RECLAMATION

Managing Water in the West

Desalination and Water Purification Research and Development Report No. 173

Pilot-Scale Evaluation of High Recovery Desalination of Agricultural Drainage Water with Smart Integrated Membrane Systems (SIMS)

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

June 2016

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
June 2016	Final	9/29/2011 – 10/31/2015

4. TITLE AND SUBTITLE Variable Salinity Desalination	5a. CONTRACT NUMBER 5b. GRANT NUMBER R11AC81533 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Yoram Cohen Anditya Rahardianto Panagiotis D. Christofides John F. Thompson Larry Gao	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Regents of the University of California University of California, Los Angeles 11000 Kinross, Suite 102 Los Angeles, CA 90095-1406 310-825-876	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Bureau of Reclamation, Department of the Interior Denver Federal Center PO Box 25007 Denver Colorado 80225-2007	10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation 11. SPONSOR/MONITOR'S REPORT NUMBER(S) -

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available from https://www.usbr.gov/research/dwpr/DWPR_Reports.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A pilot-scale evaluation of desalination of agricultural drainage water with high mineral scaling propensity was carried out with a novel smart integrated membrane system (SIMS) technology. The field study successfully demonstrated autonomous/self-adaptive ultrafiltration (UF)-reverse osmosis (RO) operation at the Panoche Drainage District field test site. SIMS used novel direct online monitoring for membrane scaling and self-adaptive model-based control of UF-RO membrane operations. The project demonstrated technologies that enable desalting high salinity agricultural drainage brackish water at the optimal feasible recovery while adapting to real-time variations in feed water quality and scaling/fouling potential.

15. SUBJECT TERMS

brackish water, reverse osmosis, membrane mineral scaling, desalination, self-adaptive treatment systems

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Yuliana Porras-Mendoza
a. REPORT U	b. ABSTRACT U	a. THIS PAGE U	SAR		19b. TELEPHONE NUMBER (Include area code) 303-446-2265

Desalination and Water Purification Research and Development Program Final Report No. 173

Pilot-Scale Evaluation of High Recovery Desalination of Agricultural Drainage Water with Smart Integrated Membrane Systems (SIMS)

by
Yoram Cohen
Anditya Rahardianto
Panagiotis D. Christofides
John F. Thompson
Larry Gao

Water Technology Research Center
Chemical and Biomolecular Engineering Department
University of California, Los Angeles
420 Westwood Plaza
5531 Boelter Hall
Los Angeles, CA 90095-1592

U.S. Department of the Interior Bureau of Reclamation Technical Service Center
Denver, Colorado

June 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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

Disclaimer

The views, analysis, recommendations, and conclusions in this report are those of the authors and do not represent official or unofficial policies or opinions of the United States Government, and the United States takes no position with regard to any findings, conclusions, or recommendations made. As such, mention of trade names or commercial products does not constitute their endorsement by the United States Government.

Acknowledgements

The project team acknowledges Reclamation's Desalination and Water Purification Research Program (DWPR) sponsorship and the contributions to the project by the Panoche Drainage District, California Department of Water Resources, Summers Engineering, Grundfos Pumps Inc., Georg Fischer Piping Systems, Inge GmbH, Toray Membrane USA, BWA Water Additives, and CJI Process Systems. In particular, we appreciate the support of the following individuals (in no particular order) from the above agencies and companies to the project:

- Dennis Falasci, Betty Lindeman, Jeff Moore (Panoche Drainage District)
- Chris Linneman (Summers Engineering)
- Jose Faria, David Lara, Joseph Tapia, Margaret Dutton (California Department of Water Resources)
- Greg Bashian, Henrik Laursen, Vahan Bagdasarian (Grundfos USA)
- Rick Hines, Dave Vollaire, Michael Gallagher, and Terence Zhao (Georg Fischer Piping Systems)
- Peter Berg, Martin Heijnen, Josef Wunram, Scott Caothien (Inge GmbH)
- Steve Cappos and Tom Wolfe (Toray Membrane USA)
- Todd Horman (BWA Water Additives)
- John Cholakian, Eddie Na, Ryan Jackson (CJI Process Systems)

Acronyms and Abbreviations

ACH	Aluminum chlorohydrate (an aluminum-based coagulant for water treatment)
CDPH	California Department of Public Health
FO	forward osmosis
FWF	Fresh water flush (i.e., an online water rinse of RO elements).
MCL	maximum contaminant limit
MCO	model-based controller and real-time optimization
MD	membrane distillation
MED	multiple effect distillation
MF	microfiltration
MMS	membrane monitoring system
MMT	membrane monitoring technology
NL	notification limit
ORP	oxidation reduction potential
PDD	Panoche Drainage District
RO	reverse osmosis
SEM-EDS	scanning electron microscopy with electron dispersive spectroscopy
SIMS	smart integrated membrane system (reverse osmosis)
SIx	Saturation index with respect to a mineral salt
RO	Reverse Osmosis
SJV	San Joaquin Valley
TDS	total dissolved solids
TS-3	Tile Sump No. 3 at PDD treatment site
UCLA	University of California Los Angeles
UF	ultrafiltration
VFD	variable frequency drive
WRDP	Westside Regional Drainage Plan

Measurements

^{o}C	degrees Celsius
GPD	gallons per day
GFD	gallons per square feet per day
gpm	gallons per minute
m^2	square meter
mg/L	milligrams per liter
mm	millimeter
nm	nanometers
NTU	Nephelometric Turbidity Units
psid	pounds force per square inch, differential
psi	pounds force per square inch.
pm	parts per million
kW	kilowatt
V	volt

Contents

Tables

Figures

Synopsis

A novel smart integrated membrane system (SIMS) technology of autonomous/self- adaptive ultrafiltration (UF)—reverse osmosis (RO) operation was developed as a highly reconfigurable, mobile water treatment platform. The SIMS technology was field demonstrated for desalination of agricultural drainage water in the Panoche Drainage District (PDD) in California, where agricultural drainage water management is a major challenge. The project goal was to demonstrate a capability for desalting high salinity brackish water of high mineral scaling/fouling potential.

Fine particles (as small as ~ 20 nanometers [nm]) may promote heterogeneous nucleation of mineral salts. The study revealed that removing these fine particles was an essential RO feed pretreatment requirement for source water with high concentrations of sparingly soluble mineral salts. Optimal RO feed pretreatment was achieved using UF with inline coagulation. The field study also demonstrated that system operating conditions must be continually adapted to changes in feed water salinity (~9,000 - 20,000 milligrams per liter [mg/L] total dissolved solids [TDS]) and quality (e.g., turbidity range of ~0.1 -1.2 Nephelometric Turbidity Units [NTU], gypsum saturation index range of ~0.8 – 1.5, respectively) to optimize water recovery and avoid mineral scaling. Such an approach is only feasible if the plant is self-adaptive and by using a direct method for mineral scale detection, such as the use of the direct membrane monitoring technology (MMT) used in this project. Furthermore, it was shown that antiscalant selection and dose optimization can be carried out directly with SIMS interfaced with the University of California Los Angeles' (UCLA) MMT. Early detection of the onset of mineral scaling was critical since once scaling commenced, then further antiscalant dose increases were not effective in inhibiting the progression of mineral scaling. It was shown, however, that at the early stage of mineral scaling, fresh water (i.e., permeate) flushes of the RO system, using only a small percentage of water production (< 0.6%), were effective in removing the formed scale. Accordingly, it was demonstrated that early detection of mineral scaling is necessary to: a) optimize water recovery and antiscalant dose, and b) ensure triggering of corrective actions upon occurrence of time- sensitive mineral scaling events.

Using the self-adaptive SIMS, as enabled by real time membrane scale/fouling monitoring, makes high recovery of up to in the range of 70-80% feasible for PDD drainage water desalting. The estimated operating costs for desalting the PDD agricultural drainage water were estimated to be in the range of $200 - $300 per acre-foot of product water. Based on the current study, it is recommended that future studies should focus on further enhancing water recovery (e.g., via accelerated precipitation processed coupled with secondary desalting), followed by final concentrate treatment to zero liquid discharge (e.g., via solar evaporation). Studies should also investigate potential uses of product water (in addition to potable use), which may require further polishing of permeate quality with respect to trace contaminants such as boron.

1. Introduction

Reverse osmosis (RO) has emerged as the dominant desalination technology—primarily due to its relative simplicity, compactness, modularity, and scalability [1, 2]. By using electrical energy for pressure generation, pressure-driven RO desalination has significant deployment flexibility for harnessing renewable energy (e.g., via solar photovoltaic cells and wind turbines), while maintaining consistent operability through the conventional power grid as backup power [3, 4]. Various approaches to reducing RO energy consumption are also well established, such as using energy recovery devices and staged operation with booster pumps [5, 6].

RO water production is pressure driven, avoiding the complexity, relatively higher energy use, and higher capital costs of osmoticallly- or heat-driven desalination processes (i.e., forward osmosis, membrane distillation, solar evaporation) [7, 8]. In fact, osmotically-driven (with thermolytic draw solutions) and heat-driven desalination processes are cost-effective only if low-cost heat (or "waste heat") sources are readily available locally [7, 8]. More importantly, unlike most other desalination technologies, RO desalination technologies have been commercially successful; RO desalination operations and maintenance are supported by a diverse and well-established supply chain of off-the-shelf components and consumables (membrane elements, prefilters, compatible antiscalants, etc.). While promising, applications of conventional RO desalination approaches for agricultural drainage water treatment, reuse, and reduction remain technically and economically challenging [9-11]. Some of the primary challenges that must be addressed are described the following subsections.

1.1. High Potential for Mineral Salt Precipitation

Agricultural drainage water often contains high levels of precursors (e.g., calcium, sulfate, barium, strontium, silica) of sparingly water soluble mineral salts (e.g., gypsum, silica, calcium carbonate, barium sulfate, strontium sulfate) [9, 12]. As product water is recovered during desalination, mineral salt precursors in the RO retentate stream may become concentrated beyond their solubility limits and precipitate as mineral salts. The potential for mineral salt precipitation, as quantified by the solution saturation indices with respect to the mineral salts of concern exists when the saturation index of the limiting mineral salt exceeds unity (SIx >1) as shown in Equation 1:

$$SIx=IAPx/Ksp,x \qquad (1)$$

Where: IAPx and Ksp,x are the ion activity and solubility product of mineral salt x, respectively),

If not effectively suppressed (i.e., with the appropriate dosage of antiscalants), mineral salt precipitation will lead to membrane mineral scaling, loss of water productivity, and eventual membrane damage. Although modular construction of conventional RO systems allows for relatively simple and fast replacements and/or chemical cleaning of mineral-scaled RO elements, frequent replacements and cleaning are undesirable due to increased operational costs.

The challenge of mineral scaling is not unique to RO desalination, but is also inherent in other processes for brackish water desalination. Thus, irrespective of the desalination process, effective methods for mitigation of mineral scaling are required. For example, in a recent pilot study of solar desalination via multiple effect distillation (MED) at PDD [13], significant decline (>50%) in the overall heat transfer coefficient (i.e., the coefficient which governs the rate of heat transfer and thus the water evaporation rate) was observed after a short, 20-day period of operation. The decline was attributed to mineral scaling of heat transfer surfaces, which necessitated opening and manual cleaning of MED plates [13]. Mineral scaling in emerging desalination processes such as forward osmosis (FO) and membrane distillation (MD) are also well documented in the literature [7, 14]. In all of these processes, the use of antiscalants (at sufficient dosages) is necessary for suppressing mineral scaling; however, desalination recovery is limited even with antiscalants use [7, 13, 14]. Furthermore, a recent UCLA study [15] has also demonstrated that effective feed filtration (well below the commonly accepted standard turbidity level for RO desalting) prior to desalination is critical to effectively remove particulates (to the submicron level) that can promote scaling due to enhanced mineral crystal nucleation.

1.2. High Temporal Variability of Water Salinity and Mineral Scaling Potential

1.2.1. Need to Self-Adapt to Feed Variability

Temporal variability of water salinity and mineral scaling potential present significant challenges in conventional operations of RO desalination. Under conventional practices [16], RO desalination operations are typically fixed at or near a design water recovery level, selected based on an acceptable range of mineral scaling potential (i.e., saturation index of the limiting mineral scalant). The acceptable range must be selected to be within the limits of antiscalant effectiveness (e.g., Figure 1), either based on more conservative or more progressive estimates provided by antiscalants manufacturers [17].

Furthermore, antiscalants are commonly dosed at a constant level based on a maximum expected mineral scaling potential in the RO system (at the design water recovery level). The desired RO recovery level is typically achieved through either manual or basic automated control of RO feed pressure and retentate flow rate [16]; an operator must manually input the pressure and flow set-points into the control interface. Potential occurrence of membrane mineral scaling is determined indirectly via monitoring of normalized permeate flow, which can be used to trigger an alarm for manual operator intervention [16]. While adequate for conventional applications such as seawater desalination, the above conventional practices are ineffective when there are measurable and frequent changes in feed water salinity and membrane scaling potential.

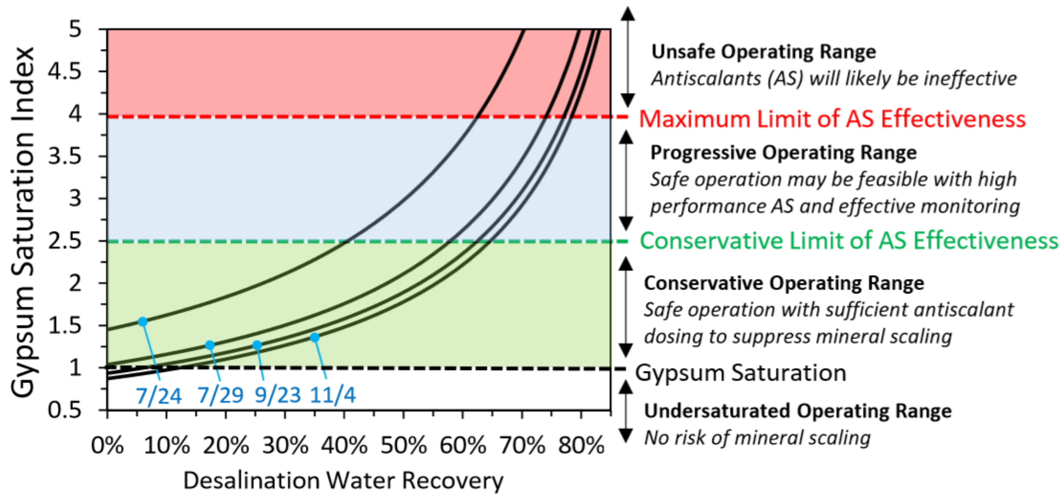

Figure 1. Relationship between gypsum saturation index in desalination concentrate and product water recovery, calculated based on water quality data of Panoche Drainage District (PDD) Tile Sump No. 3 (July-November 2014). Limits of antiscalant effectiveness are based on typical recommendations for antiscalants dosing by RO membrane manufacturers [17].

