***$899,700***
B.	**ANNUAL CHEMICAL COSTS**					
	1	AWC C-227 (organic cleaner for RO)	10,000	lb	5.56	$55,600
	2	Caustic soda (50% wt) (for pH adjustment)	104	gal	2	$218
	3	AWC C-227 (organic cleaner FO membrane cleaning)	1,787,363	$/m2	0.60	$1,072,418
	4	Salt (NaCl)	9,340,715	lb	0.060	$560,443
				ANNUAL CHEMICAL COST SUBTOTAL		***$1,688,700***
C.	**ANNUAL LABOR COSTS**					
	1	Supervisor	0.50	staff	147,600	$73,800
	2	Operators	2.00	staff	73,710	$147,420
	3	Mechanical	0.75	staff	147,600	$110,700
	4	Electrical/Instrumentation	0.75	staff	147,600	$110,700
				ANNUAL LABOR SUBTOTAL		***$442,600***
D.	**MEMBRANE REPLACEMENT COSTS**					
	1	FO Membrane Replacement (3.5 gfd)	1	LS	588778.4	$588,778
	2	RO Membrane	1	LS	80,571	$80,571
				ANNUAL MISCELLANEOUS COST SUBTOTAL		***$669,350***
E.	**MECHANICAL MAINTENANCE AND MISCELLANEOUS**					
	1	RO Pumping	1	LS	44,250	$44,250
	2	Potable Water, Gas, Communication	12	months	1,000	$12,000
				ANNUAL MISCELLANEOUS COST SUBTOTAL		***$56,250***
				ANNUAL COST SUBTOTAL		***$ 3,756,600***

ORANGE COUNTY WATER DISTRICT

GWRS Brine Recovery

TASK : PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

ESTIMATE PREPARATION DATE : 11/7/2019

JOB # : FO 20 MGD CAPEX

PREPARED BY : MFS

LOCATION : OCWD

REVIEWED BY : GJ

TITLE :

ITEM NO.	DESCRIPTION	QTY	UNIT	UNIT COST	SUBTOTAL	TOTAL
1	**FO Equipment and Materials**					
	10 MGD FO System (PFO-1500 Module) (1)	1	LS	$8,000,000	$8,000,000	
	Brinemaker Tank (50 ton)	2	LS	$76,500	$153,000	
	Completely Automated Clean-in-Place (CIP)	2	EA	$150,000	$300,000	
	Feed Boost Pumps	5	EA	$25,000	$125,000	
	Draw Solution Pumps	5	EA	$20,000	$100,000	
	Total					$8,678,000
2	**Building/Structure**					
	FO Building	24000	SF	$150	$3,600,000	
	Draw Solution Concrete Tank (15x15x10)	5	LS	$30,000	$150,000	
	Electrical Building	1000	SF	$150	$150,000	
	Salt Storage Concrete Pad	1	LS	$20,500	$20,500	
	Total					$3,920,500
3	**Equipment Installation**					
	FO System Installation	50	%		$4,339,000	
	Total					$4,339,000
4	**Site Work - Grading, Paving, Yard Pipes**					
	36" Pipeline for 20 mgd FO Feed Line	1	LS	$234,000	$234,000	
	24" Pipeline for 8 mgdFO Permeate Line	1	LS	$134,000	$134,000	
	28" Pipeline for 12 mgd FO Concentrate Line	1	LS	$99,900	$99,900	
	FO Piping	5	%		$433,900	
	General Site Work	2	%		$173,560	
	Total					$1,075,400
	ITEM NOS. 1-4 SUBTOTAL					**$18,012,900**
5	**Allowances**					
	Electrical	10	%		$1,801,290	
	Instrumentation Allowance	8	%		$1,441,032	
	Total					$3,242,000
	SUBTOTAL					**$21,254,900**
	Estimating Contingency	30	%			$6,377,000
	SUBTOTAL					**$27,631,900**
	General Conditions	10	%			$2,763,190
	SUBTOTAL					**$30,395,090**

	General Contractor Overhead & Profit	15	%			$4,559,264
	SUBTOTAL					**$34,954,354**
	Escalation	0	%			$0
	SUBTOTAL					**$34,954,354**
	Sales Tax on 50% of Subtotal Above	7.75	%			$1,071,000
	CONSTRUCTION COST SUBTOTAL					**$36,025,000**
	Engineering, Management, and Legal	30	%			$10,808,000
	PROJECT COST (April 2019 Dollars)					**$46,833,000**

(1) FO Equipment cost provided by Porifera. Includes FO membranes, FO stacks, and RO equipment for draw solution processing.

The cost estimate herein is based on our perception of current conditions at the project location. This estimate reflects our professional opinion of accurate costs at this time and is subject to change as the project design matures. Carollo Engineers have no control over variances in the cost of labor, materials, equipment; nor services provided by others, contractor's means and methods of executing the work or of determining prices, competitive bidding or market conditions, practices or bidding strategies. Carollo Engineers cannot and does not warrant or guarantee that proposals, bids or actual construction costs will not vary from the costs presented as shown.

Engineers...Working Wonders With Water®

OPERATION AND MAINTENANCE COSTS
DETAILED PROJECT SUMMARY

Project: PRELIMINARY EVALUATION OF TWO BRINE TREATMENT TECHNOLOGIES FOR THE GROUNDWATER REPLENISHMENT SYSTEM

Updated: 11/1/2019
Estimator: MFS
Project Status:

Job #: FO 20 MGD
Location: ***OCWD***

Item No.		Description	Unit Qty.	Std. Unit	Unit Price	Total Annual Cost
A.	**ANNUAL POWER COSTS**					
	1	FO Pumping	21,067,114	kW-hr	0.0850	$1,790,705
	2	HVAC Systems	51,252	kW-hr	0.0850	$4,356
					ANNUAL POWER COST SUBTOTAL	***$1,795,100***
B.	**ANNUAL CHEMICAL COSTS**					
	1	AWC C-227 (organic cleaner for RO)	20,000	lb	5.56	$111,200
	2	Caustic soda (50% wt) (for pH adjustment)	208	gal	2	$437
	3	AWC C-227 (organic cleaner FO membrane cleaning)	3,574,726	$/m2	0.60	$2,144,836
	4	Salt (NaCl)	18,681,430	lb	0.06	$1,120,886
					ANNUAL CHEMICAL COST SUBTOTAL	***$3,377,400***
C.	**ANNUAL LABOR COSTS**					
	1	Supervisor	0.50	staff	147,600	$73,800
	2	Operators	2.00	staff	73,710	$147,420
	3	Mechanical	0.75	staff	147,600	$110,700
	4	Electrical/Instrumentation	0.75	staff	147,600	$110,700
					ANNUAL LABOR SUBTOTAL	***$442,600***
D.	**MEMBRANE REPLACEMENT COSTS**					
	1	FO Membrane Replacement (3.5 gfd)	1	LS	1,177,557	$1,177,557
	2	RO Membrane	1	LS	161142.857	$161,143
					ANNUAL MISCELLANEOUS COST SUBTOTAL	***$1,338,700***
E.	**MECHANICAL MAINTENANCE AND MISCELLANEOUS**					
	1	RO Pumping	1	LS	73,750	$73,750
	2	Potable Water, Gas, Communication	12	months	1,000	$12,000
					ANNUAL MISCELLANEOUS COST SUBTOTAL	***$85,750***
					ANNUAL COST SUBTOTAL	***$ 7,039,550***