RECLAMATION

Managing Water in the West

Desalination & Water Purification Research and Development Program Report No. 186

Evaluation of a Small Rural Community Zero Liquid Discharge Desalination System

U.S. Department of the Interior
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Technical Service Center
Water and Environmental Services Division
Water Treatment Engineering Research Team
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14. ABSTRACT
A zero liquid discharge (ZLD) water treatment system constructed and operated in Santa Paula, California was evaluated for application to small rural communities reliant upon impaired groundwater for drinking water supply. The Search Dog Foundation evaluated several alternatives and ultimately selected a reverse osmosis treatment system combined with a high rate solar evaporator for brine disposal. The system was evaluated for approximately one year in 2014 - 2015. A small reverse osmosis (RO) skid requiring minimal chemical input and operator expertise was found to be a viable method to treat compromised well water. High-rate solar evaporation is also a viable and relatively economical method to implement a ZLD system.

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zero liquid discharge, impaired groundwater, desalination, reverse osmosis

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Prepared for Reclamation Under Agreement No. R13AC80019

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

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Acronyms and Abbreviations

Center	National Training Center
CIP	clean-in-place
DWPR	Desalination and Water Purification Research Program
DWR	Department of Water Resources
HBSL	health-based screening level
HMI	human machine interface
HRT	hydraulic residence time
LSI	Langelier Saturation Index
MCL	maximum contaminant level
RO	reverse osmosis
SDF	Search Dog Foundation
TDS	total dissolved solids
XRD	X-ray powder diffraction
ZLD	zero liquid discharge

1.1. Chemicals

$CaCO_3$	calcium carbonate
Cl_2	chlorine
N	nitrogen
Na_2SO_4	thenardite
$Na_6(CO_3)(SO_4)_2$	burkeite
P	phosphorus

1.2. Measurements

°C	degrees Celsius
gfd	gallons per day per square foot
gpm	gallons per minute
gpm/sf	gallons per minute per square foot
kW	kilowatt
kWh	kilowatt hours
mg/L	milligrams per liter
mm	millimeters
mS/cm	millisiemens per centimeter
NTU	nephelometric turbidity unit
psi	pounds per square inch
µg/L	micrograms per liter

2. EXECUTIVE SUMMARY

Small, rural communities typically rely on local groundwater as their water supply. However, a significant amount of this groundwater has impaired water quality. Reverse osmosis (RO) is the conventional and often ideal technology used to produce high quality product water with reduction of many inorganic contaminants. Brine disposal remains a key issue and is often the deciding factor when considering RO. Already a challenge for larger municipalities, desalination of impaired groundwater is very nearly infeasible for small and rural communities due to their lack of funding and trained staff. Rural, inland communities face the additional issue of typically needing a zero liquid discharge (ZLD) solution (i.e., due to lack of local sewer facilities or regional brine disposal line).

The Search Dog Foundation (SDF) encountered all of these challenges when looking to create their National Training Center on a large parcel of donated land in Santa Paula, CA. Trussell Technologies, Inc. evaluated several alternatives for treating this impaired groundwater to drinking water quality. Ultimately, an RO treatment system combined with the high rate solar evaporator was selected for installation and construction. The solar evaporator consists of a system of regularly-spaced nozzles that spray the brine over a bed of dark rocks warmed by the sun. Evaporation occurs at a rate higher than that of a traditional evaporation pond due to the spray and the additional surface area provided by the rock bed. Excess water drains to a large underground sump and is pumped back through the spray system for further evaporation. Key philosophies in the design of the RO system were allowing for a low level of operator expertise and time, minimal chemical usage, and drinking water safety.

This research project aims to evaluate the performance of this combined ZLD and RO system for twelve months of operation to provide much-needed information for this unique type of installation. The ultimate goal of this research is to aid in development of a ZLD water treatment system for small rural communities at a reasonable cost and with a realistic operating strategy. Many lessons were learned throughout the duration of this study. Those most significant are:

- A small RO skid requiring minimal chemical input and human intervention, operated by personnel with minimal training, can be a viable method to treat compromised well water to be safe and aesthetically pleasing drinking water.

- High Rate Solar Evaporation is a viable means to implement a ZLD system, when a large footprint for passive evaporation ponds is not feasible. The footprint in this case was approximately one-third as large as it would have needed to be with a conventional evaporation pond.

- High Rate Solar Evaporation is an economical option compared to continuous hauling of waste water associated with RO systems. Hauling water away is estimated to cost $500,000/year while operating the High

Rate Solar Evaporation system was shown to cost approximately $10,000/year, in this rural county in southern California.

3. BACKGROUND

3.1. General Information

Small, rural communities typically rely on local groundwater as their water supply. However, a significant amount of groundwater is not considered usable for drinking unless treated, due to impaired water quality. Studies have shown that 22% of groundwater from public wells and 23% of domestic wells sampled across the nation have one or more contaminants at concentrations greater than regulated Maximum Contaminant Levels (MCL) or Health-Based Screening Levels (HBSL) (Toccalino and Hopple, 2010 and DeSimone et al., 2009). Most of these contaminants were naturally occurring trace elements (e.g., manganese and boron). In particular, 16.7% of public wells and 15% of domestic wells had total dissolved solids (TDS) greater than 500 milligrams per liter (mg/L) (a secondary MCL) (Toccalino et al., 2010 and DeSimone, 2009).

Reverse osmosis is the conventional technology used to remove total dissolved solids and is generally an ideal technology to produce high quality product water and to reduce many inorganic contaminants. However, brine disposal remains a key issue and is often the deciding factor when considering RO treatment for desalination. Brine disposal options are typically surface water discharge (e.g., ocean, river, or lagoon), sewer discharge, deep well injection, land application, evaporation ponds, and thermal evaporation methods (Sethi et al., 2009). Brine minimization is also often necessary to allow the above brine disposal options to be feasible. These include brine concentrators, crystallizers, thermal evaporators, secondary RO, precipitative softening (prior to RO), and usage of significant amounts of chemical to increase RO recovery. Each of these methods increases cost, as well as the operator training and chemical usage necessary to implement an RO desalination facility.

Already a challenge for larger municipalities to implement, desalination of brackish and impaired groundwater is very nearly infeasible for small and rural communities due to their lack of funding and trained staff. Rural, inland communities face the additional issue of typically needing a ZLD solution (e.g., due to lack of local sewer facilities or regional brine disposal line), along with the fact that ZLD solutions often remain the most expensive of all brine disposal and minimization options.

3.2. Evaluation Site Background

The Search Dog Foundation encountered all of these challenges when looking to create their National Training Center (Center) on a large parcel of donated land in the rural foothills of Santa Paula, California. SDF is a non-profit organization dedicated to producing highly trained, certified canine disaster search teams, who are trained to search for live victims of natural disasters or terrorist attacks. Residents and businesses (e.g., ranches) in this area have neither direct access to municipal water treatment, nor sewers for wastewater discharge, and rely upon local groundwater wells and septic systems. At this site, a new well was drilled in 2010 to support this small community and enable developing the training center. However, this water supply was found to be impaired by high levels of TDS, sulfates, boron, iron, and manganese. Measured values taken during well startup are summarized in Table 1.

Table 1.—Water Quality

Parameter	Well Water Maximum (mg/L)	Product Water Goals (mg/L)
TDS	6010	500
Sulfates	3360	250
Boron	3.9	0.2
Iron	17.6	0.3
Manganese	0.21	0.05

The selected water treatment train would require a reasonable method for disposing the water treatment wastewater, as the Ventura County Department of Environmental Health restricts inflow to the septic system to be domestic wastewater only. In addition, overland discharge of any type of wastewater is not possible due to adverse impacts on the environmentally sensitive watershed. Regular trucking of brine was evaluated and found to be prohibitively expensive at approximately $500,000 per year, with near-daily disruptions of the Center’s activities. As a result, a ZLD or near-ZLD system was a necessary criterion in evaluating treatment alternatives.

Trussell Technologies, Inc. evaluated several alternatives for treating this impaired groundwater to drinking water quality, including unconventional thermal and solar distillation systems as well as reverse osmosis. The only reasonable brine disposal alternatives were traditional evaporation ponds and a high rate solar evaporator system previously tested by the California Department of Water Resources (DWR) for farm drain management. Between 2003 and 2005, DWR piloted 10,000 square-foot high rate solar evaporators at Red Rock Ranch in San Joaquin Valley, California. DWR found the system to be feasible for evaporation of high TDS agricultural drainage waters. Evaporation was enhanced up to 3.3 times normal pan evaporation rates (Faria et al., 2011).

Ultimately, an RO treatment system combined with the high rate solar evaporator was selected for installation and construction for a variety of reasons typical for a small, rural, and isolated community (e.g., costs, level of technical support, energy usage, known reliability of the technology, and land availability). Trussell Technologies, Inc. was commissioned by SDF to manufacture a 3 gallons per minutes (gpm) (as product water), skid-mounted, RO system, to provide water to a 125,000 gallon finished water storage tank and to provide the process design for the high rate solar evaporator system for brine disposal. Civil design for the high rate solar evaporator was provided by a separate contractor.

3.2.1. SDF RO System

Key goals in the design of the RO system were to allow for a low level of operator expertise and time, minimal chemical usage, and drinking water safety. The resulting treatment train consists of robust RO pretreatment steps and additional post-treatment for stabilization and disinfection:

- Pretreatment
  - Tray aerator for iron, manganese, and hydrogen sulfide oxidation and removal
  - Deep media greensand filtration for turbidity removal and backup iron and manganese removal

- Reverse osmosis membranes for total dissolved solids removal

- Post-treatment
  - Ion exchange for boron removal
  - Calcite filtration for permeate stabilization
  - Tablet chlorinator for chlorine disinfection

To minimize onsite chemical storage and usage, the RO system was designed so that antiscalants were not necessary, and the greensand filtration was designed to operate in an intermittent regeneration mode (regenerate with chlorine only when offline). Chemicals for infrequent clean-in-place (CIP) of the RO system are brought onsite as needed. In addition, normal operation is automated.