Water salinity and mineral scaling potential (i.e., saturation indices) of agricultural drainage water can vary significantly (Figure 2 and Figure 3) due to seasonal variations of drainage water quality, as well as due to the impact of local activities of agriculture and drainage water management. Under such challenging dynamic conditions, maintaining water recovery at or near the design level using conventional practices would be impractical. Significant operator expertise and frequent operator intervention would be needed to adjust RO feed pressure and retentate flow rate set-points to the required levels. Furthermore, operations under fixed RO recovery and antiscalant dosage levels are risky when there is a significant variability in mineral scaling potential. For example, a system optimized for operation in the conservative operating range of antiscalant effectiveness (Figure 1) may (and without operator knowledge) slip into the progressive or even the unsafe operating range when there is an increase in mineral scaling potential. In such a case, timely adjustments of antiscalant dosage would be needed to avoid antiscalant underdosing, while reducing RO recovery rates may also be necessary to avoid slipping into unsafe operational zones (Figure 1). Such adjustments are difficult to make in the absence of real-time information regarding the onset of mineral scaling/fouling. In this regard, it is noted that normalized permeate flow monitoring is of insufficient resolution to enable early detection (or onset) of mineral scaling/fouling [15, 18].

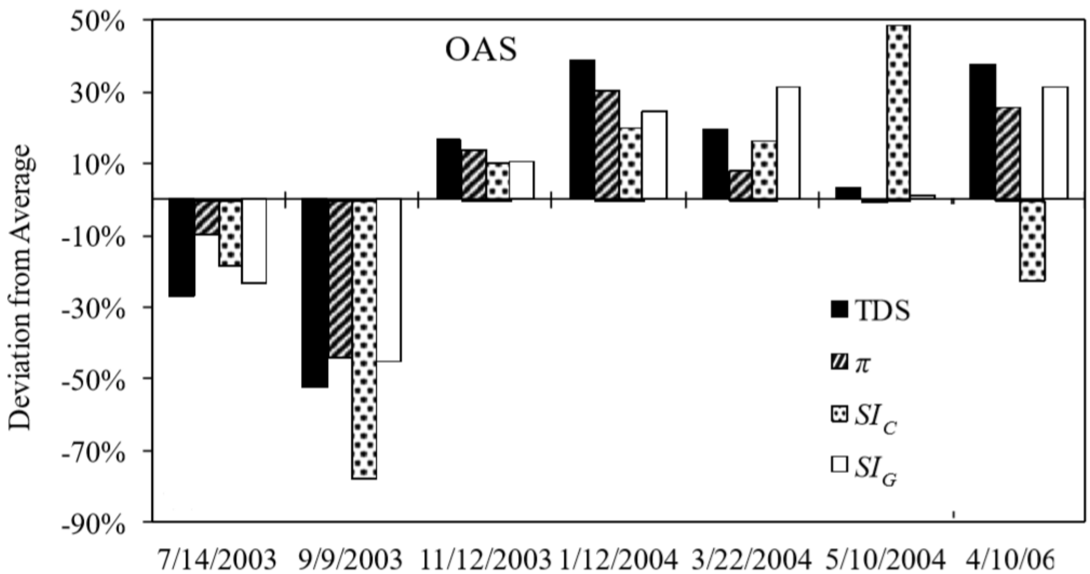

Figure 2. Measured temporal water quality variations at a drainage monitoring station (OAS 2548, [9]) in California San Joaquin Valley. π: osmotic pressure, SI_C: calcite saturation index, SI_G: gypsum saturation index.

The difficulty in applying conventional practices for RO desalination of agricultural drainage water is evident from previous studies at PDD in which catastrophic membrane failure was previously reported for water recovery above 50% [19]. New RO operational methods are therefore needed to enable RO operations that can automatically handle or "self-adapt" to high temporal variability of feed water salinity and mineral scaling potential. In self-adaptive RO operations, RO recovery and/or antiscalant dosing are automatically varied based on real-time information of mineral scaling potential, with automated adjustments of pressure, retentate flow, and antiscalant dosing rate set points to maintain safe RO operations and avert mineral scaling. Consequently, capabilities for real-time membrane scaling detection, coupled with real-time model-based optimization and control, are critical.

1.2.2. Need to Maximize RO Water Recovery to Minimize Residual Drainage Water Volumes

To minimize the impact of temporal water quality variability, conventional RO application for drainage water desalting is often limited to low water recovery (typically $\lesssim$50% at PDD). At PDD, recent water quality data indicated that, at the upper limit of aggressive antisalant dosing, there is potential for RO operation at up to 78% water recovery (Figure 1). However, conventional RO operation at high recovery would result in catastrophic system failure (due to scaling) when the source water mineral scaling propensity rises (Figure 1). Thus, new methods for self-adaptive RO operation must address the need to maximize RO water recovery, while allowing RO operation near the mineral scaling threshold.

The above challenges had been addressed to various degree by developing various diagnostic methods, RO operational strategies, scale/fouling monitoring capability, integrated and self-adaptive UF and RO technology, and unique control and optimization methods [5, 20-24]. The present project reflects the integration of these technologies and knowledgebase by developing and field demonstrating a novel, pilot-scale smart integrated membrane system (SIMS). Specifically, the SIMS approach integrates RO desalination with UF feed pre-treatment, combining novel direct online monitoring of membrane scaling and advanced, self-adaptive model-based control of UF-RO membrane operations. In this project, the pilot unit was developed as highly reconfigurable, mobile water treatment platform with 24 gpm RO feed capacity, capable of water recovery as high as ~ 75%. The field operation of SIMS technology was demonstrated in the field for agricultural drainage water desalination in the Panoche Drainage District (PDD) treatment site, where the agricultural drainage management is a major challenge. The goal was to demonstrate to field demonstrate the technologies for enabling desalting high salinity brackish water at the optimal feasible recovery, adapting to real-time variation in feed water quality and scaling/fouling potential.

2. Pilot Study Project Partners

The UCLA SIMS plant development and pilot demonstration was a close-collaboration between Federal and State government agencies, academia, and industry (Figure 3). Leveraged by initial funding from Reclamation's Desalination and Water Purification Research (DWPR) program, a consortium of water agencies and industry partners provided additional support for the SIMS development and construction, as well as a general framework for sharing technical information. Affiliates in the consortium included:

- Panoche Drainage District
- California Department of Water Resources
- Georg Fischer, LLC
- Grundfos Pumps Corporation
- Inge GmbH (subsidiary of BASF)
- Toray Membrane USA
- BWA Water Additives
- CJI Process Systems

Figure 3. UCLA research team and project industry affiliates at the inauguration of the UCLA mobile SIMS unit (May 2014).

The Panoche Drainage District (PDD) contributed significant portions of SIMS development and demonstration costs (through California Proposition 50 funding), as well as provided invaluable infrastructure support that included a secure test area with all needed permitting (already in place), drainage water supply, electricity, waste management, and field technical support. Also, essential water quality analysis of grab samples data was obtained through analytical support from the Bryte Laboratory of the California Department of Water Resources. Significant portions of SIMS parts and consumables (pumps, chemical metering, sensors, valves, membrane modules, piping) were contributed by the consortium industry partners.

3. Project Overview

The goal of the project was to field demonstrate technologies for enabling desalting of brackish water with high mineral scaling potential at its optimal water recovery, adapting to real-time variations in feed water quality. Toward this goal, the objectives of the proposed project were to:

- Develop and construct a pilot-scale smart integrated membrane system (SIMS) equipped with real-time direct membrane surface monitoring
- Develop and implement operational and control methods for SIMS operation
- Field deploy SIMS for high recovery desalting of agricultural drainage water
- Demonstrate SIMS capabilities for online optimization of operating conditions
- Determine optimal conditions and potential operating costs of desalting using SIMS

The project was organized along the 12 tasks summarized below.

Tasks 1, 2, and 5: Develop pilot SIMS design, construct pilot SIMS, and shakedown the pilot SIMS. SIMS was designed as a comprehensive water treatment and desalination system consisting of feed pretreatment unit that included microfiltration (MF) and ultrafiltration (UF) technologies, coupled with a reverse osmosis membrane desalting unit. Based on the design, materials and components were acquired and the SIMS plant (***Section 4***) was constructed in collaboration with project partners. A membrane monitoring unit (see ***Section 5***) was also adapted into the SIMS plant.

Task 3. Design and implement advanced monitoring and control capabilities. The UCLA mineral scale monitoring strategies for real-time scale detection and diagnostics was the basis for constructing a membrane fouling/scaling monitor which was initially tested at UCLA. Subsequently, controllers for the UF and RO units were developed and implemented, in addition to developing, testing and implementing capabilities for remote access to SIMS operational control via the internet. A summary of SIMS control and monitoring components is given in ***Section 5***.

Task 4 and 7. Prepare San Joaquin Valley (SJV) field testing and install pilot SIMS. A field testing site, located at 11000 North Russell Ave, Firebaugh, California, was selected for the project in collaboration with PDD. Supporting infrastructure was prepared at the field site, including testing area, feed water line, residual discharge, and electrical panels. SIMS was shipped to test site and installed to treat one of the agricultural drainage wells at the site. Track feed water quality data commenced in preparation for system commissioning. An overview of the field testing site and SIMS installation is given in ***Section 6***. An overview of the field testing plan and summary of feed water quality data is given in ***Section 7***.

Task 8. Setup pilot SIMS operational settings at SJV field site. This task focused on evaluating feed pretreatment requirements, including UF backwashing/cleaning and coagulant use and antiscalant treatment for RO. This part of the work utilized the standalone membrane monitoring system a field diagnostic system. The results are summarized in ***Section 8.1***. SIMS shakedown/control system refinement was conducted in the field, along with necessary refinement of pilot SIMS equipment.

Tasks 9-10. Conduct pilot testing of continuous SIMS operation at SJV field test site and compile cost data for SJV agricultural drainage water desalting. SIMS was operated in a long-term field study to evaluate UF operational performance, self-adaptive RO operational control, online RO water recovery optimization, and the overall agricultural drainage water desalination performance. The work included routine maintenance and trouble-shooting of system operation. Feed and product water samples were collected for water quality analysis, in collaboration with the California Department of Water Resources. Membrane surface analysis was done to confirm type of mineral scalants. Data were compiled for estimating treatment costs. The results are summarized in ***Sections 8.2 - 8.5.***

Task 11. Dismantle and ship pilot SIMS. No dismantling of pilot SIMS was required as the SIMS plant currently remains operating under a separate continuation project funded by the California Department of Water Resources.

Task 6 and 12. Preparation and submission of reports. Quarterly progress reports were prepared and submitted to Reclamation. The project was completed with the submission of this final report.

4. Pilot System Design, Construction, and Shakedown

The Smart Integrated Membrane Systems (SIMS) plant for brackish water desalination integrated feed pretreatment via UF and inline coagulation, coupled with RO desalting. SIMS was designed to handle a feed capacity of 24 gallons per minute (gpm) with product water recovery of up to 75%. The plant design specifications are listed in Table 2. Designed for rapidly deployment and remotely monitored operation, the SIMS plant, housed in a 40-foot shipping container, is fully automated mobile field facility equipped with a full suite of process equipment and instrumentations, including:

- Self-cleaning centrifugal separator and screen filters for particle removal (>300 microns)
- An inline chemical coagulation system
- An advanced multi-bore ultrafiltration system for fine particle and colloid removal (>0.02 microns)
- An RO system (with 4-inch RO elements) reconfigurable to single- and two-stage operations, as well as two-pass operations
- A feed (150 gallons) tank, reconfigurable to a chemical cleaning tank
- UF filtrate and RO permeate collection tanks (400 gallons each)
- High performance multi-stage centrifugal pumps with variable frequency drive
- Fully automated flow and pressure controls with electrically actuated valves
- Chemical dosing systems for coagulant, pH adjustment, antiscalants, and chemical cleaning
    - A full suite of online sensors for flow, pressure, pH, oxidation reduction potential (ORP), temperature, energy consumption, valve positions, and turbidity
- Centralized electrical distribution panel
- Advanced control system with embedded computing for plant monitoring and autonomous control
- 4g wireless internet connection, enabling full remote control of plant operation
- A separate operator room with touch-panel plant controls
- Air conditioning and exhaust fans
- Stream sampling points

UCLA SIMS plant design specifications included:

Specifications

- Max. Water Input/Output: 43,200 gallons per day (GPD)
- Max. RO Feed Input: 34,560 GPD
- RO Max. Water Recovery: 75% (without Concentrate Recycle)
- Max. Product Water Output: 25,920 GPD
- Electrical: 480 V 3-Phase (40 kW Max)

Configuration

- *Feed Pretreatment*
  - Pumps: 3 Units (Well Pump UF Feed Pump, UF Backwash Pump)
  - Centrifugal Separator: 1 Unit
  - Chemical Storage & Metering: 5 Units (Acid, Base, NaMBS, NaOCl, Coagulant)
  - Screen Filtration: 1 Unit (300 micron)
  - Ultrafiltration: 2 Modules (0.02 micron)
  - Tanks: 2 Units (150-gal Feed Tank & 450-gal UF Backwash Tank)

- **RO Desalination**
  - Pumps: 5 Units (Booster 1, HP Pump 1, HP Pump 2, HP Pump 3, Product Pump)
  - Cartridge Filter: 2 Units
  - Chemical Dosing: 2 Units (Antiscalant, Other)
  - Reverse Osmosis: 2 Stage or 2 Pass (6 Vessels, Convertible Configuration), 21 x 4" x 40" RO Elements
  - Tank: 1 Unit (450-gal Product Water Tank)

Other Infrastructure

- Internet Access
- Air Conditioning
- Exhaust Fans
- Monitoring & Control Unit (Onsite and Remote)

SIMS uses two sequential process trains. The first feed pretreatment train (Figure 4) consists of centrifugal separator to remove large solids (e.g., sand particles), feed tank, screen filter (300 microns), ultrafiltration membranes (2 x Inge Dizzer XL modules, 60 square meter [m^2]/module, 0.9 millimeter [mm] bore (inside-out filtration), 0.02 micron nominal pore diameter), and a 400-L UF filtrate tank. The pretreatment train is equipped with a chemical metering system for inline coagulation, as well as metering capabilities for pH adjustment, stream chlorination and for membrane cleaning. The UF feed pump (Grundfos CRNE5-6, 30 gpm/140 feet, variable frequency drive [VFD]) was installed to allow two UF module to operate in parallel at a flux of up to 39 gallons per square foot per day (GFD).

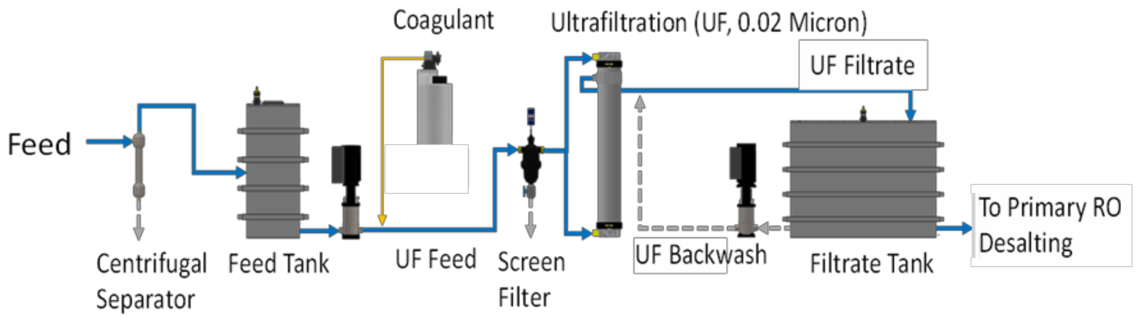

Figure 4. Process diagram of the feed pretreatment train of the UCLA SIMS plant.

The UF modules can be backwashed either with UF filtrate or RO permeate at a permeate flux up to 120 GFD using a backwash pump (Grundfos CRNE15-3, 80 gpm/160 feet, VFD). The RO train was designed to operate in a single, two- stage, and two-pass configurations (Figure 5). The first RO stage contained 14x2.5-inch x40-inch brackish water RO elements (Toray TM710D) as two rows of 7 elements arranged in series. The second stage contained 7x2.5-inch x 40-inch seawater RO elements (Toray TM810D) arranged in series. The pumps for the RO unit are listed in **Table 4.2**. SIMS instrumentation allowed for online measurements of temperature (GF 2350), conductivity (GF 2850), pH (GF 2750), flow rate (GF 2551 magmeters and GF 2537 paddlewheel flow sensors), as well as pressure (Wika Model S-10, S-11).

Table 1. RO Pumps in the SIMS Plant

Pump[(a)]	Model Number	Size	Note
Stage 1 RO feed booster pump	CRN5-4	24 gpm/103 ft	On/off
Stage 1 RO feed pump	CRNE3-23HS 10Hp	24gpm/910ft	VFD
Stage 2 RO HP interstage pump	CRNE1-23HS 6Hp	12.5gpm/945ft	VFD

(a) Manufactured by Grundfos Pumps Corp

Layout of the processing units is provided in Figure 6, showing the fully containerized plant complete with all needed storage and chemical tanks and a separate control room. Photos of the system are shown in Figure 7. The constructed 40-foot containerized system was mounted on a trailer chassis, which allowed the plant to be highly mobile (Figure 8).

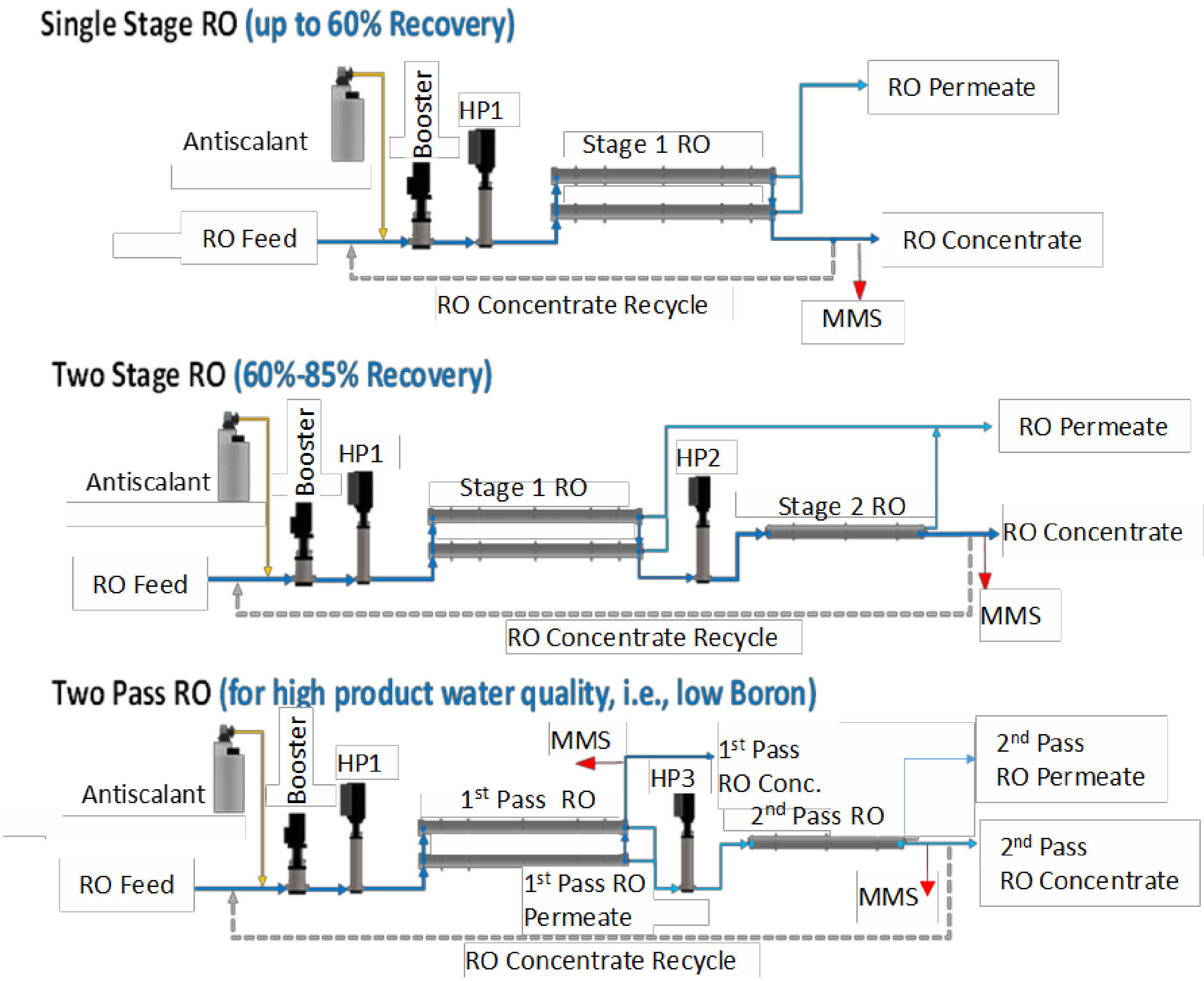

Figure 5. Process diagrams of the RO desalination train of the UCLA SIMS plant, illustrating various possible operational configurations. A continuous high-pressure side-stream for real-time *ex-situ* membrane monitoring system (MMS) can be taken from various locations.

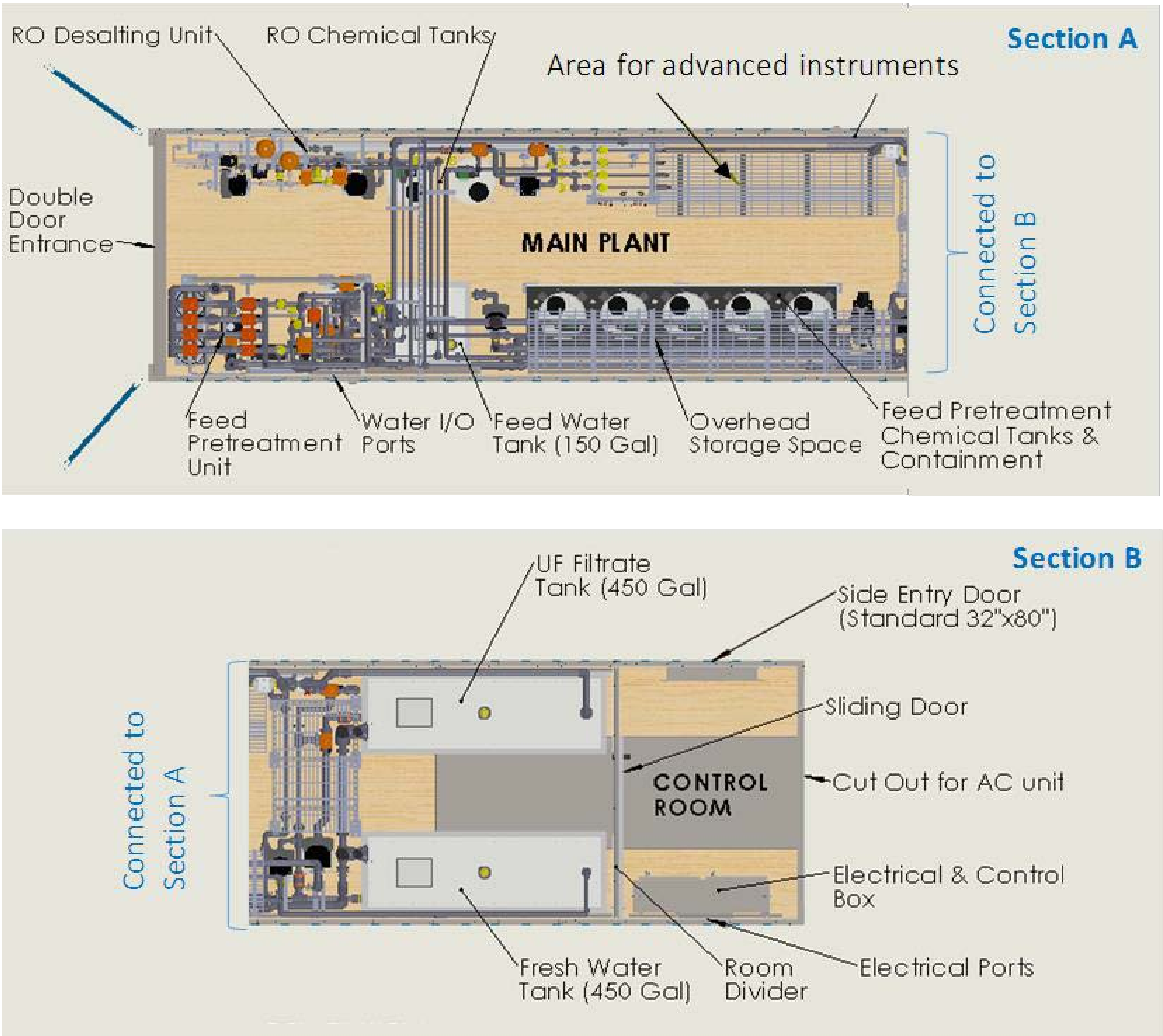

Figure 6. Interior layout design (top view) of the UCLA SIMS plant in a 40-ft ISO container.

Figure 7. Interior photos of UCLA SIMS plant.

Figure 8. The mobile SIMS plant.

5. Advanced Monitoring and Control

The implemented SIMS capabilities for self-adaptive high recovery RO desalting relies on an advanced architecture for real-time process monitoring and feedback control (Figure 9 and Figure 10), developed in part through the project and published in [25, 26]. A unique and enabling aspect of this architecture is the use of direct membrane surface imaging via the UCLA membrane monitoring system (MMS) for real-time detection and monitoring of mineral scaling (Figure 11, [27]) to direct RO system optimization and control. Online data from MMS and other process sensors (i.e., pressure, flow, conductivity, and temperature) are integrated and analyzed along with operator specifications (i.e., target water production) in a model-based controller and real-time optimization (MCO) module. Based on analyzed data, MCO algorithms predicting RO operation and water recovery limits are used to determine the necessary operational set-points (i.e., pressure, flow, and antiscalant dose) for maximizing RO water recovery. Using these set-points, the feed pump, valve, and metering pump controllers in the MCO direct the appropriate signal the associated process actuators to make the necessary process adjustments. Through a feedback mechanism, any RO process disturbances (e.g., changes in feed water quality, membrane scaling potential, temperature, etc.) detected by the process sensors are handled in real time by the MCO via system process actuators. Finally, another important part of the advanced monitoring and control capabilities of SIMS that was implemented was remote monitoring and control. This enabled monitoring and control of the pilot SIMS throughout most of the project's field testing remotely from UCLA.

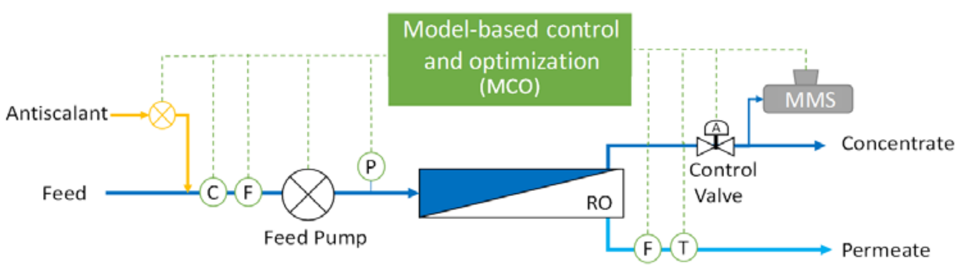

Figure 9. Schematic of process monitoring and feedback control for self-adaptive high recovery RO operation.

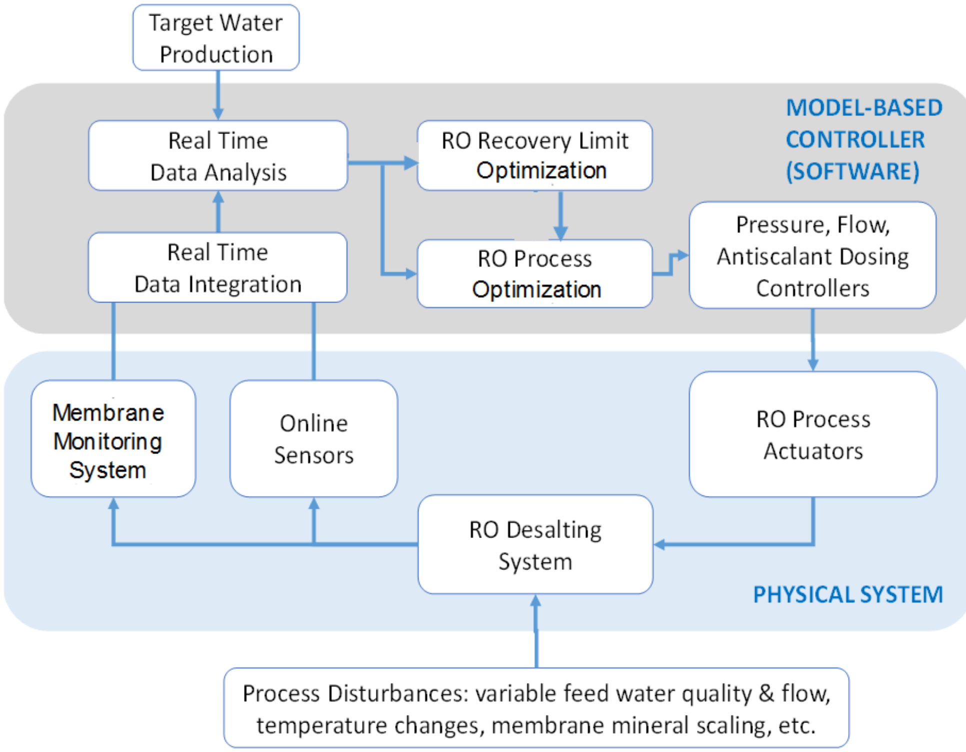

Figure 10. Process monitoring and feedback control architecture for self-adaptive high recovery RO operation.