Technical risks associated with the proposed investigation are low. The design incorporated appropriate safety factors for highly variable water quality and covered most potential inorganic chemicals. Additionally, the aquifer is not known to be contaminated with organic or anthropogenic chemicals. The tray aerator for the RO system was selected for oxidation of iron and manganese (RO foulants) due to its simple and fundamental design. While design criteria exist in the literature (e.g., Kawamura, 2000), performance data is scarce. As a result, deep media greensand filters were included as redundant iron and manganese removal. The media filters themselves are uniquely deep (24 inches of anthracite over 24 inches of greensand) to allow for variable influent conditions, larger solids loading, better iron and manganese removal, and improved effluent turbidity. Unconventionally low chemical usage will be used with the greensand filters, but provisions have been made for the more conventional continuous regeneration mode (with chlorine) and subsequent chlorine quenching prior to the RO membranes. Additional safety factors have been designed for in the RO system. The low recovery (50 percent) should allow for no antiscalant usage. A rendition of the RO Skid is shown in Figure 1. Key design parameters are shown in Table 2.

The hydraulic flow through the treatment processes, as well as larger components on the skid, sampling ports, instrumentation and control, and chemical addition points are shown in Figure 2.

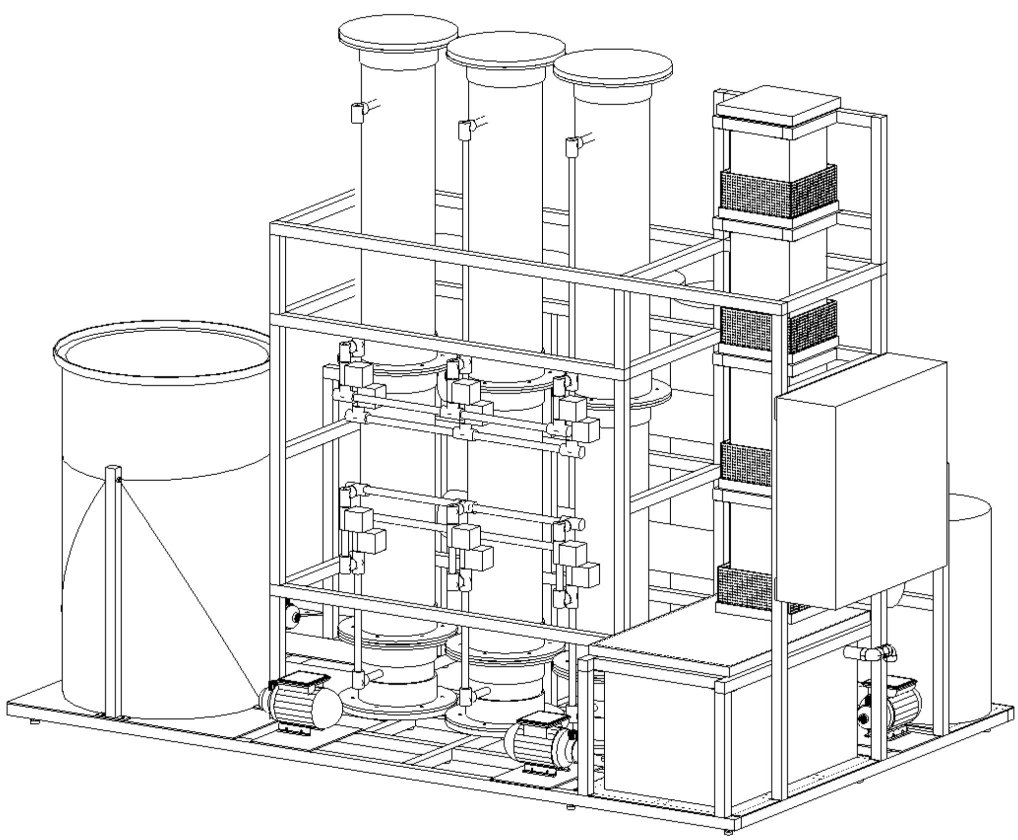

Figure 1.—RO treatment skid graphic.

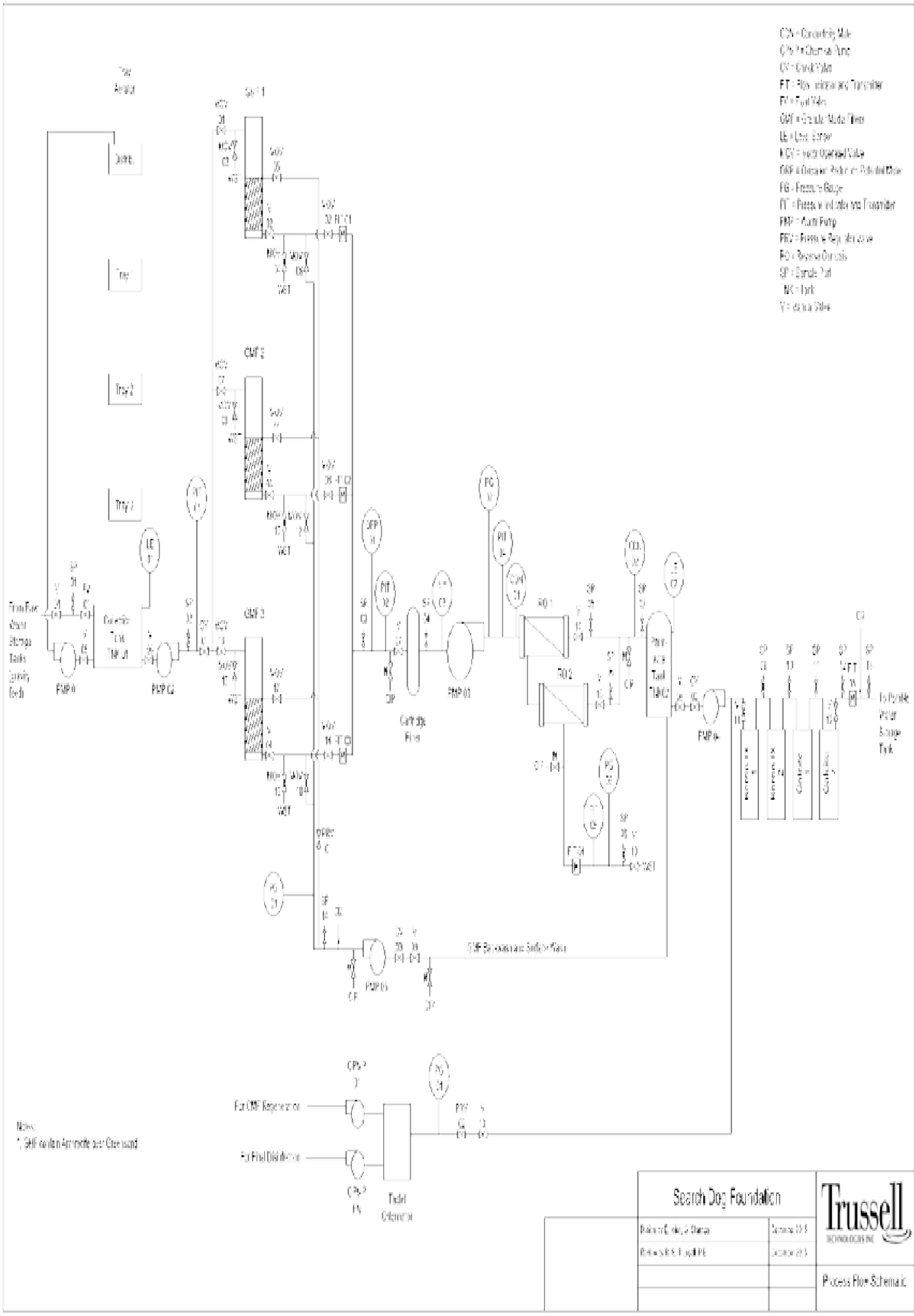

Figure 2.—Process flow diagram.

Components and Instrumentation Key for Figure 2:

- Treatment components
  - Tray Aerator
  - Granular Media Filters (GMF1, GMF2, GMF3)
  - Cartridge Filter
  - Reverse Osmosis (RO1, RO2)
  - Boron Ion Exchange (Boron IX 1, Boron IX 2)
  - Calcite Contactors (Calcite 1, Calcite 2)
  - Tablet Chlorinator
- Tanks (TNK)
  - Tray aerator collection tank (TNK01)
  - RO permeate tank (TNK02)
- Water pumps (PMP) and chemical pumps (CPMP)
  - Tray aerator pump (PMP01)
  - Media filter feed pump (PMP02)
  - RO feed pump (PMP03)
  - Product water pump (PMP04)
  - Backwash pump (PMP05)
  - NaOCl greensand regeneration pump (CPMP01)
  - NaOCl disinfection pump (CPM_FN)
- Flow indicators and transmitters (FIT)
  - Media filter 1 flow transmitter (FIT01)
  - Media filter 2 flow transmitter (FIT02)
  - Media filter 3 flow transmitter (FIT03)
  - Concentrate flow transmitter (FIT04)
  - Product flow transmitter (FIT05)
- Level sensors (LE)
  - Tray aerator collection tank level sensor (LE01)
  - RO permeate tank level sensor (LE02)
- Motor operated valves (MOV)
  - Media filter 1 influent valve (MOV01)
  - Media filter 1 effluent valve (MOV02)
  - Media filter 1 backwash waste valve (MOV03)
  - Media filter 1 forward waste valve (MOV04)
  - Media filter 1 surface wash valve (MOV05)
  - Media filter 1 backwash valve (MOV06)
  - Media filter 2 influent valve (MOV07)
  - Media filter 2 effluent valve (MOV08)
  - Media filter 2 backwash waste valve (MOV09)

  - Media filter 2 forward waste valve (MOV10)
  - Media filter 2 surface wash valve (MOV11)
  - Media filter 2 backwash valve (MOV12)
  - Media filter 3 influent valve (MOV13)
  - Media filter 3 effluent valve (MOV14)
  - Media filter 3 backwash waste valve (MOV15)
  - Media filter 3 forward waste valve (MOV16)
  - Media filter 3 surface wash valve (MOV17)
  - Media filter 3 backwash valve (MOV18)
- Manual valves (V)
  - Raw water feed valve (V01)
  - Media filter 1 effluent valve (V02)
  - Media filter 2 effluent valve (V03)
  - Media filter 3 effluent (V04)
  - Tray aerator pump inlet valve (V05)
  - Media filter pump inlet valve (V06)
  - Cartridge filter inlet valve (V07)
  - Product water pump inlet valve (V08)
  - Backwash pump inlet valve (V09)
  - RO concentrate valve (V10)
  - Boron pressure vessel 1 influent valve (V11)
  - Product water valve (V12)
  - Tablet chlorinator feed valve (V13)
  - RO pressure vessel 1 permeate valve (V14)
  - RO pressure vessel 2 permeate valve (V15)
- Water quality indicators and transmitters
  - RO feed ORP transmitter (ORP01)
  - RO feed conductivity transmitter (CND01)
  - Permeate conductivity transmitter (CND02)
- Pressure indicator and transmitters (PIT)
  - Media filter influent pressure transmitter (PIT01)
  - Media filter effluent pressure transmitter (PIT02)
  - Cartridge filter effluent pressure transmitter (PIT03)
  - RO feed pressure transmitter (PIT04)
  - RO concentrate pressure transmitter (PIT05)
- Pressure gauges (PG)
  - Media filter backwash pressure gauge (PG01)
  - RO feed pressure gauge (PG02)
  - RO concentrate pressure gauge (PG03)