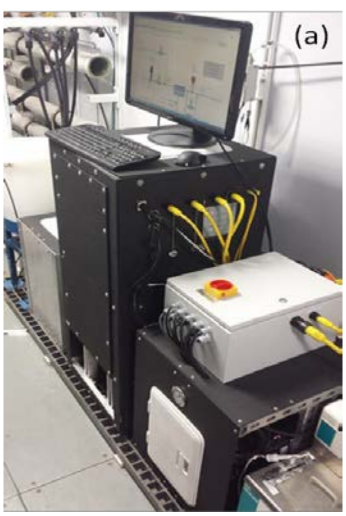

Figure 11. UCLA Membrane Monitoring System (MMS) deployed in the UCLA SIMS. The MMS can be connected to various streams (e.g., UF feed and filtrate, RO feed and concentrate) from the UCLA SIMS.

6. Field Test Site and SIMS Installation

SIMS field deployment in the project was conducted within the boundaries of the PDD Treatment Site at 11000 North Russell Avenue, Firebaugh, California, which is about an hour west of Fresno, California. The site (Figure 12), owned and operated by PDD, is part of the San Joaquin River Improvement Project under the Westside Regional Drainage Plan (WRDP). The WRDP is a regional plan for reducing the volume of saline agricultural drain water that is discharged to the San Joaquin River through source control, groundwater management, treatment, and reuse.

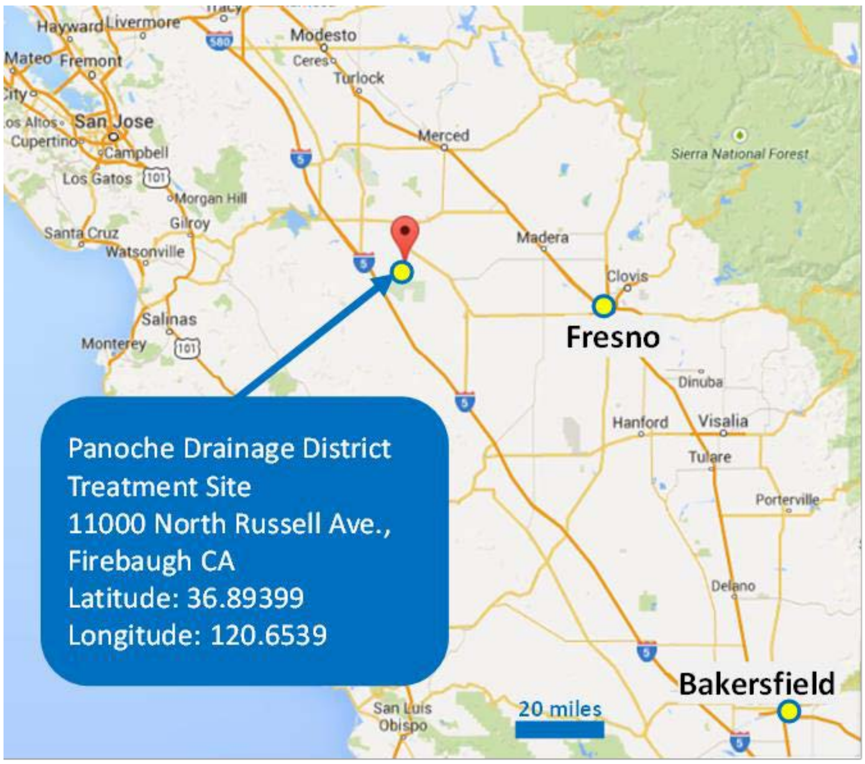

Figure 12. Project site location.

Site infrastructure (Figure 13) included a 50 foot x 150 foot secure test area (i.e., fenced and gated), equipped with electrical outlets (460 volt [V] 3 phase), sand filters, hydro-pneumatic tanks, and drain water flow control (i.e., valves). Using a submersible pump, up to 35-40 gpm of subsurface drain water can be delivered from PDD Tile Sump No. 3 (TS-3) to the test area through an existing underground piping (Figure 14). In the UCLA desalination plant operation at the site, RO permeate and concentrate was combined and discharged into the RP-1 irrigation ditch (owned and operated by PDD), which is located next to the test area (Figure 13).

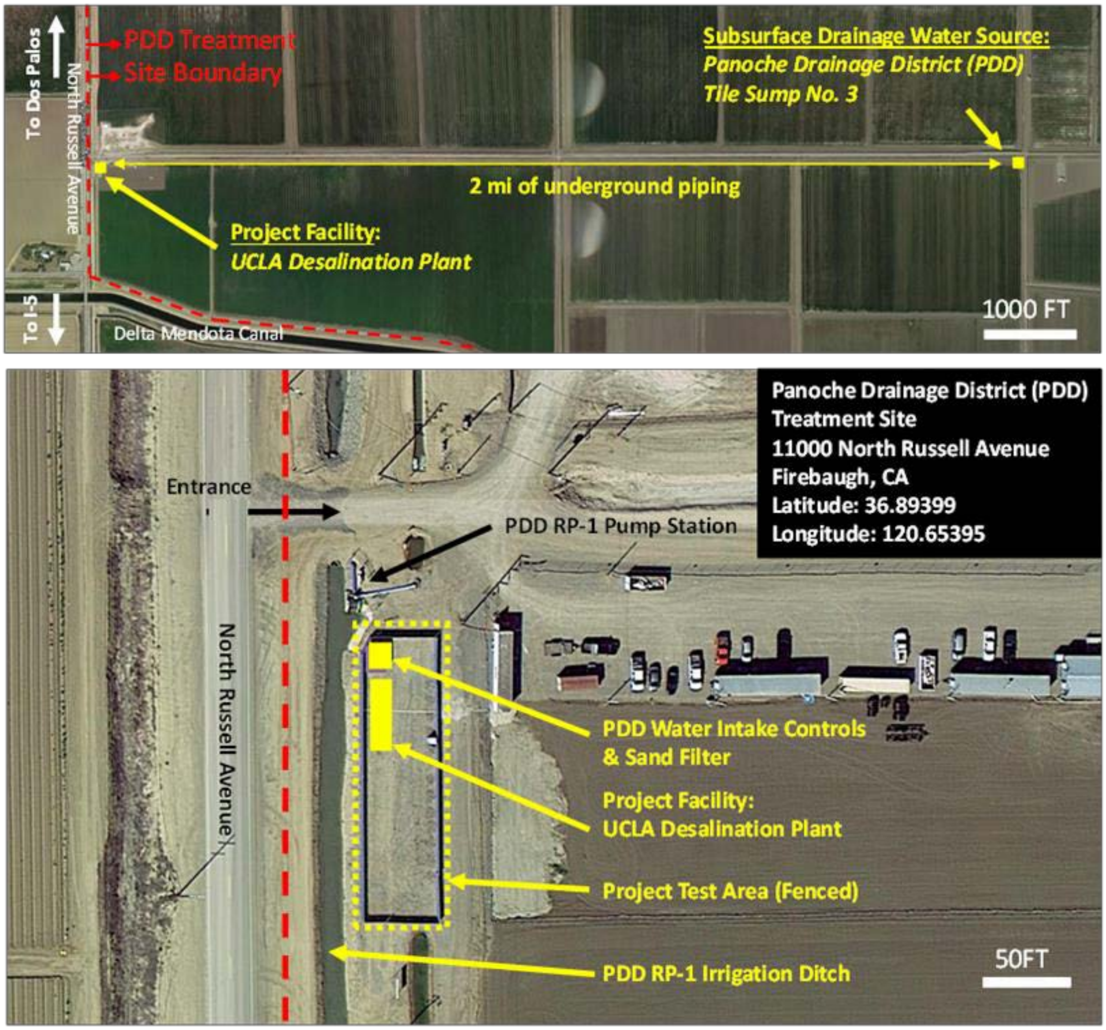

Figure 13. Map of the project site at the PDD treatment site and the SIMS pilot unit.

Figure 14. Field infrastructure at Panoche Drainage District treatment site, supporting operation of the UCLA desalination mobile unit.

7. Materials and Methods

7.1. Feed water quality and materials

SIMS was deployed at the field test site for pilot testing of desalination of subsurface agricultural drainage water from Tile Sump No. 3 (TS-3) at the Panoche Drainage District (PDD) treatment site. Water quality data based on analysis of water samples taken over the course of the project Table 2) indicated that desalination of this source water is very challenging due to high and variable drainage water salinity (15,698 ± 23- 28% mg/L) and high mineral scaling potential (primarily by gypsum, with gypsum saturation index range of 0.87-1.45). Major ions in the source water included sulfate (38-40%wt), sodium (26-28%wt), chloride (23-24%wt), and calcium (3-6%wt). It is also noted that both nitrate (149 mg/L) and selenium (~0.4-0.5 mg/L) were significantly above California Department of Public Health (CDPH) drinking water maximum contaminant limit (MCL) of 45 mg/L and 0.01 mg/L, respectively. Boron was present at 58 ± 30-72% mg/L mg/L, which is above the CDPH notification limit (NL) of 1 mg/l.

Table 2. Feed Water Quality from TS-3 Well at PDD Test Site (from analysis of water samples during the period of July 2014 to December 2015).

Analyte	Average	Std. Dev.	Min.	Max
Turbidity (NTU)	0.66	0.66	0.15	1.17
pH	7.65	0.19	7.38	8.00
Total Dissolved Solids (mgl/L)	15698	2630	11370	19370
Total Organic Carbon (mgl/L)	9.6	2.1	6.9	13.9
Total Alkalinity (mgl/L as $CaCO_3$)	340	66	211	414
Dissolved Boron (mgl/L)	58	15	40	100
Dissolved Calcium (mgl/L)	576	124	480	975
Dissolved Chloride (mgl/L)	3627	1090	1805	5742
Dissolved Magnesium (mgl/L)	392	106	270	676
Dissolved Nitrate (mgl/L)	149	37	90	213
Dissolved Potassium (mgl/L)	12.6	9.1	5.5	42.8
Dissolved Selenium (mgl/L)	0.5	0.05	0.5	0.4
Dissolved Silica (mgl/L)	38.4	6.1	20.7	46.8

Analyte	Average	Std. Dev.	Min.	Max
Dissolved Strontium (mg/L)	9.3	6.1	1.0	27.2
Dissolved Sodium (mgl/L)	4187	827	2799	5310
Dissolved Sulfate (mgl/L)	6566	1045	5530	9647

Table 3 Mineral Saturation Indices of Feed Water from TS-3 Well at PDD Test Site (Jul. 2014 - Dec. 2015)

Mineral Scaling Potential	Average	Std. Dev.	Min	Max
Calcium Carbonate Saturation Index	7.1	1.2	5.9	8.7
Gypsum Saturation Index	0.98	0.17	0.79	1.45
Strontium Sulfate Saturation Index	0.96	0.20	0.74	1.22
Silica Saturation Index	0.31	0.05	0.18	0.37

Inline coagulation was carried out using aluminum chlorohydrate (ACH) solution (5% wt. aluminum), injected with no prior dilution into the UF feed water. ACH was obtained from Qemi International, Inc. (QEMIPAC 7580). Antiscalants solution, injected with no prior dilution into the RO feed, were Flocon 260 (AS 1) and Flocon 135 (AS 2) obtained from BWA Water Additives.

7.2. Analytical Methods

7.2.1. Water Quality

Samples from the feed and permeate streams were collected and analyzed by the Bryte Laboratory of the California Department of Water Resource to provide detailed water quality analysis via standard methods. Membrane samples were analyzed via scanning electron microscopy and elemental dispersion spectroscopy (SEM-EDS) at the UCLA Water Technology Research Center laboratory. In addition, measurements temperature, turbidity, flow rates, pressure and conductivity were acquired online for various SIMS streams as per Table 4.

Table 4. Key Online Measurements

	UF Feed	UF Filtrate	RO Feed	RO Permeate 1st Stage	RO Permeate 2nd Stage	RO Interstage Concentrate	RO Concentrate
Temperature	X			X	X		
Turbidity	X						
Flow	X	X	X	X	X		X
Pressure	X	X	X	X	X	X	X
Conductivity			X	X	X		X

7.2.2. Real-time Membrane Surface Image Analysis

Real time membrane monitoring was accomplished using the UCLA membrane monitoring system (MMS) as per the method described in [27]. Briefly, in the optically- observable MMS membrane cell, concentration polarization develops whereby the concentration at the membrane surface (C_m) is higher than the bulk solution (C_b) by a factor $CP_{MMS} = C_m/Cb$. CP_{MMS} can therefore be selected to mimic the conditions that exist at the SIMS plant concentrate exit where the equivalent recovery given by Equation 2:

$$Y_{eq} = 1 - \frac{1}{CP_{MMS}} \quad (2)$$

When the feed water to MMS is the concentrate from SIMS plant, the equivalent water recovery of an RO process mimicked by MMS is given by Equation 3:

$$Y_{eq} = 1 - \frac{1}{CP_{MeMo} \cdot CF_{SIMS}} \quad (3)$$

Where the SIMS concentrate concentration factor is given by Equation 4:

$$CF_{SIMS} = \frac{1 - Y_{SIMS} \cdot \beta_{nom}}{1 - Y_{SIMS}} \quad (4)$$

In which

Y_{SIMS} is the SIMS water recovery level and

$\beta_{nom} = c_p / c_f$ is the nominal membrane salt passage.

Images of the RO membrane surface were analyzed using specialized in-house software. The image analysis algorithm uses image segmentation to highlight and quantify surface changes due to mineral scaling or fouling. Prior to analysis, images are first converted to grayscale and enhanced based on histogram equalization to increase image contrast, and are subsequently aligned to enable accurate image comparison. Image background subtraction is then carried out to identify the evolution of surface changes over time. Subsequently, the identified scaled areas are quantified with respect to the surface area coverage, and the number of identified scaled entities (i.e., particles) are enumerated.

7.3. System Operational Settings

The UF and RO units were operated according to the set points listed in Table 5. SIMS operated in an autonomous mode to handle fluctuations in the feed water (e.g., with respect to salinity) in real time to maintain stable system productivity. UF was operated at filtrate flux of 27-31 GFD at >95% recovery. The RO unit was operated at feed flow range of up to 8-15 GFD at 50-75%. It is noted that, the UF unit was designed to enable UF performance evaluation at high flux. Accordingly, the UF unit was somewhat oversized with respect to the feed flow rate required by the RO unit. The UF unit productivity can be regulated and match the feed flow rate required by the RO unit and for UF backwash, given the sufficiently large holding capacity of the UF-RO intermediate (i.e., 450-gallon UF backwash tank; see Figure 4).

Table 5. Key Operating Parameters for the SIMS Testing

Parameter	Set Point
UF Filtrate Flux (GFD)	27-31
RO Permeate Flux (GFD)	8-15
UF Recovery Level	>95%
RO Recovery Level (%)	50 %-75%

8. Results and Discussion

8.1. Implementation of Real Time Mineral Scale Detection to Evaluate RO Feed Filtration Requirements

To establish effective RO operations, one must first assess the adequacy of RO feed pretreatment. Such an assessment can be accomplished based on standalone MMS operations that focus on optimizing feed pretreatment. MMS evaluations revealed that RO feed pretreatment with media filters, hydraulic separator and a rotating self-cleaning microfilter, without antiscalant dosing, was insufficient (Figure 15). MMS RO membrane surface images for RO operation at 50% recovery without antiscalants dosing revealed that small mineral scale crystals had developed. It was postulated that the nucleation of these crystals was facilitated by fine particles that were not removed via the RO feed pretreatment—despite the fact that the treated feed turbidity was <1 NTU, which is well within the recommended range for RO desalting.

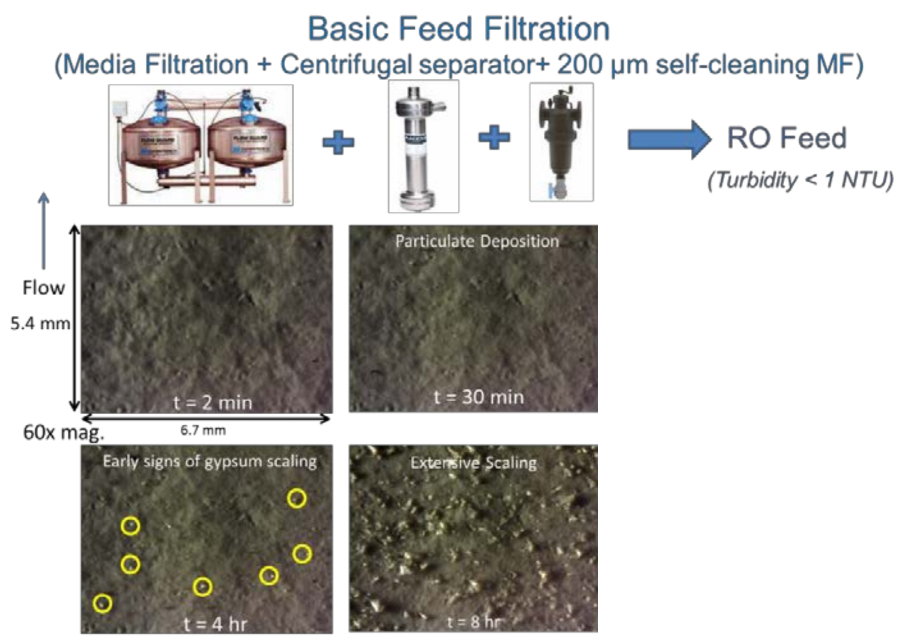

Figure 15. RO Membrane surface images for feed pretreatment via media filtration, centrifugal separator and microfiltration. The membrane was exposed to a concentrate with an equivalent RO recovery of 50% produced without antiscalants feed dosing.

Once feed pretreatment was upgraded to include UF, media filtration was unnecessary. Turbidity of the treated RO feed was below 0.1 NTU, and mineral scaling (without using antiscalants) was significantly reduced (Figure 16). Analysis of membrane surface images (Figure 17) clearly demonstrated that the number and density of mineral crystals was significantly higher without UF feed filtration. Direct observation of the state of the membrane surface scaling was the only way to detect this. For water with a high mineral scaling propensity, fine particles removal (down to ~20 nm) is critical to reduce the potential for mineral crystal nucleation associated with fine particles in the treated feed water.

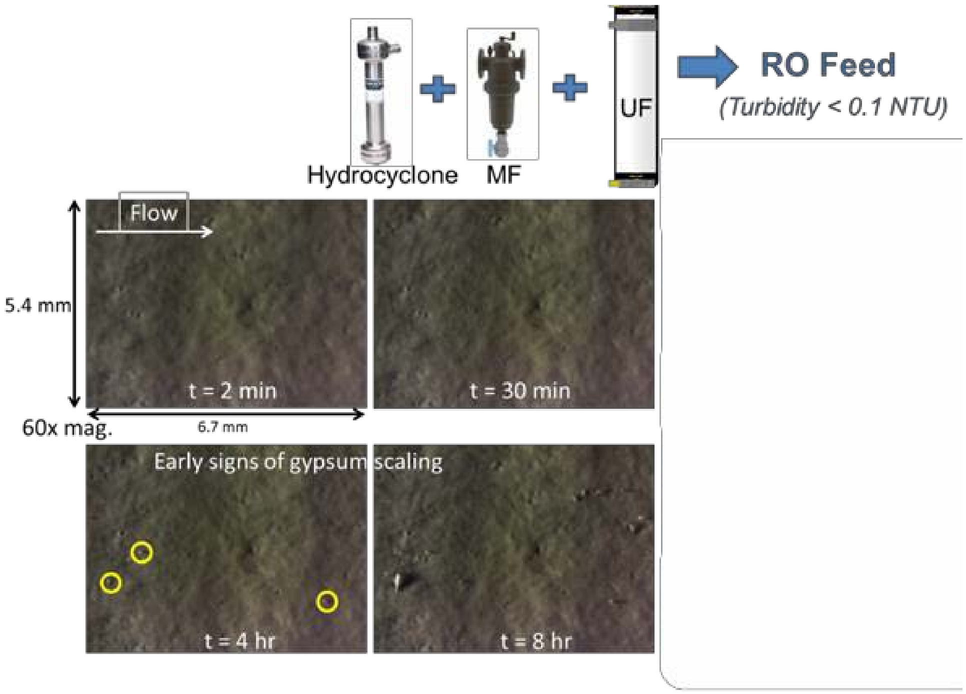

Figure 16. RO membrane surface images showing a significant reduction in membrane scaling (and particulate fouling) by adding UF treatment of the RO feed and without media filtration. The RO system was operated under the same conditions as for the test as in Figure 17.

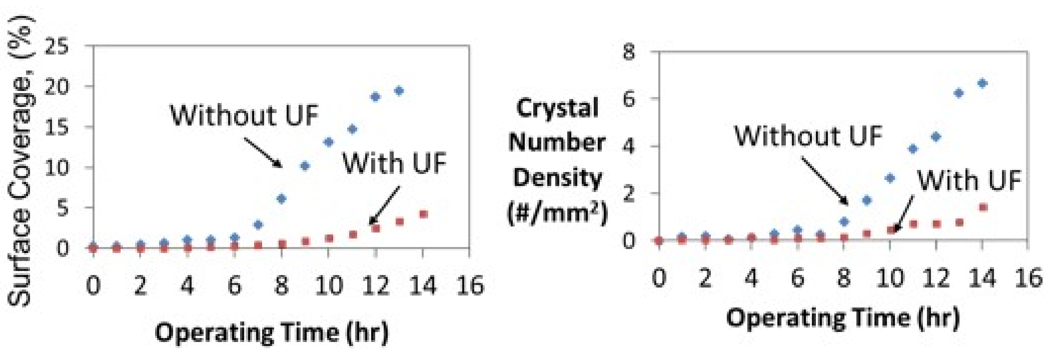

Figure 17. Evolution of mineral scaling, quantified by (left) surface area scale coverage and (b) number density of mineral crystals, for RO operation with and without ultrafiltration feed pretreatment.

8.2. Ultrafiltration (UF) operational performance

The UF unit was operated at high water recovery (>96%; Figure 18) by maximizing filtration time (up to 60 minutes) and minimizing backwash duration (to 50 seconds). For enhanced filtration performance, inline coagulation was implemented with a relatively low coagulant dose (0.08 mg/L Alum), achieved through a rapid injection of 5 parts per million (ppm) for 10 minutes at the beginning of each filtration cycle. Transmembrane pressure remained relatively stable below 8 pounds force per square inch, differential (psid) even after four months of operation at a flux of 27 GFD, (Figure 19). Therefore, the flux was increased to 31 GFD. After six months of UF operation without any chemical cleaning, the transmembrane pressure remained below 10 psid (at 31 GFD flux, i.e., filtration resistance of <0.35 PSI/GFD; Figure 20), which was well within typical maximum limit before chemical cleaning would be required (~20 psid). The above field performance suggested that the established UF operating conditions (60 minute filtration duration at flux of up to 31 GFD, 50 seconds backwash, 98 GFD backwash flux), coupled with inline coagulation (at ACH average concentration of 0.08 mg/L Aluminum) was adequate for operation at high UF recovery (96.5-98% recovery) with expected UF operation of 6 to 12 months before needing in place UF chemical cleaning.

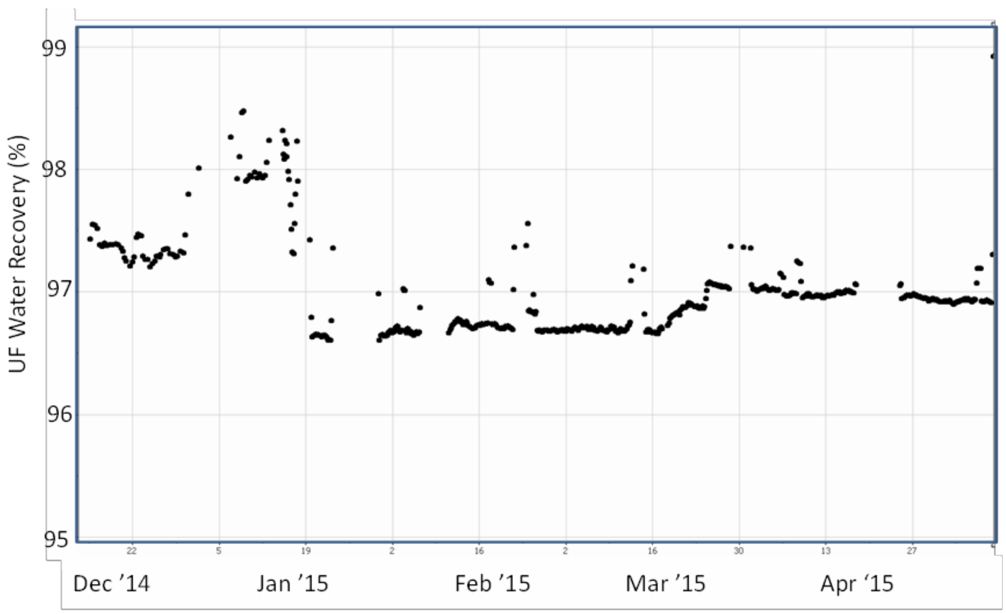

Figure 18. Example time profile of UF water recovery. Operating conditions: average coagulant (ACH) dose: 0.8 mg/L Al, filtration duration: 60 minutes, backwash duration 50 seconds, backwash flux 98 GFD.

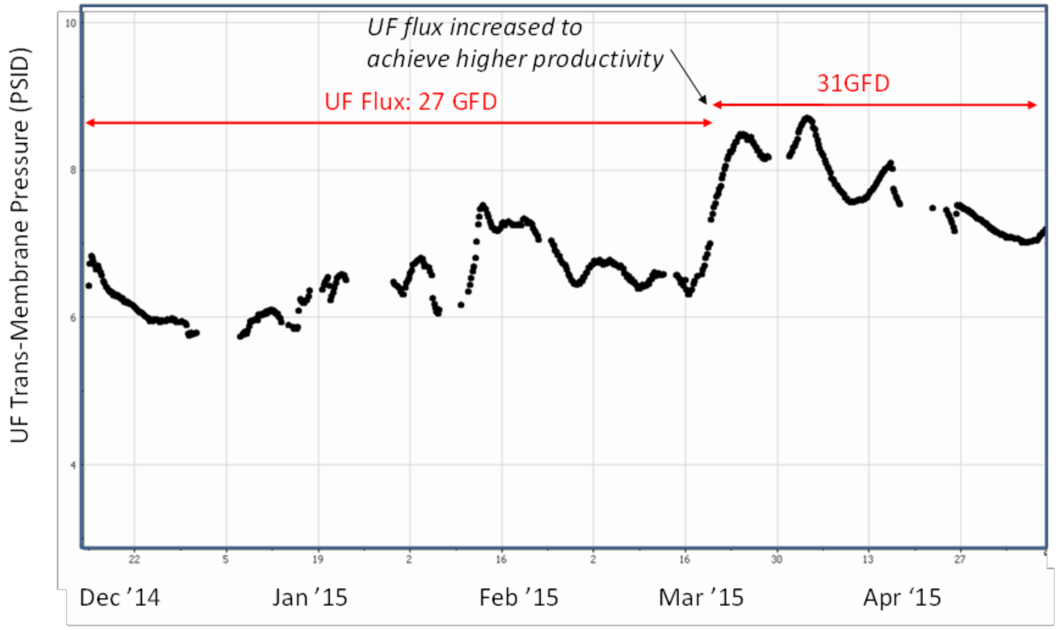

Figure 19. Example time profile of UF trans-membrane pressure. Operating conditions: average coagulant (ACH) dose: 0.8 mg/L Al, filtration duration: 60 minutes, backwash duration 50 seconds, backwash flux 98 GFD.

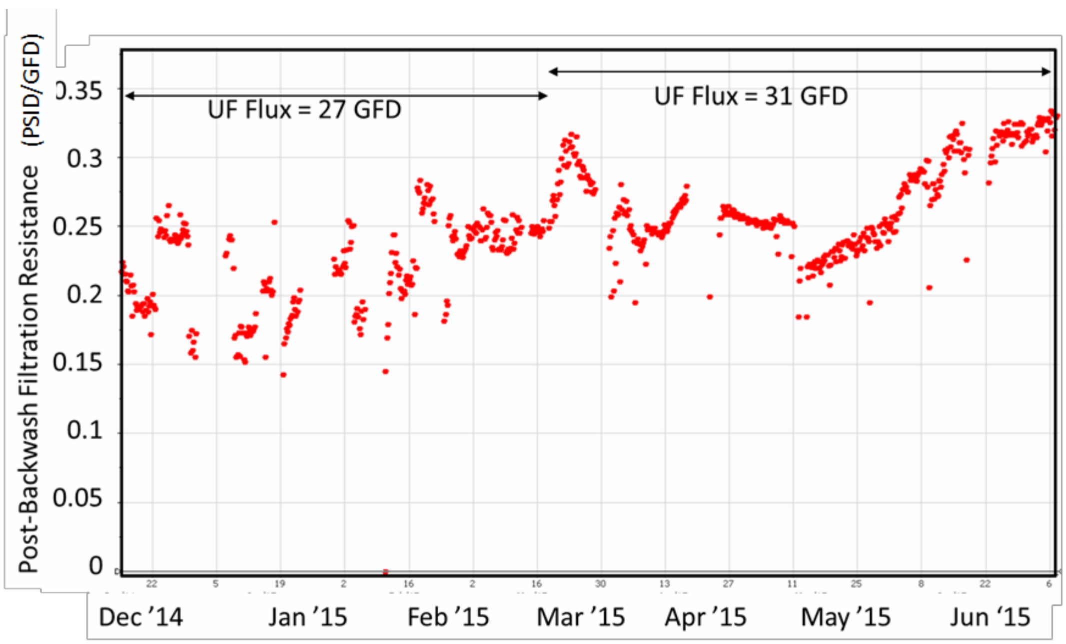

Figure 20. Example time profile of UF filtration resistance (post backwash). Operating conditions: average coagulant (ACH) dose: 0.8 mg/L Al, filtration duration: 60 minutes, backwash duration 50 seconds, backwash flux 98 GFD.