    - Tablet chlorinator feed pressure gauge (PG04)
- Sample ports (SP)
    - Raw water sample port (SP01)
    - Media filter influent sample port (SP02)
    - Combined media filter effluent sample port (SP03)
    - Cartridge filter effluent sample port (SP04)
    - RO vessel 1 permeate sample port (SP05)
    - RO vessel 2 permeate sample port (SP06)
    - Combined RO permeate sample port (SP07)
    - RO concentrate sample port (SP08)
    - Boron pressure vessel 1 effluent sample port (SP09)
    - Boron pressure vessel 2 effluent sample port (SP10)
    - Calcite pressure vessel 1 effluent sample port (SP11)
    - Calcite pressure vessel 2 effluent sample port (SP12)
    - Product water after chlorine addition sample port (SP13)
    - Media filter backwash after chlorine addition sample port (SP14)
- Check valves (CV)
    - Media filter influent check valve (CV01)
    - Product water pump inlet check valve (CV02)
    - Backwash pump inlet check valve (CV03)
- Pressure regulator valves (PRV)
    - Surface wash (PRV01)
    - Tablet chlorinator pressure regulator (PRV02)
- RO CIP skid
    - CIP tank (TNK03)
    - CIP tank heater (HTR01)
    - CIP tank outlet valve (V16)
    - CIP feed valve/quick connection (V17)
    - CIP cartridge filter valve (V18)
    - RO feed pump (PMP03)
    - CIP pressure vessel 1 permeate valve/quick connection (V19)
    - CIP pressure vessel 2 permeate valve/quick connection (V20)
    - CIP concentrate/quick connection (V21)
    - CIP overflow return/quick connection (V22)
    - CIP fill valve/quick connection (V23)
- Other
    - Float valve (FV01)

Table 2.—RO System Key Design Parameters

Tray Aerator	Number of trays (including top distributor tray) = 4 Distance between trays = 12 inches Depth of media in each tray = 12 inches Media type = Coarse anthracite coal (#6 mesh size, $1\frac{3}{8}$ x $\frac{13}{16}$ inch chips) Tray perforation spacing = 1 to 3 inches (on center) Loading rate = 6.25 gpm (maximum)
Deep Media Greensand Filters	Number of filters = 3 (2 duty/1 standby) Capacity per filter = 3.13 gpm Filter rate (duty online) = 4 gpm/sf Filter run time = 48 hours Anthracite media depth = 24 inches (minimum) Anthracite media effective size = 0.6 – 0.8 mm Greensand media depth = 24 inches (minimum) Greensand media model and manufacturer = Greensand Plus by Inversand Greensand media effective size = 0.30 – 0.35 mm Backwash type = Backwash with surface wash Chlorine soak dose = 1,000 mg/L Frequency of backwash = 1 filter per day
Reverse Osmosis	Membrane type = Brackish water design Membrane element model and manufacturer = Toray CSM RE4040-BE Recovery = 50 percent Capacity = 3.12 gpm Average design flux = 13 gfd Number of pressure vessels = 2 Number of membrane elements per vessel = 2
Boron Ion Exchange	Number of units = 2 Media type = Boron selective anion exchange resin Media model and manufacturer = Purolite S108 Loading rate = 2 gpm/sf Bed depth = 52 inches Regeneration frequency = As needed
Calcite Filters	Number of units = 2 Media type = Calcite chips (16 x 40 mesh) Loading rate = 2 gpm/sf Target LSI = -0.5 Target HRT = 30 minutes
Disinfection by Chlorine	System type = Tablet chlorinator Dose = 1 mg/L as Cl_2

gfd = gallons per square foot per day
gpm/sf = gallons per minute per square foot
HRT = hydraulic residence time
LSI = Langelier Saturation Index
mm = millimeters

3.2.2. SDF High Rate Solar Evaporator Design

RO brine and greensand filter wastewater (backwash and filter-to-waste) are sent to the high rate solar evaporator for disposal. The solar evaporator consists of a system of regularly-spaced nozzles that spray the brine over a bed of dark rocks warmed by the sun. Evaporation occurs at a rate higher than that of a traditional evaporation pond due to the spray and the additional surface area provided by the rock bed. Excess water drains to a large underground sump and is pumped back through the spray system for further evaporation.

The design for the high rate solar evaporator was primarily based on a 10,000 square foot system piloted by the California DWR (lead investigators Jose Faria, P.E., and Joseph Tapia, P.E.). The published white paper describing the study results included testing different rock media types, spray nozzle types, nozzle configurations and height, and fencing to control salt drift. Discussion with Joseph Tapia helped to refine the design details, and a visit to a similar system (non-recirculating) at Andrews Ag Ranch in Bakersfield, which has been in operation for 10 years, supported design decisions. Table 3 provides key design parameters for the SDF high rate solar evaporator system.

Table 3.—High Rate Solar Evaporator Key Design Parameters

Capacity	4,500 gallons per day
Area	12,000 square feet
Depth of Rock Bed	6 inches
Type of Spray Nozzles	Hollow Cone Spray BETE TF12-XW
No. of Spray Nozzles	42
Volume of Sump	50,000 gallons
Storm Accommodation	25-year storm
Liner Type	Double
Brine Mist Control	8-foot tall covered fencing

The greatest risk associated with the high rate solar evaporator is overflow of brine due to a large sudden storm event. The evaporator has been sized to easily accommodate the rainfall from a 25-year storm for 24 hours. During such an event, the water treatment system could be shut off so that the evaporator would not receive brine.

4. PURPOSE

This research project aims to evaluate the performance of this combined ZLD and RO system for twelve months of operation to provide much-needed information for this unique type of installation. Performance data on RO treatment systems designed for intentionally low chemical usage and minimal technical support is lacking in an industry typically focused on high water recovery. This study may demonstrate that iron and manganese, common RO foulants present in groundwater, could be removed with no chemical usage via the tray aerators.

Additionally, SDF's high rate solar evaporator with brine recirculation is the first full-scale operating in California. Although a seemingly simple technology, more data is needed to test the current design criteria to enable wider usage among ZLD applications.

The ultimate goal of this research is to aid in developing a ZLD water treatment system for small rural communities at a reasonable cost and with a realistic operating strategy. This research helps the Bureau of Reclamation meet its Desalination and Water Purification Research and Development Program (DWPR) goals by reducing costs for small rural communities who have no other option than ZLD to develop a local brackish groundwater source, thus augmenting their usable water supply.

It is hoped that the results of this study will allow for easy replication of the system, particularly the high rate solar evaporator. For communities with available land, the high rate solar evaporator may be a preferable option over evaporation ponds, which can be an environmental and aesthetic nuisances.

5. APPROACH

SDF's RO Treatment and High Rate Solar Evaporator systems combine to make up the ZLD process that this report assesses to determine its applicability for small, rural communities. The system was commissioned for operation in early 2014.

The principal objectives of this research are to evaluate the performance of :

1. An RO treatment system intentionally designed for use in a small, rural, and isolated community

2. A high rate solar evaporator for onsite brine disposal

5.1. RO Skid Evaluation

Evaluating the RO skid focused on comparing raw water quality against final water quality and operational changes that were made to address unique limitations encountered during start-up of the system. The system was operated by the onsite operator in a manner that best met the needs of the facilities.

The water quality parameters monitored during this project (Aug 2014 to May 2015) are summarized in Table 4 for the water quality entering the RO Skid and Table 5 for the final product water leaving the RO Skid. All parameters except alkalinity, conductivity, pH, and temperature were measured by Eurofins Eaton Analytical, Inc., a certified laboratory (ELAP #2813) in Monrovia, California. Temperature was measured in the field by a Trussell Technologies field engineer during sample collection. Alkalinity, conductivity, and pH were measured by Trussell Technologies Laboratory in Pasadena, California.

The performance of the reverse osmosis step was also monitored using recovery and specific flux. Typically, a CIP is performed when specific flux declines by 15%. Recovery is the efficiency at which the RO membranes produce permeate at a given operational condition. Flux is the permeate flow being generated per unit membrane area. For comparison purpose,s it is important to correct the flux for temperature since RO performance is impacted by the temperature of the water. Specific flux is also an important value for evaluating RO performance because this value is normalized against pressure.

Table 4.—Raw Water Quality Parameters and Analytical Method

Parameter	Method
Alkalinity	SM2320B
Ammonia	EPA 350.1
Barium	EPA 200.8
Boron	EPA 200.7
Calcium	EPA 200.7
Chloride	EPA 300.0
Conductivity	SM2510B
Fluoride	SM4500F-C
Iron	EPA 200.7
Magnesium	EPA 200.7
Manganese	EPA 200.8
Nitrate	EPA 300.0
pH	SM4500H-B
Potassium	EPA 200.7
Silica	EPA 200.7
Sodium	EPA 200.7
Strontium	EPA 200.7
Sulfate	EPA 300.0
Sulfide	SM4500SD/376.2
Temperature	SM2550
Total Dissolved Solids	E160.1/SM2540C
Phosphorus	SM4500-PE/EPA 365.1

Table 5.—Final Product Water Quality Parameters and Analytical Method

Parameter	Method
Alkalinity	SM2320B
Boron	EPA 200.7
Conductivity	SM2510B

Nitrate	EPA 300.0
pH	SM4500H-B
Sulfide	SM4500SD/376.2
Temperature	SM2550
Total Dissolved Solids	E160.1/SM2540C

5.2. High Rate Solar Evaporator Evaluation

The performance of the High Rate Solar Evaporator was studied in June 2015. The system's evaporation rate and energy consumption were recorded and compared against weather parameters such as wind, temperature, humidity, and solar radiation. At the same time, solids left on the brine bed rocks over approximately 2 years of operation were analyzed by Camet Research, Inc., located in Goleta, California. The solids accumulated on the brine bed rocks were assessed using a technique called X-ray powder diffraction (XRD) to identify the crystalline phases present on the rocks.

The water quality parameters monitored during this project (Aug 2014 to May 2015) are summarized in Table 6 for brine water quality. All parameters except alkalinity, conductivity, pH, and temperature were measured by Eurofins Eaton Analytical, Inc., a certified laboratory (ELAP #2813) located in Monrovia, California. Temperature was measure in the field by a Trussell Technologies field engineer during sample collection. Alkalinity, conductivity, and pH were measured by Trussell Technologies Laboratory in Pasadena, California.

Table 6.—Brine Water Quality Parameters and Analytical Method

Parameter	Method
Alkalinity	SM2320B
Ammonia	EPA 350.1
Barium	EPA 200.8
Boron	EPA 200.7
Calcium	EPA 200.7
Chloride	EPA 300.0
Conductivity	SM2510B
Fluoride	SM4500F-C
Iron	EPA 200.7
Magnesium	EPA 200.7
Manganese	EPA 200.8
Nitrate	EPA 300.0
pH	SM4500H-B
Potassium	EPA 200.7
Silica	EPA 200.7

Parameter	Method
Sodium	EPA 200.7
Strontium	EPA 200.7
Sulfate	EPA 300.0
Sulfide	SM4500SD/376.2
Temperature	SM2550
Total Dissolved Solids	E160.1/SM2540C
Phosphorus	SM4500-PE/EPA 365.1

6. FINDINGS

The initial delays were caused by lack of power and water to the RO skid. The contractor successfully procured electricity and water in March 2015, which allowed for this study begin. The operational system is shown in Figure 3.

Figure 3.—RO Skid.

6.1. Automation

Throughout this study, SDF worked with the contractor responsible for control integration of the RO skid system. Improvements to the automation continued for the duration of this study. The sequence that required the most attention was enabling accurate flow meter readings (to allow appropriate flow distribution among the online media filters) and the correct sequencing of the media filters. Three media filters are included on the skid, and each is scheduled to perform water filtration, backwashing, regeneration via a chlorine soak, and rinsing before returning to service. This sequencing became stable and automatically functioning in June 2015. From June to October 2015, the treatment skid operated intermittently in manual and occasionally in automatic mode, as the controls continued to be worked on by the controls contractor. In mid-February 2015, data-logging functionality was implemented in the automation system to reduce manual data collection in the future.

Data logging is essential for monitoring RO performance to determine when a CIP is necessary. However, data logging systems were deemed unusable, because the RO feed pressure values displayed on the human machine interface (HMI) were not consistent with those on the mechanical dial pressure gauge at the same location. SDF is working with the contractor responsible to resolve this issue. For this study, RO operational parameters were recorded manually daily to assess RO performance.

6.2. Well Water

6.2.1. Flowrate

Initially, the well produced nearly 10 gpm, but during the course of this study, the supply well continued to decrease its production. At the completion of this study, the well was producing approximately 4.5 gpm maximum, which is significantly lower than the design of 7 gpm.

6.2.2. Turbidity

Upon initial operation, raw well water was found to have greater turbidity levels (>30 nephelometric turbidity units [NTU]) than expected, and greater than the treatment system was designed to accommodate. After continued operation, the turbidity decreased but still remained at concerning levels. Well turbidities ranged from 2.66 to 7.24 NTU, as measured by a portable turbidimeter, from April 9 - 14, 2014. At that time, corresponding turbidities in the water just ahead of the reverse osmosis pressure vessels ranged from 1.2 to 3.75 NTU. These turbidity values were much higher than should be in the RO feed to prevent irreversible fouling of the membranes.

As a result, SDF implemented coagulant dosing at the well using ferric chloride. Dosing was achieved using a temporary setup of a 55-gallon chemical drum and a pump at the well site. Mixing was achieved as the well water traveled to the raw water storage tanks, which are 650 feet northeast of the well with a vertical elevation difference of about 30 feet. To enable floc settling, each of the 2,500 gallon raw water storage tanks were modified to operate in series with the first tank acting as a settling tank and the second tank acting as an equalization tank for the decanted water. The ferric dose was determined with limited on-site testing.

In mid-May, despite some continued variability in the raw water turbidity, the RO membranes were installed, and potable water production and storage began. By the end of May, the raw well turbidity had stabilized to 1 to 2 NTU, which was what was initially expected of the well. As a result of this stabilization of wellhead turbidity, coagulant usage was suspended in June 2014. From July to October 2014, turbidity was consistently below 2 NTU, with the exception of two occasions when the skid was turned off, due to lack of operator availability. When the skid was placed back online after being idle, the turbidity tended to be high initially, but within a couple of days of operation, the turbidity decreased to below 2 NTU.

Turbidity spikes were also observed less than a day after rain events and persisted for several days, as seen after several days of significant rain in early November. In November, turbidity increased 4.6 fold from an average of 0.77 to 3.54 approximately 20 hours into the rain event. Increased turbidity continued to be observed after rainfall, as summarized in Table 7.

Table 7.—Monthly Rainfall and Turbidity

Month	Total Rainfall[1], inches	Turbidity, NTU		
		Average	Minimum	Maximum
August 2014	0.02	1.29	0.85	2.44
September 2014	0.00	1.17	0.85	1.69
October 2014	0.01	0.75	0.26	1.01
November 2014	0.78	0.79	0.49	1.03
December 2014	3.69	no data	no data	no data
January 2015	1.57	10.30	5.50	18.50
February 2015	0.67	3.58	2.30	6.10
March 2015	1.01	2.31	1.30	3.40
April 2015	0.07	5.81	1.10	11.80
May 2015	0.56	1.63	0.79	2.41
June 2015	0.07	2.97	0.61	4.00
July 2015	1.37	2.48	0.60	5.50
August 2015[2]	0.00	3.06	0.70	11.30

[1] Rainfall data from Ventura County Watershed Protection District Hydrologic Data Webpage: www.vcwatershed.net/hydrodata/php/getstation.php?siteid=245B#rain_day
[2] Spikes in turbidity were seen in early and mid-August 2015 because the RO skid feed tanks were cleaned to remove settled accumulated silt and grit from the well.

While the raw wellhead turbidity continues to remain variable and the average turbidity levels are higher than the treatment system was designed to accommodate, SDF has chosen to continue operating the system knowing that cartridge filter and RO membrane change out will be needed at more frequently.

6.3. Hardware Improvements

Trussell Technologies continued to troubleshoot and improve small issues with the RO skid throughout the duration of the study. Slight misting from between trays of the tray aerator was enough to cause significant buildup of salt deposits in the general area of the process over time. Loose fitting plastic sleeves which still permitted good air circulation were installed between trays to help control misting of the high TDS water. Installed sleeves and salt buildup, prior to being cleaned away, are shown in Figure 4. Salt deposition was not an issue thereafter.

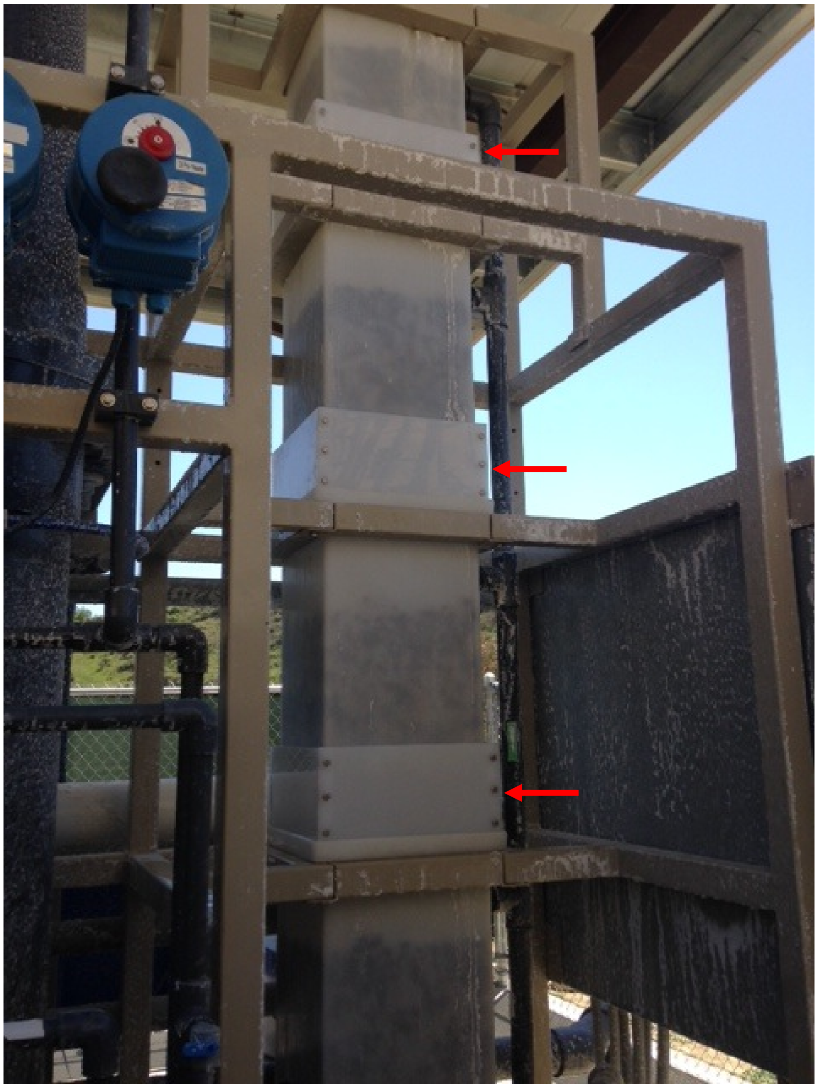

Figure 4.—Tray aerator sleeves installed to prevent salt buildup (4/25/2014)

6.4. RO Skid Performance

6.4.1. Water Quality

A profile of the raw water entering the skid is summarized in Table 8.