8.3. RO Operational Control Performance

Process control methods for self-adaptive RO operation were developed based on advanced model-based control framework developed in earlier studies [25, 26]. The model-based control method enabled automatic selection of optimal RO operating conditions, given user input of permeate productivity and target water recovery level—allowing the system to adapt operating conditions to feed water quality variations. As illustrated in Figure 21, the SIMS model-based controller correctly predicted and adjusted the first and second stage RO pressures to maintain RO production and water during a period of significant water salinity variations (by ~5,000 mg/L TDS) caused by a rain event.

In addition to handling feed salinity variations, capabilities to vary water recovery based real-time detection of membrane scaling were also investigated. Real-time MMS image analysis was implemented based on UCLA's membrane monitoring [28]. Time evolution of membrane surface coverage by mineral scale (in the MMS membrane cell) was automatically tracked in this automated membrane image analysis (Figure 22**)**. A feedback controller was implemented to allow triggering of SIMS fresh water flush when the surface scale coverage monitored in MMS reaches a specified threshold.

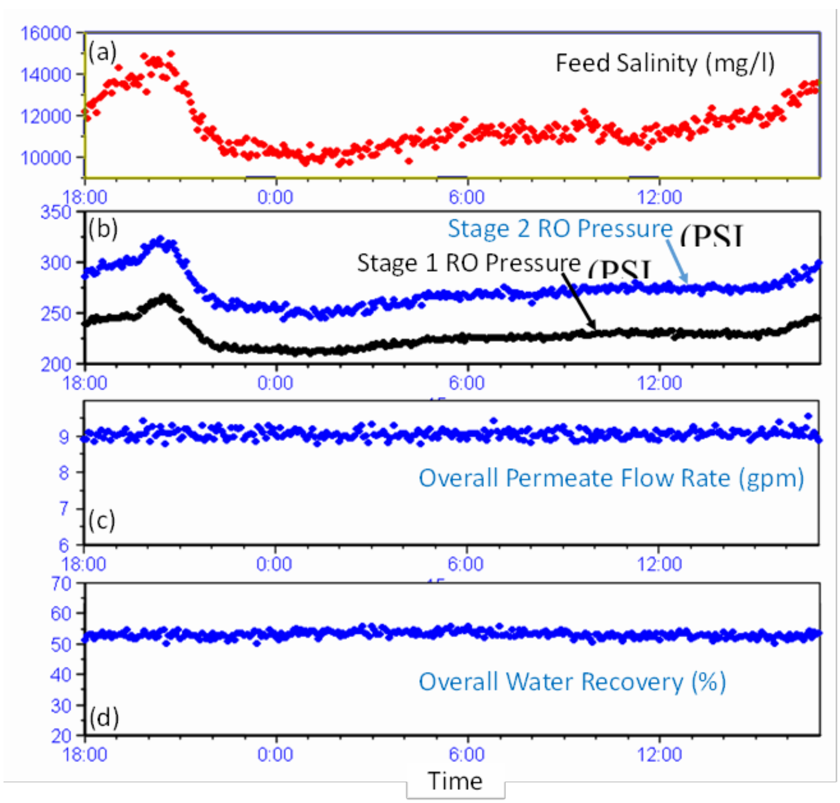

Figure 21. Feed salinity, RO feed pressures, permeate flow rate, and overall water recovery in the UCLA SIMS RO unit during a rain event (December 14-15, 2014).

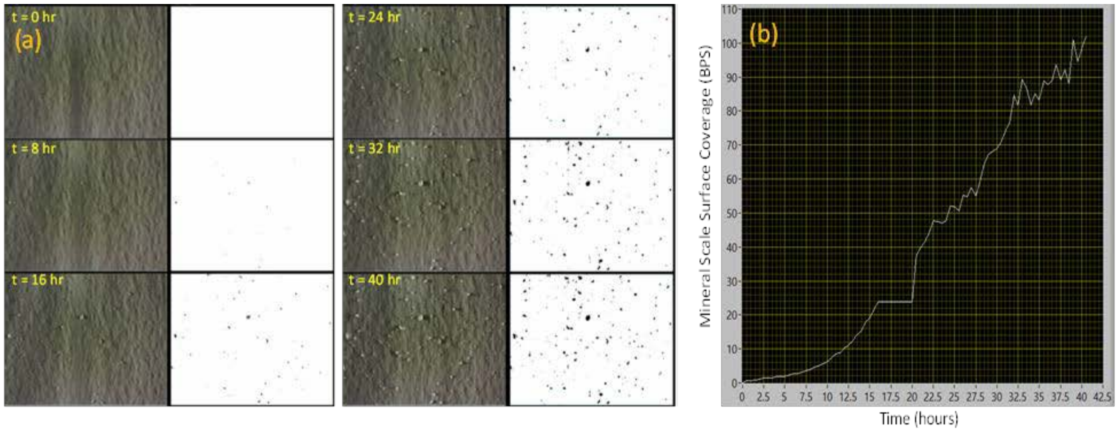

Figure 22. Automated online (a) membrane image analysis and (b) of gypsum mineral scale coverage in a MMS standalone operation using ultra filtered PDD TS-3 drainage water (TDS~17,000). Equivalent RO recovery: 50%; no antiscalant. Fractional mineral scale surface coverage over the membrane surface area is expressed in basis point unit, in which 1 BPS = 1/10,000 = 0.01 % area scaled).

8.4. Online RO Recovery Optimization

Long-term continuous RO desalting operations were conducted to demonstrate online RO water recovery optimization. Two types of antiscalants were used (AS1 and AS2). The recovery levels of SIMS during this test period are shown in Figure 23. The equivalent RO recovery rate monitored by MMS was set higher to ensure early detection of mineral scale detection. In the initial period (Days 0-35), 5 ppm of AS1 was sufficient to inhibit mineral scaling up to a water recovery level of 71%, when mineral scaling was finally detected on Day 31 via MMS (Figure 24). Fresh water flush (FWF) was subsequently triggered on Day 35. It is important to note that the permeate flux of the RO tail section of SIMS remained constant (Figure 25) even after the MMS detected mineral scaling. This demonstrated the MMS' ability to detect mineral scaling early. Subsequent SIMS fresh water flushes were effective in re-dissolving/cleaning the scaled membrane (Figure 24), while at the same time ensuring that the SIMS RO elements to remained free of mineral scale.

In the subsequent stage of operation (Days 36 - 60), dosing the RO feed with 5 ppm antiscalant AS1 inhibited mineral scaling up to SIMS water recovery of 68% (at Day 58; Figure 26). Subsequent increases in antiscalants dosing to 6 - 7 ppm did not measurably enhance mineral scale inhibition as illustrated in Figure 27. In this example, RO desalting was carried out at 68% recovery with 5 ppm antiscalants dosing and mineral scaling was allowed to develop to cover ~7.5% of the monitored membrane area with scale. Subsequently, the antiscalant dose was increased incrementally up to a dose of 7 ppm. However, as shown in Figure 27 mineral scaling was not retarded and continued at essentially the same rate as before the increased antiscalants dosage. The above finding suggests that, at least for the antiscalants used in the study, additional antiscalant dose increases may be ineffective in retarding scaling once mineral scale is established on the membrane surface.

Upon exposing the membrane surface to RO permeate (from the SIMS product water tank), mineral scale was removed from the membrane surface via fresh water flushes. An illustration of tracking of a single crystal formation and dissolution is provided in Figure 28**.** Dissolution of the crystal, when exposed to fresh water flush, is achieved in about 20 minutes. This behavior confirms that scale removal is feasible if carried out sufficiently early in the evolution of surface scaling by exposing the membrane surface to a sufficiently undersaturated solution with respect to the target mineral scalant. It is noted that approximately 400 gallons are typically needed for a fresh water flush (FWF) for the SIMS plant RO elements. Based on the experience with SIMS operation, a scale mitigation strategy via FWF of the RO system would use less than 0.6% of the produced RO permeate.

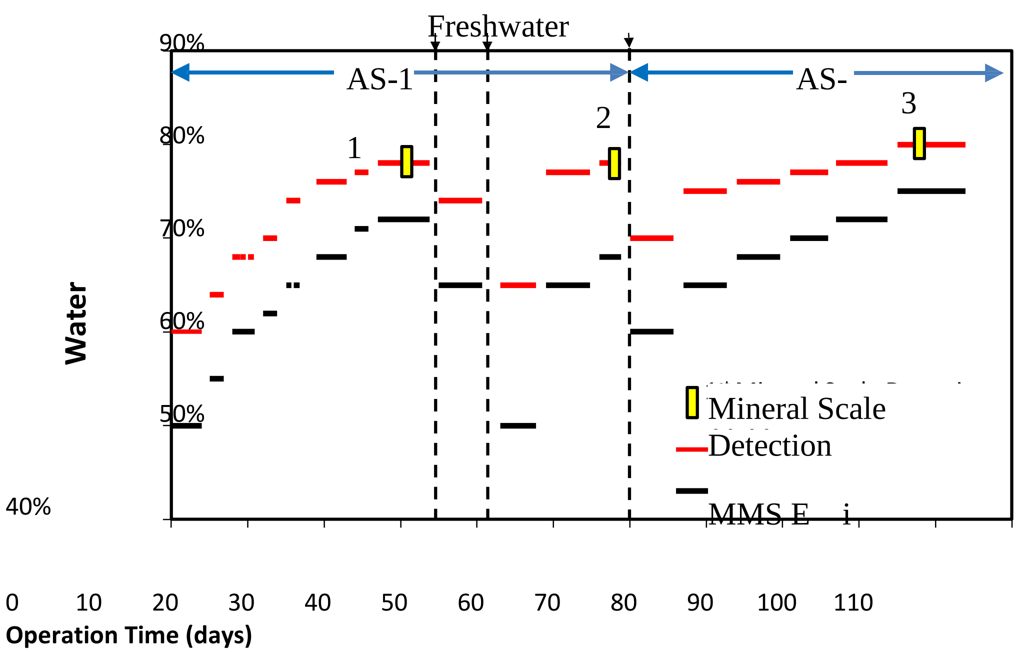

Figure 23. RO water recovery in the SIMS plant and the corresponding equivalent RO water recovery conditions monitored by MMS (via MMS concentration polarization settings). Times when mineral scaling are detected (detection points 1-3) and freshwater flush are triggered are indicated by the yellow rectangles. Operating conditions: 5 ppm antiscalant dose except for days 60-61 (6-7 ppm) and days 97-105 (2.5-4 ppm.), RO average flux: 13 GFD, Feed salinity 9,000 -18,000 mg/L TDS, SI_G raw RO feed = 0.8-1.0.

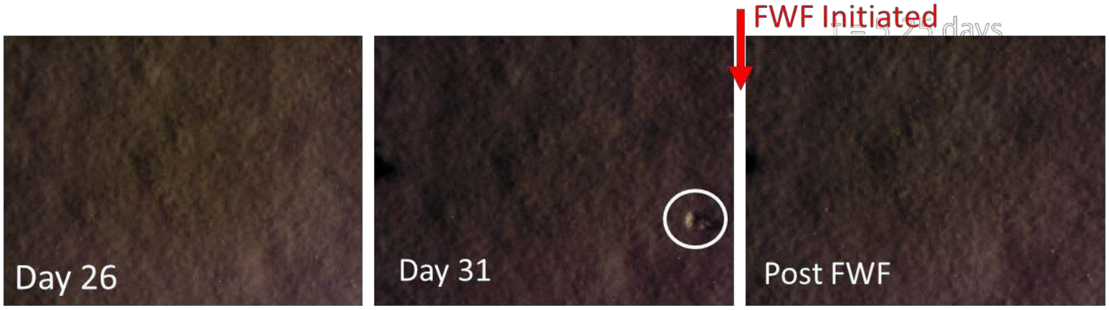

Figure 24. MMS RO membrane images at days 26-31 (detection point 1 in Figure 23), indicating mineral scale detection within five days after the SIMS recovery was raised from 50% to 71%. Freshwater flush was triggered at day 35. Antiscalant dose: 5 ppm AS1. RO average flux: 13 GFD, feed salinity ~13,500 mg/L TDS.

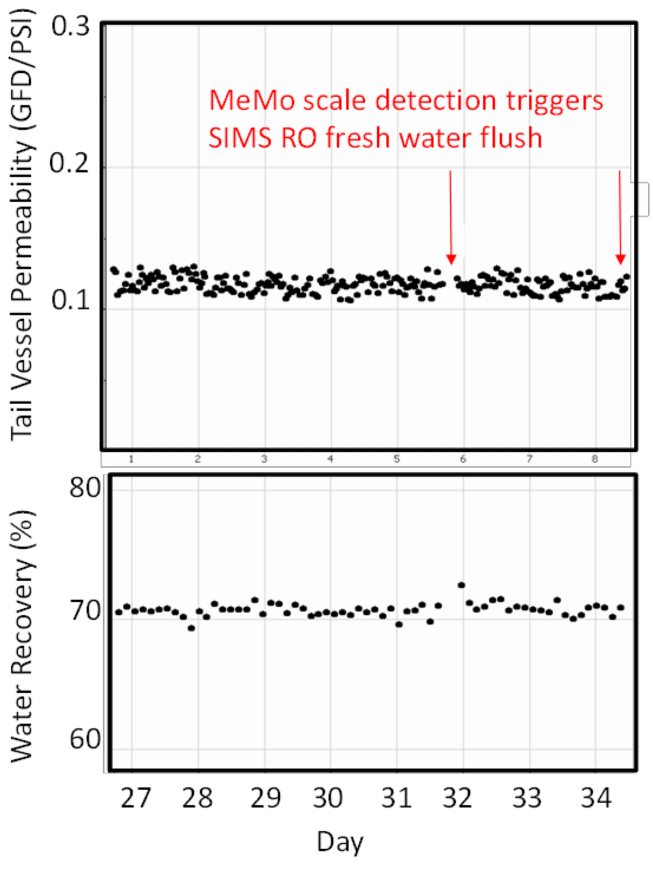

Figure 25. SIMS tail element membrane permeability and overall RO water recovery during mineral scale detection shown in Figure 24 for the same SIMS and MMS operating conditions.

Figure 26. MMS images at days 58-60, indicating mineral scale detection (detection point 2 in Figure 22), within three days after the SIMS recovery was raised to 68% (at day 57). Initial antiscalant dose: 5 ppm AS1. Antiscalant dose was raised to 6-7 ppm in day 59-60. RO average flux: 13 GFD, feed salinity ~9,000 mg/L TDS.