Table 8.—Raw Water Quality entering the RO skid since startup (August 2014 to May 2015)

Parameter	Units	Average [a]	Number of Samples	Minimum	Maximum
Alkalinity	as $CaCO_3$	935	20	794	1,300
Ammonia as N	mg/L	16	20	14	18
Barium Total [b]	ug/L	12	20	2.0	26
Boron Total	mg/L	3.6	20	3.2	4.0
Calcium Total	mg/L	53	20	48	59
Chloride	mg/L	35	20	32	39
Conductivity	mS/cm	8.2	36	7.5	8.6
Fluoride	mg/L	0.29	20	0.25	0.46
Iron Total [c]	mg/L	0.37	20	0.02	1.6
Magnesium Total	mg/L	18	20	17	20
Manganese Total [d]	ug/L	17	20	2.0	52
Nitrate as N [e]	mg/L	0.25	20	0.01	2.5
pH	pH units	7.7	22	7.4	7.9
Potassium Total	mg/L	12	20	10	14
Silica	mg/L	44	20	40	48
Sodium Total	mg/L	1,985	20	1,800	2,100
Strontium	mg/L	1.0	20	0.84	1.1
Sulfate	mg/L	3,445	20	3,200	3,600
Sulfide Total [f]	mg/L	0.05	20	0.05	0.05
Temperature	°C	24	30	21	30
Total Dissolved Solids	mg/L	5,765	20	4,500	6,200
Phosphorus Total as P	mg/L	0.26	20	0.20	0.42

[a] Averages use all data except those collected on 12/05/14 because the well was not supplying water due to well pump failure. The detection limit was used when a value was non- detect.

[b] Barium: 3 of the 20 samples were non-detect (<2 ug/L)

[c] Iron: 4 of the 20 samples were non-detect (<0.02 mg/L)

[d] Manganese: 3 of the 20 samples were non-detect (<2 ug/L)

[e] Nitrate: 16 of the 20 samples were non-detect (<0.0125 mg/L)

[f] Sulfide: 19 of the 20 samples were non-detect (<0.05 mg/L)
°C = degree Celsuis
ug/l = micrograms per liter

Preliminary water quality testing of the well water indicated that iron and manganese levels were high, so the treatment system incorporated a greensand filter with regeneration capabilities using chlorine. Upon collecting additional data after the well had been running for an extended period of time, it was found that iron and manganese were no longer concerns. Iron and manganese were being found at concentrations averaging 0.37 mg/L and 0.02 mg/L, respectively. This finding led to the decision to forego the regeneration process of the greensand media.

Provisions were included on the skid for boron ion exchange (pressure vessels, valves, etc.), but purchasing and installing the media was delayed until water quality testing could verify that this process was indeed necessary. Past boron water quality data ranged from non-detectable to 10.5 mg/L, before the well was officially in operation. It was later determined that boron wast in fact present at significant levels (well water boron averaged 3.6 mg/L) so boron ion exchange was deemed necessary. Six cubic feet of boron ion exchange media was initially installed, followed by another six cubic feet in March 2015 after the first amount was exhausted in a considerably short duration of time.

Well water quality continues to be high in TDS, which is effectively addressed by the RO skid. A profile of the product water leaving the RO skid is summarized in Table 9.

Table 9.—Finished Product Water Quality leaving the RO skid since startup (August 2014 to May 2015)

Parameter	Units	Average [a]	Number of Samples	Minimum	Maximum
Alkalinity	as $CaCO_3$	75	10	60	90
Boron Total	mg/L	1.9	10	0.71	3.2
Conductivity	uS/cm	70	24	0.04	294
Nitrate as N	mg/L	0.19	10	0.10	0.31
pH	pH units	7.3	11	2.9	8.1
Sulfide Total [b]	mg/L	<0.05	10	<0.05	<0.05
Temperature	°C	23	20	15	34
Total Dissolved Solids	mg/L	134	10	84	170

[a] Averages use all data except those collected on 12/05/14 because the well was not supplying water due to well pump failure. The detection limit was used when a value was not detected.

[b] Sulfide: 10 of the 10 samples were non-detect (<0.05 mg/L)

The product water quality is aesthetically sound, with the treatment system adequately addressing sulfides, pH, and TDS.

The recommended long-term goal for boron in the product water is 1 mg/L, which corresponds to the notification level set by the California Division of Drinking Water. The notification level is a California-specific non-regulatory health-based advisory level established for chemicals for which maximum contaminant levels have not been established. Trussell Technologies provided SDF the details for the recommended regeneration process to maintain boron concentrations at the recommended 1 mg/L level. To date, the boron media has not been regenerated.

6.4.2. Operational Parameters

The RO component was closely monitored and the performance is shown in Figure 5, Figure 6, and Figure 7.

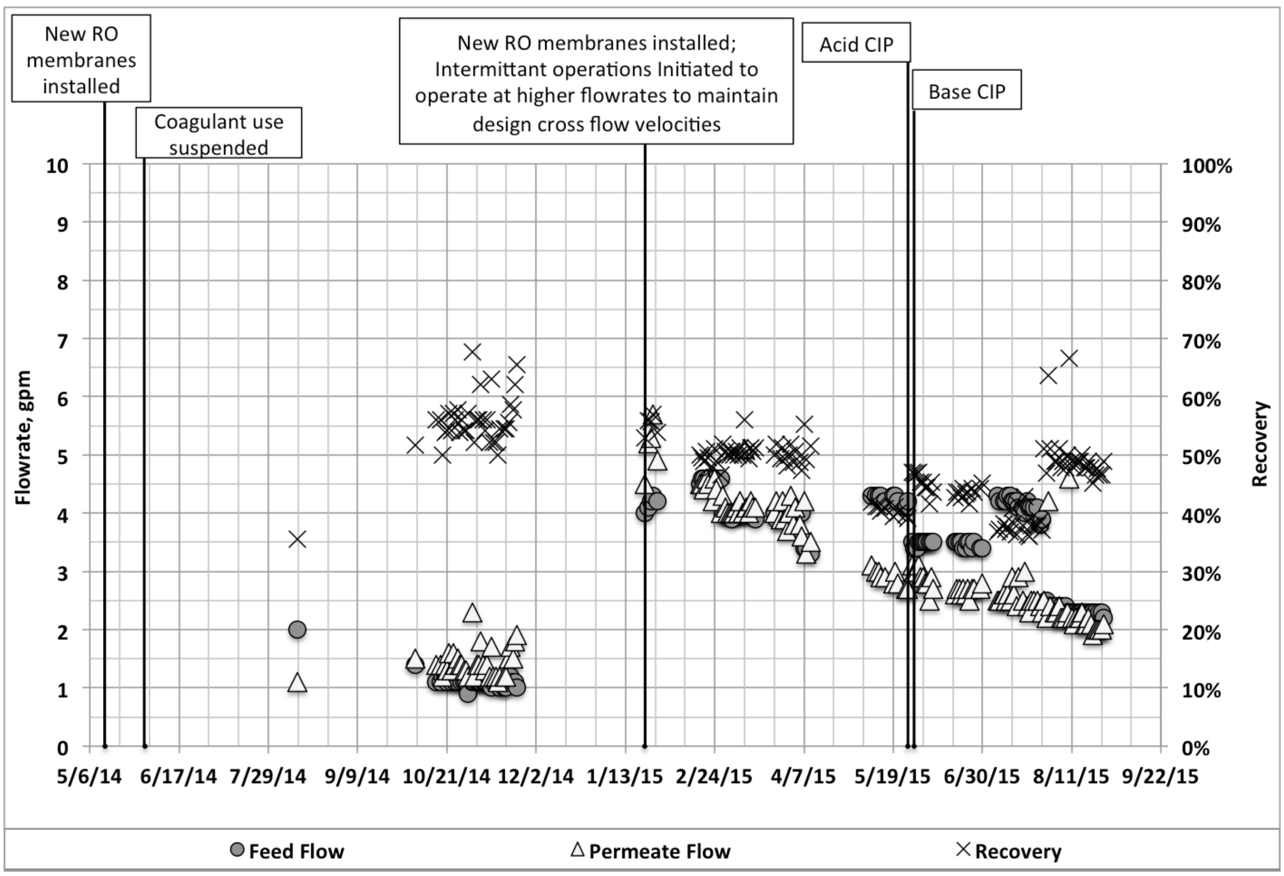

Figure 5.—RO Performance (Flowrates and Recovery)

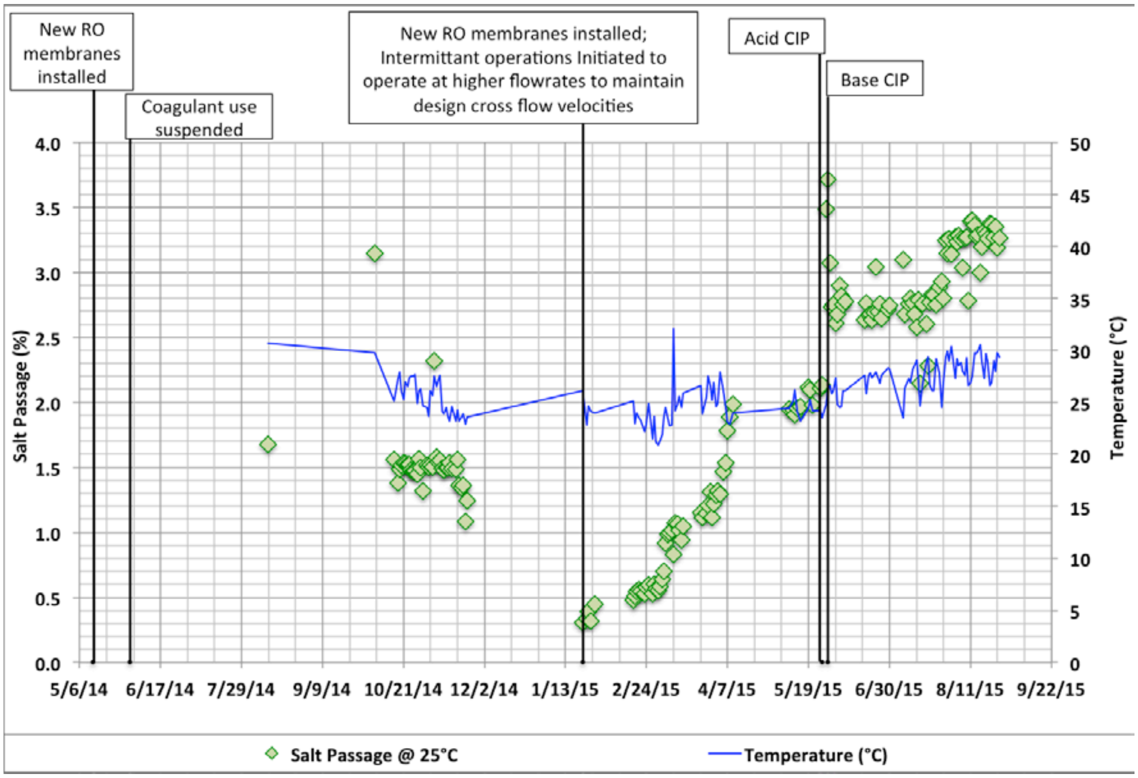

Figure 6.—RO Performance (Salt Passage)

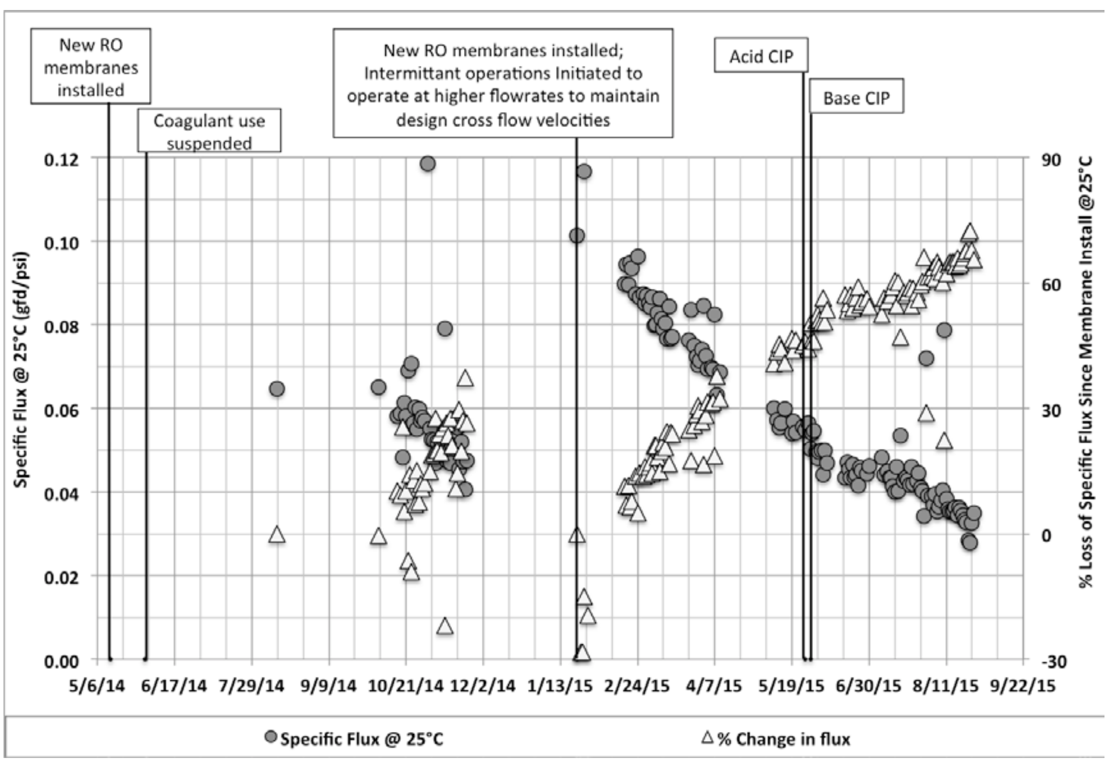

Figure 7.—RO Performance (Temperature Corrected Specific Flux)

As shown in Figure 5, the system was operated at a higher recovery in late 2014 to meet additional demands necessary to establish new native plants on the hillside to prevent erosion.

During the study period, RO performance trending was difficult due to scattered operational settings. The primary cause of variable operations was diminishing raw water well capacity. The flow supplied to the RO skid had gradually decreased to compensate for the well's limited output. The well was originally producing 10 gpm and gradually decreased to 3 gpm. This has significant implications, as the RO system was designed for a minimum feed flowrate of 6 gpm and a minimum reject flow of 3 gpm. With lower production rate, the RO system does not achieve sufficient cross-flow velocity to carry away membrane foulants to prevent premature membrane fouling. At the end of 2014, it was decided that the RO would be operated intermittently to preserve its design production rate, which is important for RO membrane lifespan. This was achieved by using liquid level high and low setpoints in the tray aerator as measured by an ultrasonic liquid level sensor and transmitter.

Intermittent operation was implemented in 2015 after correcting three separate headworks malfunctions:

- The first malfunction was related to the well flow meter and the second and third issues were related to the well pump. The first issue, the operator was not able to get the existing paddle flow meter on the well effluent line repaired and a new flow meter was ordered and installed. The new flow meter also exhibited a similar issue. Upon closer inspection, it was noticed that grit from the well water was collecting on the inside of the flow meter, preventing the mechanism from moving freely. The operator now opens and cleans the mechanism when the flow rate appears to be abnormal.

- The second issue was due to a rock caught in the impellers, which caused the pump shaft to fail.

- The third malfunction was a failed motor that was subsequently replaced.

Both repairs required the well pump to be pulled out of the well. During this period, when the RO skid was operational but the well was not, water was trucked from a nearby water source (Limonaire, a nearby agricultural business) to the RO skid to be treated. The operator did not collect data for the entire month of December because the system was idle for most of the month, and data logging had not been implemented.

For the most part, operational and standby cycle is approximately 20 minutes on and 20 minutes standby, but the cycle varies from 10 to 20 minutes on and 15 to

35 minutes standby. This variation can be explained by varying well production. However, problems with the liquid level sensor signal at five different time points throughout this quarter caused short durations of RO skid downtime. After some troubleshooting and experimentation in late March 2015, minor changes were made to the way the sensor is mounted. There was notable variation in RO feed flow that is not easily explained and warrants investigation but that may be related to the tray aerator liquid level sensor issues.

New RO membranes were installed on January 22. Prior to this, the specific flux had decreased to 0.04 gfd/pounds per square inch (psi). After replacement, RO operations were fairly stable, with flux at 0.12 gfd/psi. However, feed pressures increased and specific flux decreased rapidly within a three-month period. Specific flux decreased from 0.12 gfd/psi (after new membranes were installed on January 22nd) to 0.08 gfd/psi within 1.5 months of operations. Typically, membranes are able to operate for 3 to 6 months before needing a CIP, indicated by a 15% reduction in specific flux. However, based on the observed decline in specific flux, a CIP was necessary within 1.5 months of membrane install. A CIP was completed after 2 months of operation. The completed CIP procedure consisted first of exposing the RO membranes to an acid solution, then a base solution. Successful cleans would have been indicated by improved recovery, flux, and salt passage measurements immediately after the procedures were complete. This was not the case, and RO performance was not significantly affected, shown in Figure 6 and Figure 7. The RO membranes were likely fouled beyond the point where they could be cleaned, indicating that the CIP was performed too late. Regardless, the operator decided to continue running the RO membranes until they are not producing enough water for the facility. The operator has since been given approval to change out the membranes three times per year.

6.4.3. Maintenance and Troubleshooting

During the course of this study, it was learned that if chlorine tablets are not used at a certain rate, they disintegrate with time and make their way through the grate, resulting in a slurry in the reservoir, shown in Figure 8.

Figure 8.—Tablet chlorinator and chlorine tablet consistency.

The tablet receptacle requires occasional cleaning and appears to work best when loaded with only a single layer of tablets, rather than filling the basket completely, presumably so there is less weight on top of the wet tablets to squeeze them through the grate. The problem may in part be that the tablets remained in the chlorinator for months, since they are not being used as quickly as originally anticipated because the greensand no longer necessitates regeneration (which accounted for most of the chlorine demand). Although the chlorinator may be converted to serve simply as a household bleach receptacle, the operator has opted to continue using the tablet chlorinator and periodically cleans the system to prevent buildup of tablet slurry and to maintain lower product water turbidities.

In August 2014, the tray aerator trays and media were cleaned to remove material that was clogging the outlet ports (mainly leftover ferric chloride coagulant). The use of ferric chloride at the beginning of the study impacted both the tray aerators and greensand filter media. In late October, the tray aerator system began to overflow due to floc buildup. Although the operator attempted to clean the tray aerator media, he was unable to remove the floc residue on the media surface. New media was purchased and replaced (costing approximately $150) to avoid future overflow issues. Regarding the floc buildup in the greensand filters, the automated backwash was not able to adequately dislodge the floc. Two solutions appear to assist with this problem:

(1) A 12-hour chlorine soak (completed on Filter 1 on November 6)

(2) An extended duration (15-minutes) backwash completed in two steps, first for 10 minutes (which uses all the water in the permeate tank), then another 5 minutes after the permeate tank is recharged.

Increased turbidity impacts the frequency at which the cartridge filters must be replaced. Typically, the cartridge filters are changed out once every month. After rain events that impact well turbidity, the cartridge filters are replaced once every 2 days.

6.5. Brine Bed Performance

Brine beds have been operational since April 2014. Photos of the brine beds and the nozzles from the high rate solar evaporator are shown in Figure 9 and RO brine data are shown Table 10.

Figure 9.—High rate solar evaporator bed and nozzle

Table 10.—RO Brine Water Quality

Parameter	Units	Average [a]	Number of Samples	Minimum	Maximum
Alkalinity	as $CaCO_3$	1548	20	1112	2080
Ammonia as N	mg/L	25	20	17	32
Barium Total [b]	µg/L	46	20	2.0	470
Boron Total	mg/L	4.6	20	3.8	5.7
Calcium Total	mg/L	93	20	62	120
Chloride	mg/L	62	20	42	78
Conductivity	mS/cm	13	20	10	17
Fluoride	mg/L	0.48	20	0.34	0.61
Iron Total [c]	mg/L	0.06	20	0.02	0.56
Magnesium Total	mg/L	32	20	21	42
Manganese Total	µg/L	333	20	41	2400
Nitrate as N [d]	mg/L	1.5	20	0.01	4.8
pH	pH units	7.9	20	7.5	8.2
Potassium Total	mg/L	22	20	14	26
Silica	mg/L	76	20	53	100
Sodium Total	mg/L	3490	20	2400	4500
Strontium	mg/L	1.7	20	1.1	2.2
Sulfate	mg/L	6125	20	4200	8100
Sulfide Total [e]	mg/L	<0.05	20	<0.05	<0.05
Temperature	˚C	25	17	22	30
Total Dissolved Solids	mg/L	10355	20	7100	14000
Phosphorus Total as P	mg/L	0.43	20	0.28	0.58

[a] Averages use all data except those collected on 12/05/14 because the well was not supplying water due to well pump failure. The detection limit was used when a value was not detected.