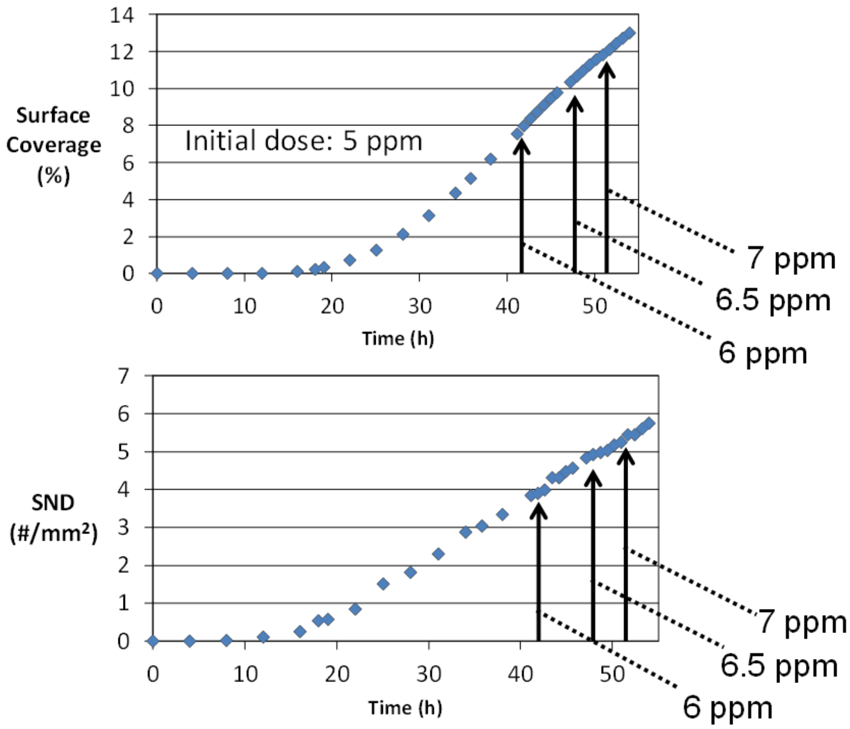

Figure 27. (a) Evolution of membrane surface mineral scale coverage, and (b) crystal number density for RO operation at 68% and where the antiscalant dose was increased progressively once measurable level of scaling was detected. Once mineral scale develops, further increase of antiscalant dose is ineffective in further retardation of membrane mineral scaling. Time zero shown above is at day 57 in Figure 25. (detection point 2 in Figure 22),

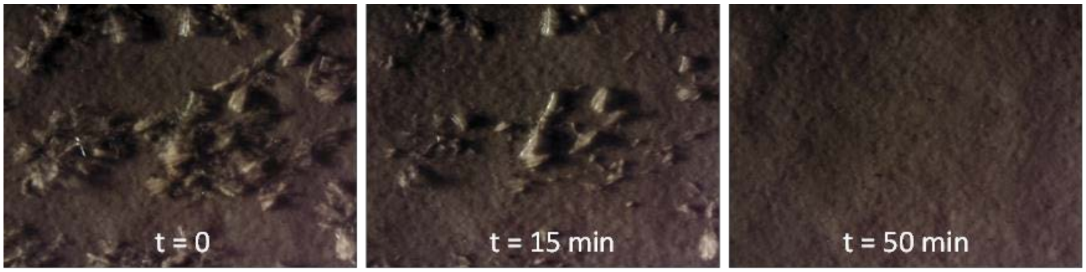

Figure 28. MMS images during fresh water flush, triggered at the end of day 60 after SIMS operation at 68% recovery.

In Days 60 - 105, SIMS was operated up to a water recovery of 75%, initially using 5 ppm of antiscalants AS2. Membrane mineral scaling was not observed through the period up of up to Day 100 (Figure 29) after antiscalants dose was reduced from 5 ppm to 4 ppm on Day 97 and subsequently to 3 ppm on Day 100, when mineral scaling finally became apparent via MMS. The growth rate of the mineral scaling was relatively low, and further reduction of AS dose to 2.5 ppm did not result in significant increases in mineral scale surface coverage by Day 105. The above tests demonstrated that AS2 was significantly more effective than AS1. SEM-EDS analysis confirmed gypsum as the primary mineral scalant, in addition to traces of silica (Figure 30).

The above field tests demonstrated that by using MMS, recovery level and antiscalant dosage can be optimized online without needing to halt water production. Furthermore, membrane samples from MMS can be taken out for autopsy (in lieu of full membrane element autopsy) to identify mineral scalants on the membrane surface.

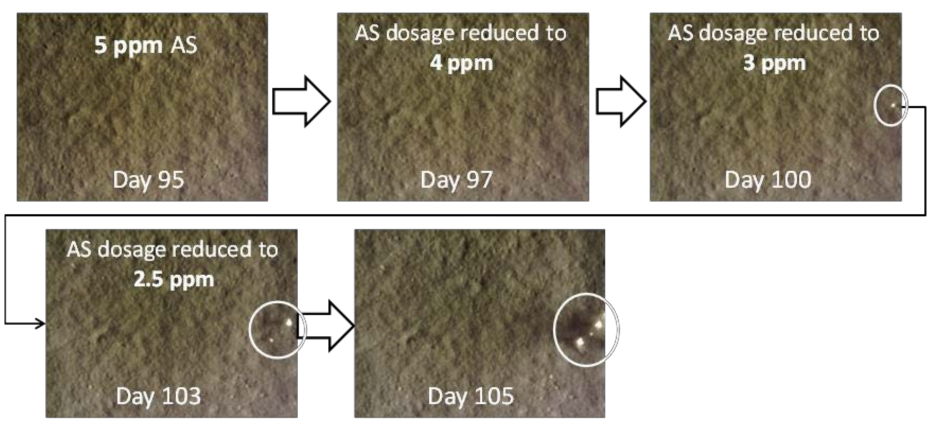

Figure 29. MMS images at days 95-105, indicating mineral scale detection within three days after the SIMS recovery was raised to 75% (at day 95). RO average flux: 13 GFD, feed salinity ~9,000 mg/L TDS.

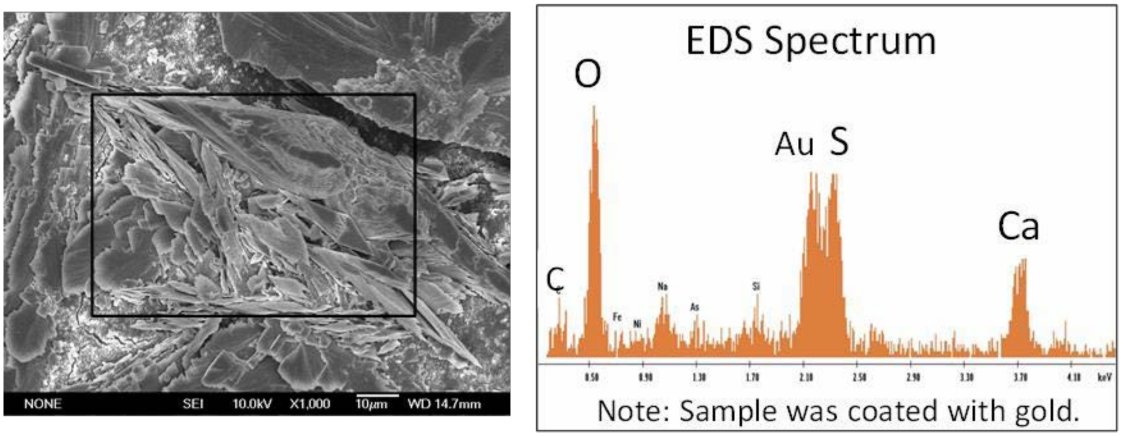

Figure 30. Scanning electron micrograph of a membrane sample (see Figure 29) indicating that calcium sulfate (i.e., gypsum) was the primary mineral scalants, with traces of silica. Note: the detection of gold (Au) was due to membrane sample coating with gold prior to analysis.

8.5. Agricultural Drainage Water Desalination Performance

Over 100 days of continuous SIMS operation indicated that it was indeed feasible to desalt high PDD salinity agricultural drainage water at recovery range of up to 75% (and possibly higher) to produce fresh water (Figure 31 and Figure 32). Self-adaptive system operation, enabled via MMS and advanced model-based process control, was critical for handling significant variations in feed water salinity (Figure 33) and mineral scaling potential. Despite significant variations in feed water and operational conditions, RO product salinity (Figure 34) and quality (Table 6) remain consistent with salinity <100 mg/L TDS and nitrate levels (<4 ppm). However, product water polishing (e.g., via two-pass RO) and/or use of higher boron rejecting membranes will be needed to further reduce boron concentration in the permeate (10 - 20 mg/L).

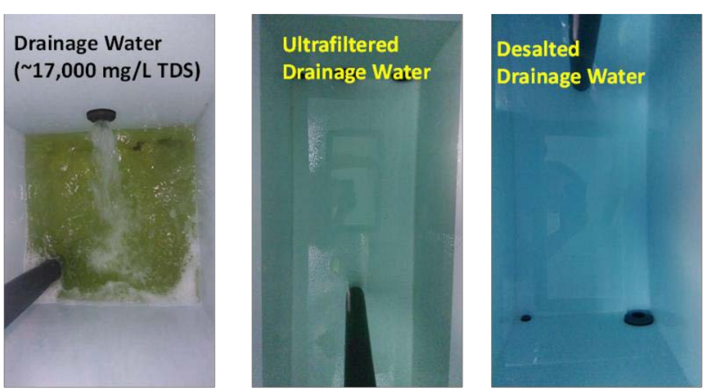

Figure 31. Images of drainage water treated at the UCLA mobile desalination unit.

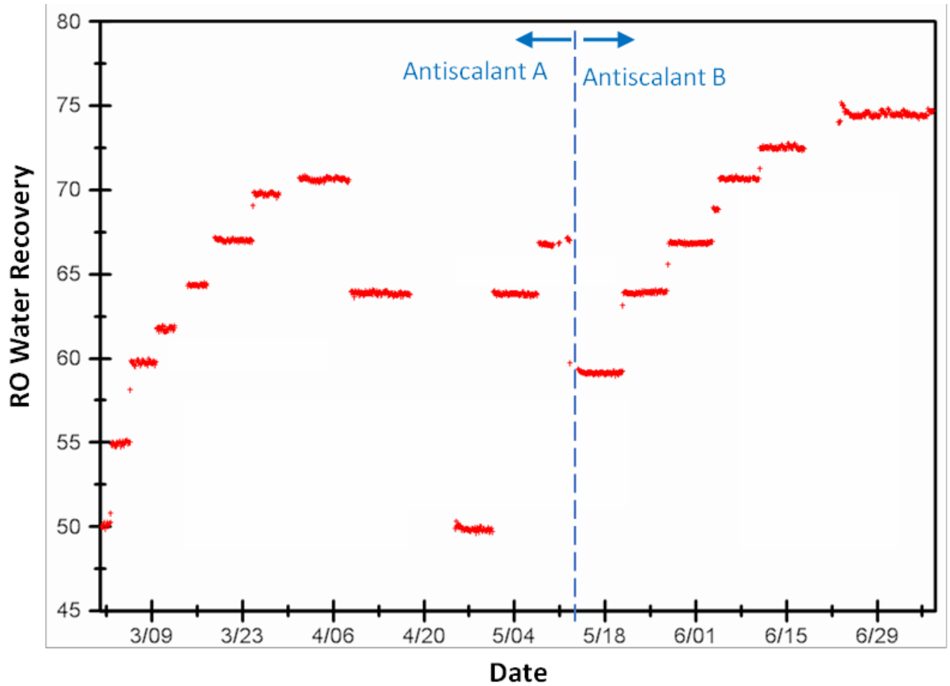

Figure 32. RO water recovery.

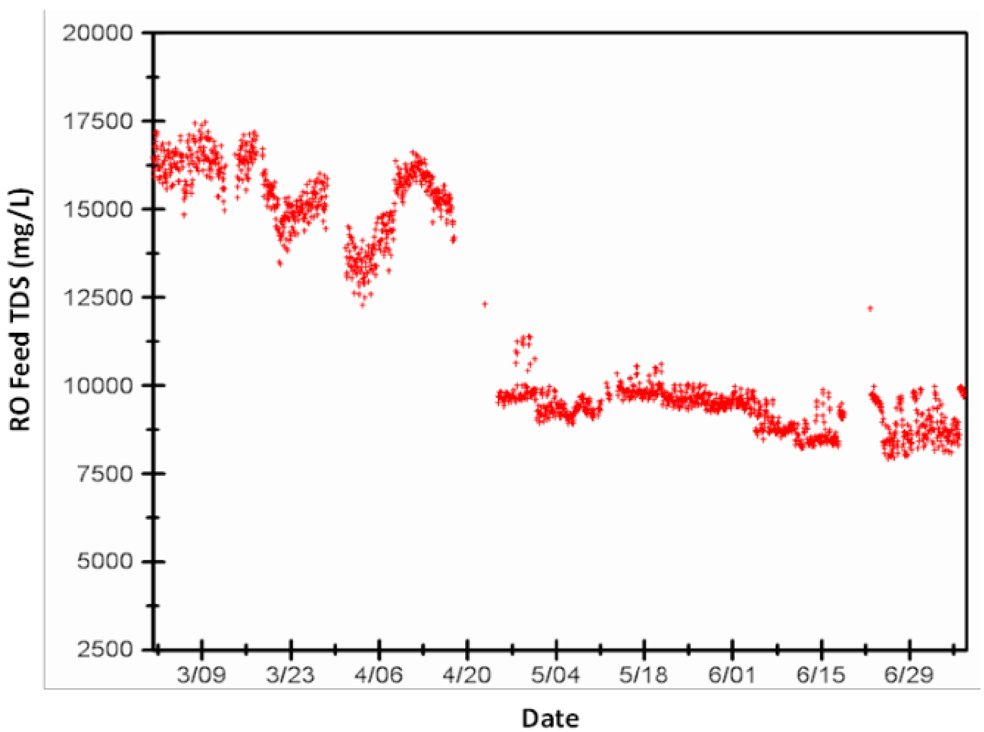

Figure 33. RO feed TDS.

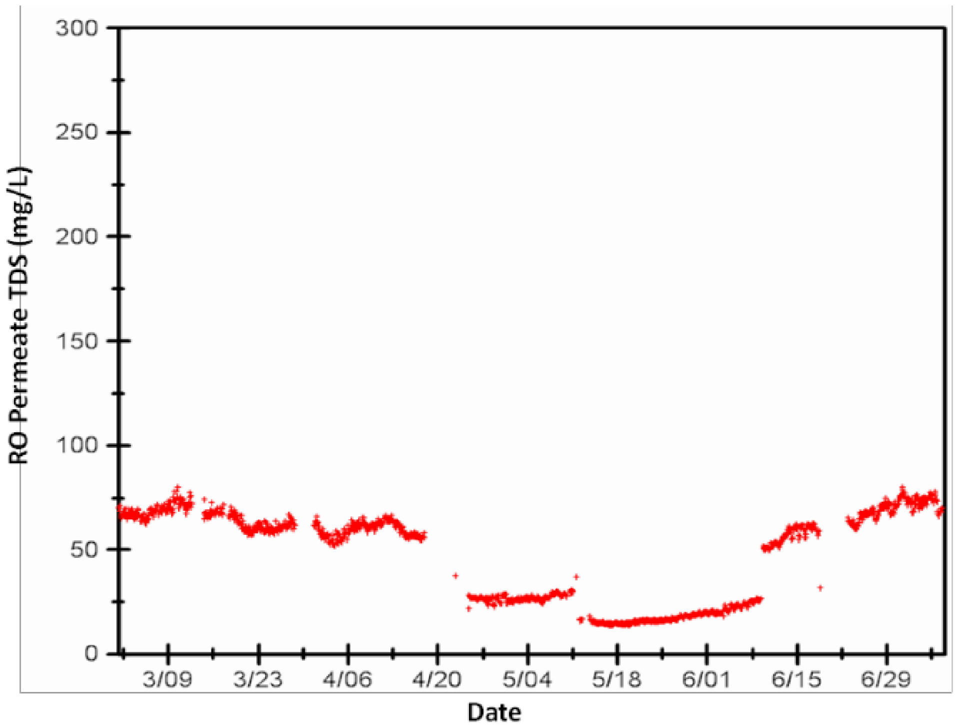

Figure 34. RO product water TDS.