[b] Barium: 3 of the 20 samples were non-detect (<2 ug/L)

[c] Iron: 18 of the 20 samples were non-detect (<0.02 mg/L)

[d] Nitrate: 10 of the 20 samples were non-detect (<0.0125 mg/L)

[e] Sulfide: 20 of the 20 samples were non-detect (<0.05 mg/L)

mS/cm = millisiemens per centimeter

Although the brine beds performed adequately during the summer season, the system was unable to evaporate enough water during the winter season using the settings used for the summer months (pumps set at 67% of full speed). To prevent overflow of the brine bed storage tanks, the operator used the brine water for dust control and other construction-related efforts. The pump setting was increased to mist water at a higher rate. Due to a mixture of brine disposal methods (evaporation and use for construction-related activities), it has been difficult to evaluate the performance of the brine beds.

Additionally, priming issues with one of the two sprinkler pumps on the brine bed system prevented it from running until the last part of February. When only one pump was functional, the system ran with only the functional pump approximately 70% of the time at 67% power. After which, both pumps were run approximately 20 hours each day for several weeks at 83% power to reduce tank levels. It was possible to extract some data during this period of mixed operations. Figure 10 is a plot of storage tank levels and conductivity for this time frame of increased pump output.

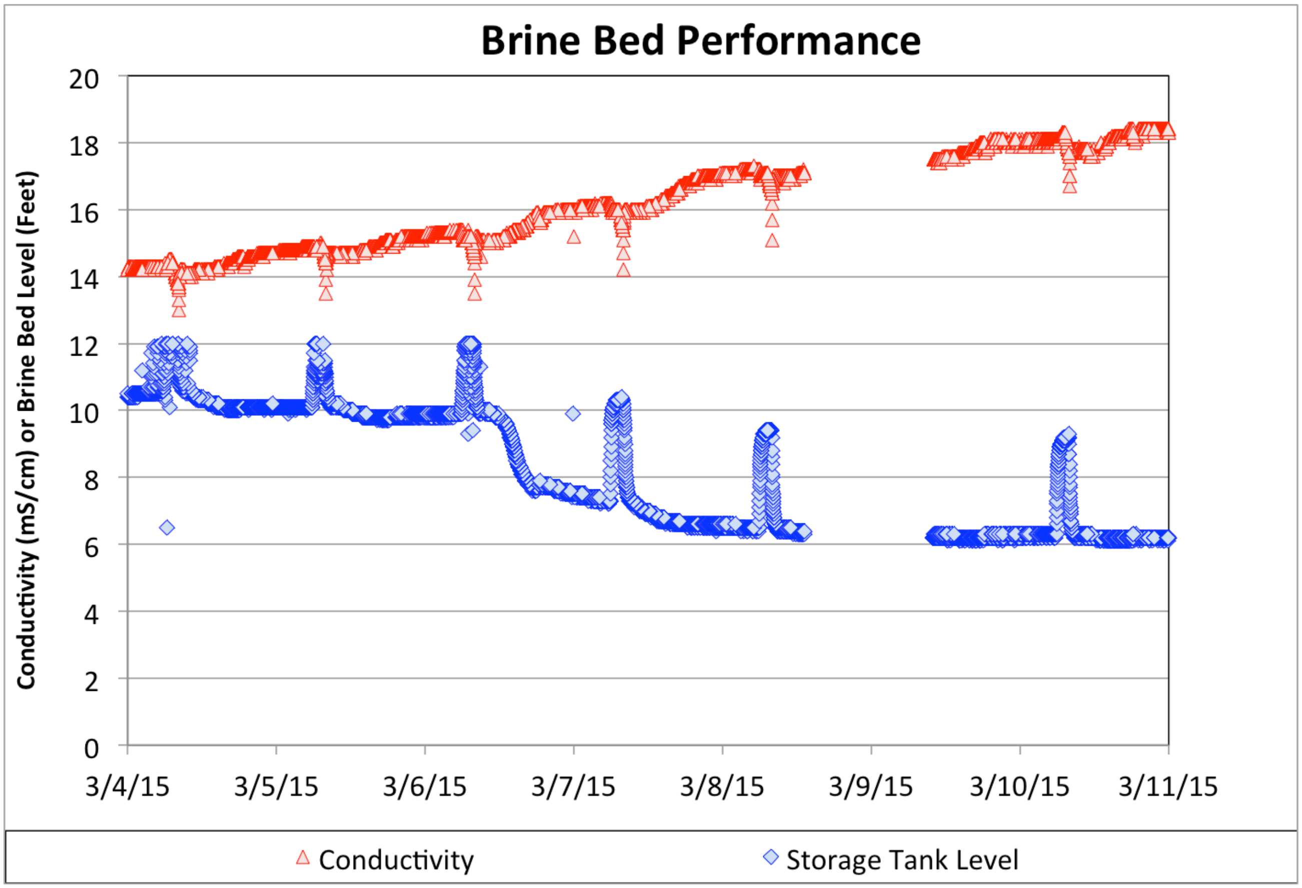

Figure 10.—Plot of storage tank levels and conductivity.

As expected, conductivity increases as more water is evaporated (indicated by storage tank level) due to higher dissolved solids concentration. The gap in data around March 9 is explained by instrumentation issues. The power monitoring equipment that was installed in the middle of March on one of the brine bed pumps indicated that one brine pump consumed 824 kilowatt hours (kWh) in 34 hours of run-time.

In June, an intensive brine bed study was performed, including a solids deposit analysis. Data collected on the brine beds for approximately two weeks in June

2015 are shown in Figure 11. During this time period, both brine pumps were run at full speed for 22 hours per day which consumed 10.8 kilowatts (kW) of power combined, which equates to approximately $780/month in energy costs.

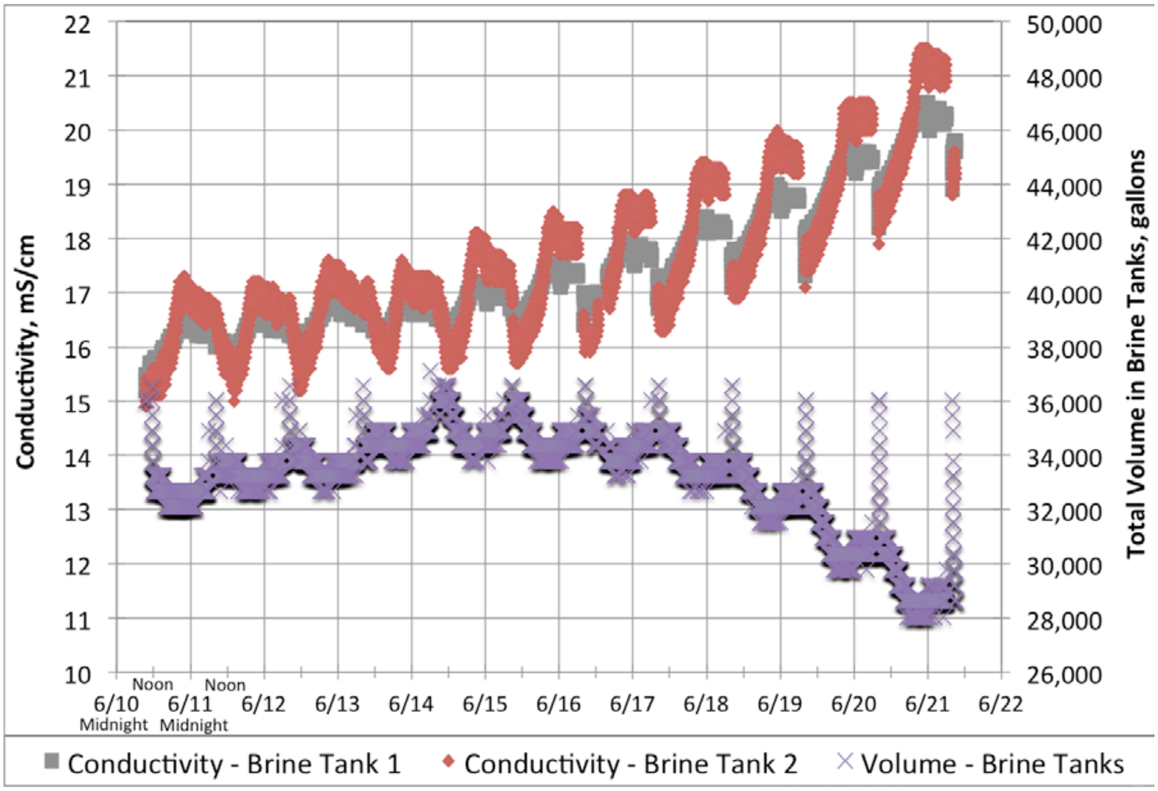

Figure 11.—Brine bed (conductivity and volume).

Figure 11 shows that conductivity is inversely correlated to volume in the brine bed storage tanks. This makes intuitive sense as the water evaporates but the solids in the brine water remains. The figure also shows that the volume in the tanks fluctuate up and down, but overall goes down over time, indicating that during this time period the brine system keeps up with the waste water production.

Correlation analyses were performed on evaporation rate with solar radiation, wind, and temperature levels. Figure 12 through Figure 14 show these results. Evaporation rate correlated best with solar radiation (r^2=0.83), followed by wind (r^2=0.71), and lastly, temperature (r^2=0.62).