Table 6. RO Product Water Quality

Sample Date		4/1/2015	4/14/2015	5/12/2015	6/23/2015
Conductance (EC)	µS/cm	82	107	54	86
Dissolved Aluminum	mg/L	< 0.01	< 0.01	<0.01	<0.01
Dissolved Boron	mg/L	14.43	15.775	12.8	17.57
Dissolved Calcium	mg/L	< 1	1.637	<1	<1
Dissolved Chloride	mg/L	15.4	18.28	8.3	14
Dissolved Hardness	mg/L	< 1	6	<1	3
Dissolved Magnesium	mg/L	< 1	<1	<1	<1
Dissolved Mercury	mg/L	< 0.0002	< 0.0002	<0.0002	<0.0002
Dissolved Nitrate	mg/L	2.86	3.305	3	3.7
Dissolved Organic Carbon	mg/L	0.6	1.1	<0.5	<0.5
Dissolved Ortho-phosphate	mg/L	< 0.01	< 0.01	< .01	< .01
Dissolved Potassium	mg/L	< 0.5	< 0.5	< .5	< .5

Sample Date		4/1/2015	4/14/2015	5/12/2015	6/23/2015
Dissolved Selenium	mg/L	< 0.001	< 0.001	< .001	< .001
Dissolved Silica (SiO2)	mg/L	0.1099	0.196	0.116	0.1773
Dissolved Sodium	mg/L	15.83	19.1	10.27	16.13
Dissolved Sulfate	mg/L	3.3	8.32	3.3	6
pH	mg/L	6.1	5.7	6.3	5.1
Total Alkalinity	mg/L	8	7	8	6
Total Aluminum	mg/L	< 0.01	< 0.01	0.01	0.012
Total Arsenic	mg/L	< 0.001	< 0.001	< .001	< .001
Total Barium	mg/L	< 0.005	< 0.005	< .005	< .005
Total Chromium	mg/L	< 0.001	< 0.001	< .001	< .001
Total Copper	mg/L	< 0.001	< 0.001	< .001	< .001
Total Dissolved Solids	mg/L	70	65	37	65
Total Iron	mg/L	0.007	0.008	0.007	0.009
Total Lead	mg/L	< 0.001	< 0.001	< .001	< .001
Total Manganese	mg/L	< 0.005	< 0.005	< .005	< .005
Total Nickel	mg/L	< 0.001	< 0.001	< .001	< .001
Total Organic Carbon	mg/L	0.5	0.5	<0.5	<0.5
Total Potassium	mg/L	< 0.5	< 0.5	<0.5	<0.5
Total Selenium	mg/L	< 0.001	< 0.001	<0.001	<0.001
Total Silica (SiO2)	mg/L	0.28195	0.2955	0.3521	0.3469
Total Strontium	mg/L	<0.005	0.018	<0.005	0.005

Based on the pilot study it is recommended that RO desalting of agricultural drainage water should incorporate UF feed pretreatment with inline coagulation to reduce the frequency of chemical cleaning and thus prolong UF membrane. Also, antiscalant treatment is necessary to inhibit scaling, coupled with system fresh water flush (2x per week). An example of a recommended set of operating conditions is provided in Table 7 for an integrated UF-RO desalination system consisting of a 2:1 array with up to fourteen elements (40 inches long) arranged in series and with an interstage pump.

Based on the recommended operating conditions, the operating costs (including energy, but excluding concentrate management) of PDD water desalting is estimated to be about $262/acre-foot product water for treatment of PDD average feed salinity of 15,700 mg/L at 75% product water recovery (Table 8). At the lowest PDD feed salinity (11,370 mg/L, Table 2) higher product recovery (~80%) would result in lower operating cost of $228 per acre-foot). On the other hand, desalting the source water with the highest salinity level encountered at PDD (19,370 mg/L, Table 2) would necessitate lower recovery and thus higher operating costs ($293 per acre-foot). Given that water production cost is a function of feed salinity and that water mineral scaling propensity of the source water can be temporally variable, self-adaptive RO operation is the only feasible mode of RO operation which can ensure both effective mitigation of membrane mineral scaling and optimization of water recovery with respect to associated operating costs.

Table 7. Summary of Effective UF-RO Operating Conditions Based on the Pilot Study

Parameter	Quantity	Unit
Coagulant Dose (ACH)	0.83	ppm
UF Resistance	0.25	PSID/GFD
UF Flux	31	GFD
UF Filtration Duration	60	minutes
UF Backwash Flux	98	GFD
UF Backwash Duration	50	seconds
UF Recovery	97%	
Antiscalant dose (Flocon 135)	5	ppm
RO Permeability	0.12	GFD/PSI
RO Flux	13.1	GFD
RO Recovery	75%	
RO Fresh Water Flush (FWF)	0.6%	permeate/FWF
RO FWF Frequency	2	per week

Table 8. Estimated Costs of Desalting PDD Agricultural Drainage Water Based on the Pilot Study

Components	Water Production	Average*	Low*	High*
UF Electricity**	1,000 gallons	$0.01	$0.01	$0.01
UF Chemicals	1,000 gallons	$0.06	$0.06	$0.06
RO Electricity**	1,000 gallons	$0.52	$0.42	$0.60
RO Chemicals	1,000 gallons	$0.20	$0.19	$0.21
RO Fresh Water Flush	1,000 gallons	$0.01	$0.01	$0.02
Total Op. Costs	1,000 gallons	$0.80	$0.70	$0.90
	1 acre-foot	$262	$228	$293
	1 cubic meter	$0.21	$0.18	$0.24

9. Conclusions and Recommendations

A pilot-scale study demonstrated a novel smart integrated membrane system (SIMS) technology of autonomous/self-adaptive UF-RO operation. A SIMS pilot system was developed and field tested at the Panoche Drainage District field test site for desalination of high-salinity subsurface agricultural drainage water of high mineral scaling propensity. Using novel direct online monitoring of membrane scaling and self- adaptive model-based control of UF-RO membrane operations, the project demonstrated technologies for: (a) enabling desalting high salinity brackish water at the optimal feasible recovery, and (b) adapting to real-time variation in feed water quality and scaling/fouling potential.

The major conclusions from the study are:

- Removing fine particles (down to 20 nm) that may promote mineral scaling (by providing surfaces for heterogeneous nucleation) is a critical feed pretreatment requirement. Removing fine particles can be done effectively using UF with inline coagulation.

- Operating conditions of the water treatment/desalination plant must be continually adapted to changes in feed water salinity and quality in order to optimize water recovery and avoid mineral scaling. Such an approach is only feasible if the plant is self-adaptive and by using a direct method for mineral scale detection, such as the use of MMS technology in the present project.

- Antiscalant selection and dose optimization should be based on field testing. This study demonstrated using a unique diagnostic approach that relied on novel membrane monitoring system.

- Once mineral scaling commences, further antiscalant dose increase may not be effective for inhibiting scaling. A more practical approach is to fresh water flush the RO system upon mineral scale detection. Such an approach would use <1% of the produced water, which is likely to be more cost effective than frequent chemical cleaning and membrane replacements. Early detection of mineral scaling, as demonstrated in the project using MMS, is therefore critical to ensure triggering of corrective actions upon occurrence of time-sensitive mineral scaling events.

- Using the approaches demonstrated in the present project, high recovery of up to ~70-80% is feasible for PDD drainage water desalting, depending on feed water salinity and mineral scaling propensity. The estimated operating costs are in the range of ~$200-$300 per acre-foot of product water.

- It is proposed that the management of RO concentrate should be explored via enhanced via accelerated precipitation of the RO concentrate coupled with secondary desalting, followed by final concentrate treatment to zero liquid discharge via solar evaporation.

- Reduction in boron concentration in the product water should be explored via two- pass RO and use of high boron rejection membranes.

10. References

[1] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: Water sources, technology, and today's challenges, Water Research, 43 (2009) 2317-2348.

[2] S.R. Gray, R. Semiat, M. Duke, A. Rahardianto, Y. Cohen, Seawater use and desalination technology, (2011).

[3] A. Ghermandi, R. Messalem, Solar-driven desalinatin with reerse osmosis: the state of the art, Desalination and Water Treatment, 7 (2009) 285-296.

[4] GE Global Research, Integrated Wind Energy/Desalination System, in: Subcontract Report NREL/SR-500-39485, National Renewable Energy Laboratory (2006).

[5] A. Zhu, P.D. Christofides, Y. Cohen, Effect of Thermodynamic Restriction on Energy Cost Optimization of RO Membrane Water Desalination, Ind. & Eng. Chem. Res., 48 (2009) 6010-6021.

[6] A. Zhu, A. Rahardianto, P.D. Christofides, Y. Cohen, Reverse osmosis desalination with high permeability membranes—cost optimization and research needs, Desalination and Water Treatment, 15 (2010) 256-266.

[7] L.M. Camacho, L. Dumée, J. Zhang, J. Li, M. Duke, J. Gomez, S.R. Gray, Advances in Membrane Distillation for Water Desalination and Purification Applications, Water, 5 (2013) 94-196.

[8] D.L. Shaffer, J.R. Werber, H. Jaramillo, S. Lin, M. Elimelech, Forward osmosis: Where are we now?, Desalination, 356 (2014) 271-284.

[9] B.C. McCool, A. Rahardianto, J. Faria, K. Kovac, D. Lara, Y. Cohen, Feasibility of reverse osmosis desalination of brackish agricultural drainage water in the San Joaquin Valley, Desalination, 261 (2010) 240-250.

[10] A. Rahardianto, High recovery desalting of brackish water, in: Ph.D. Dissertation, Chemical & Biomolecular Engineering Department, University of California Los Angeles, 2009.

[11] A. Rahardianto, B.C. McCool, Y. Cohen, Reverse osmosis desalting of inland brackish water of high gypsum scaling propensity: kinetics and mitigation of membrane mineral scaling, Environmental science & technology, 42 (2008) 4292-4297.

[12] A. Rahardianto, J. Gao, C.J. Gabelich, M.D. Williams, Y. Cohen, High recovery membrane desalting of low-salinity brackish water: Integration of accelerated precipitation softening with membrane RO, Journal of Membrane Science, 289 (2007) 123-137.

[13] M.D. Stuber, C. Sullivan, S.A. Kirk, J.A. Farrand, P.V. Schillaci, B.D. Fojtasek, A.H. Mandell, Pilot demonstration of concentrated solar-powered desalination of subsurface agricultural drainage water and other brackish groundwater sources, Desalination, 355 (2015) 186-196.

[14] M. Zhangab, J. Shanab, C. Tang, Gypsum scaling during forward osmosis process—a direct microscopic observation study, Desalination and Water Treatment, DOI: 10.1080/19443994.2014.985727 (2014).

[15] J. Thompson, A. Rahardianto, H. Gu, M. Uchymiak, A. Bartman, M. Hedrick, D. Lara, J. Cooper, J. Faria, P.D. Christofides, Rapid field assessment of RO desalination of brackish agricultural drainage water, Water Research, 47 (2013) 2649-2660.

[16] R. Singh, Membrane Technology and Engineering for Water Purification: Application, Systems Design and Operation 2nd ed., Butterworth-Heinemann, Waltham, MA, 2014.

[17] Hydranautics, Chemical Pretreatment or RO and NF, in: Technical Application Bulletin No. 111, Nitto Denko, Oceanside, CA, 2013.

[18] M. Uchymiak, A. Rahardianto, E. Lyster, J. Glater, Y. Cohen, A novel RO ex situ scale observation detector (EXSOD) for mineral scale characterization and early detection, Journal of Membrane Science, 291 (2007) 86-95.

[19] Bureau of Reclamation, San Luis Drainage Feature Re-evaluation - Feasibility Report, Appendix D: Reverse Osmosis Analysis Reports, in, U.S. Department of the Interior, Mid-Pacific Region, Sacramento, CA, March 2008.

[20] A.R. Bartman, P.D. Christofides, Y. Cohen, Nonlinear Model-Based Control of an Experimental Reverse-Osmosis Water Desalination System, Ind. Eng. Chem. Res., 48 (2009) 6126-6136.

[21] A.R. Bartman, A.H. Zhu, P.D. Christofides, Y. Cohen, Minimizing energy consumption in reverse osmosis membrane desalination using optimization- based control, J. Proc. Control, 20 (2010) 1261-1269.

[22] C.W. McFall, A. Bartman, P.D. Christofides, Y. Cohen, Control and monitoring of a high recovery reverse osmosis desalination process, Ind. & Eng. Chem. Res., 47 (2008) 6698-6710.

[23] A. Rahardianto, B.C. McCool, Y. Cohen, Reverse osmosis desalting of inland brackish water of high gypsum scaling propensity: Kinetics and mitigation of membrane mineral scaling, Environ. Sci. Technol., 42 (2008) 4292-4297.

[24] M. Uchymiak, A.R. Bartman, N. Daltrophe, M. Weissman, J. Gilron, P.D. Christofides, W.J. Kaiser, Y. Cohen, Brackish water reverse osmosis (BWRO) operation in feed flow reversal mode using an ex situ scale observation detector (EXSOD), J. Membr. Sci., 341 (2009) 60-66.

[25] L.X. Gao, A. Rahardianto, H. Gu, P.D. Christofides, Y. Cohen, Novel design and operational control of integrated ultrafiltration - Reverse osmosis system with RO concentrate backwash, Desalination, 382 (2016) 43-52.

[26] L. Gao, A. Rahardianto, H. Gu, P.D. Christofides, Y. Cohen, Energy-Optimal Control of RO Desalination, Ind Eng Chem Res, 53 (2014) 7409-7420.

[27] J. Thompson, A. Rahardianto, H. Gu, M. Uchymiak, A. Bartman, M. Hedrick, D. Lara, J. Cooper, J. Faria, P.D. Christofides, Y. Cohen, Rapid field assessment of RO desalination of brackish agricultural drainage water, Water Res, 47 (2013) 2649-2660.

[28] A.R. Bartman, E. Lyster, R. Rallo, P.D. Christofides, Y. Cohen, Mineral scale monitoring for reverse osmosis desalination via real-time membrane surface image analysis, Desalination, 273 (2011) 64-71.