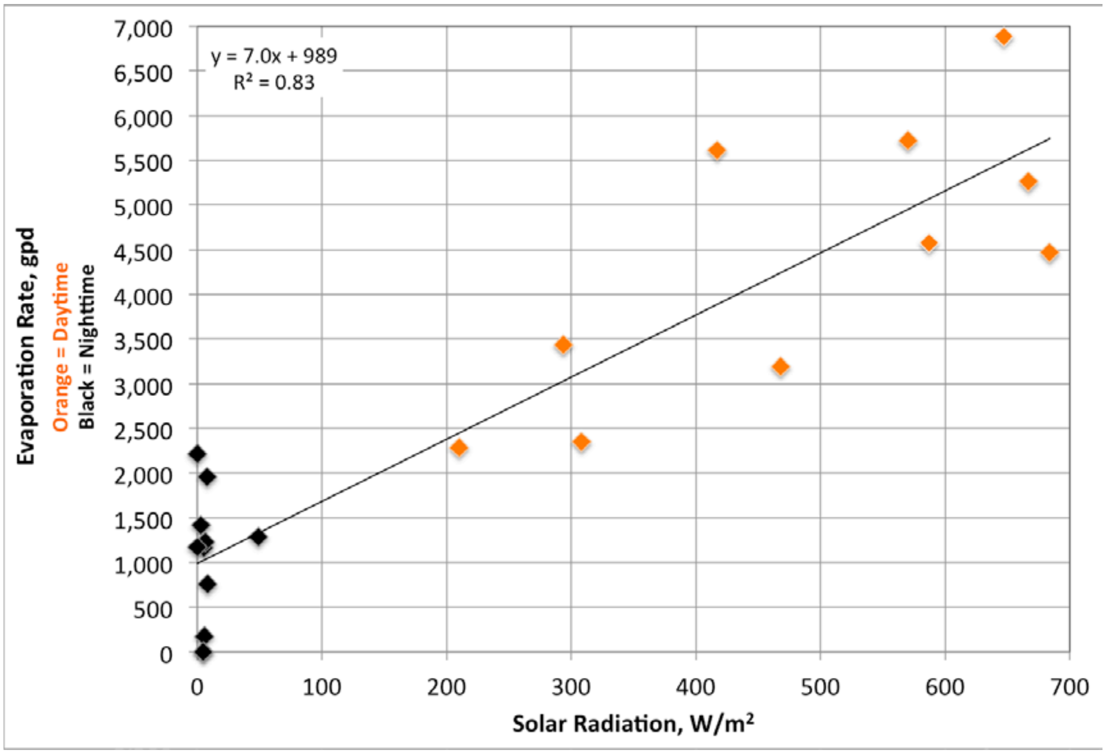

Figure 12.—Brine bed (evaporation and solar radiation correlation).

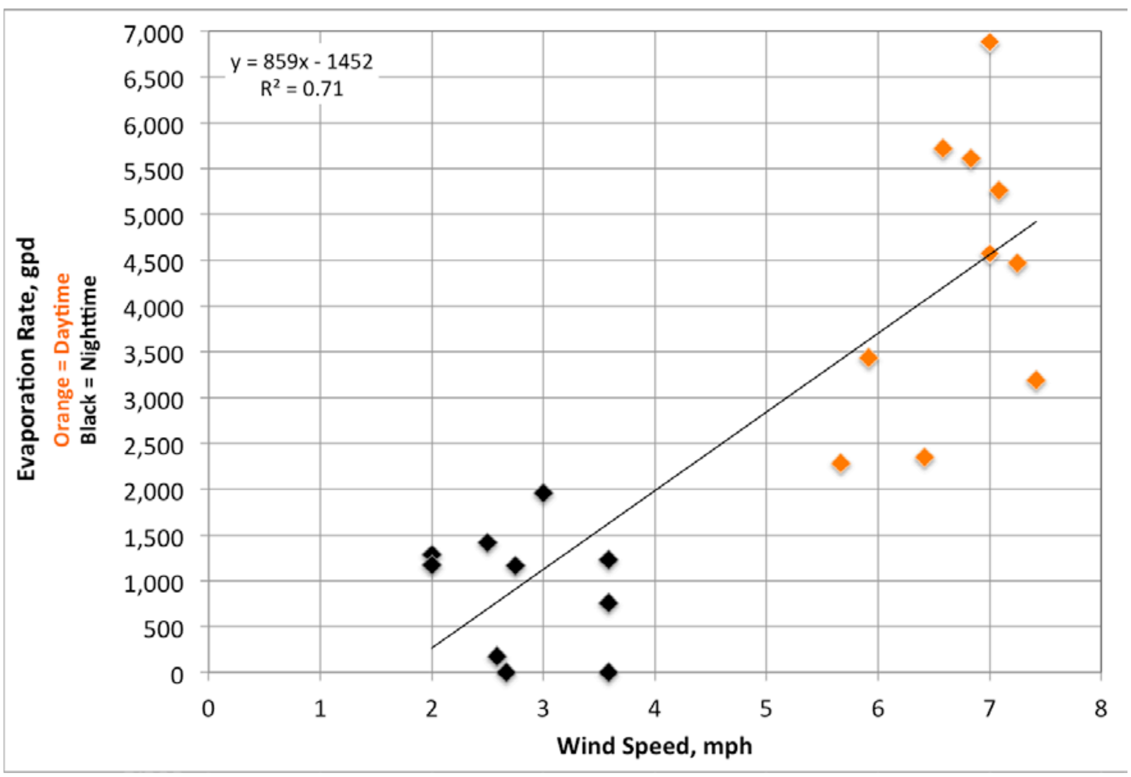

Figure 13.—Brine bed (evaporation and wind speed correlation).

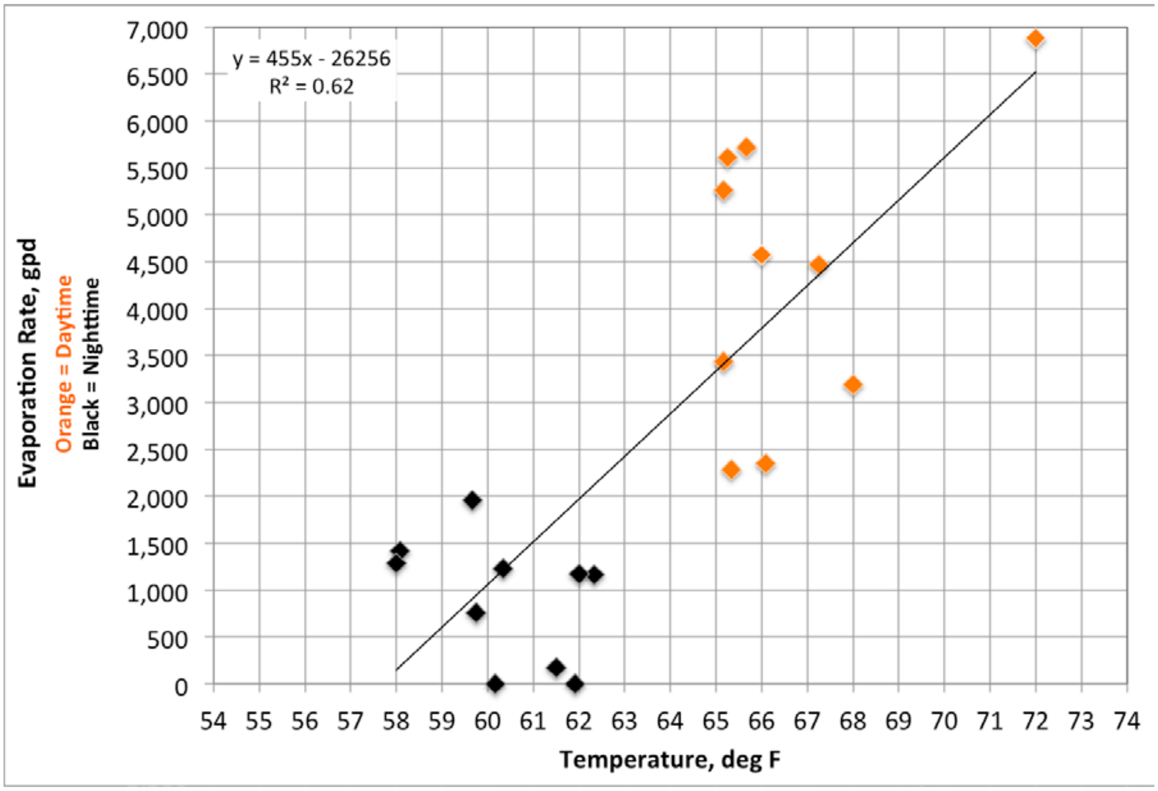

Figure 14.—Brine bed (evaporation and temperature correlation).

Figure 15 is an image of the solids left on the brine bed rocks over approximately two years of operation. There is also evidence of solids accumulating along the fence line, shown in Figure 16.

Figure 15.—Solids on brine bed rocks.

Figure 16.—Accumulation of solids along fence line.

Laboratory analysis reveal that 70% of the mass by weight deposited was thenardite [Na_2SO_4] and the remaining 30% burkeite [$Na_6(CO_3)(SO_4)_2$]. This is supported by the water quality results as they show the brine having high alkalinity (1,548 mg/L as $CaCO_3$) and substantial sodium and sulfate content. The list of compounds that would result in solids is summarized in Table 11 in the order of highest to lowest concentration. Sulfate and sodium are by far present at significantly higher concentrations than the other compounds with solids formation potential (e.g. manganese and calcium).

Table 11.—List of Salts Found in Brine Stream

Parameter	Units	Average
Sulfate	mg/L	6,125
Sodium Total	mg/L	3,490
Manganese Total	µg/L	333
Calcium Total	mg/L	93
Silica	mg/L	76
Chloride	mg/L	62
Barium Total	µg/L	46
Magnesium Total	mg/L	32
Ammonia as N	mg/L	25
Potassium Total	mg/L	22
Boron Total	mg/L	4.6
Strontium	mg/L	1.7
Nitrate as N	mg/L	1.5
Fluoride	mg/L	0.48
Phosphorus Total as P	mg/L	0.43
Iron Total	mg/L	0.06
Sulfide Total	mg/L	<0.05

7. CONCLUSIONS AND RECOMMENDATIONS

Before the ZLD system was ready for assessment in August 2014, there were several challenges, and many lessons were learned throughout the duration of this study. Those most significant which may help to avoid issues in future projects similar in nature are outlined below.

- A small RO skid requiring minimal chemical input and human intervention, operated by personnel with minimal training, can be a viable method to treat compromised well water to be safe and aesthetically pleasing drinking water.

- High Rate Solar Evaporation is a viable means to implement a ZLD system, when a large footprint for passive evaporation ponds is not feasible. The footprint in this case was approximately one-third as large as it would have needed to be with a conventional evaporation pond.

- High Rate Solar Evaporation is an economical option compared to continuous hauling of waste water associated with RO systems. Hauling water away is estimated to cost $500,000/year while operating the High Rate Solar Evaporation system was shown to cost approximately $10,000/year, in this rural county in southern California.

- The added cost of equipment and labor for instrumentation and automation, including data logging, may seem unnecessary during design and costing stages of a project, but they play a critical role in minimizing cost and operator input, reliability, system performance review, and troubleshooting, even on a system of this small of a scale. This project team recommends maintaining a strong focus on instrumentation and automation throughout the entirety of a project and to devote ample budget to that effort from the onset.

- Given the scale of this sort of project, it may be tempting to begin testing immediately upon operation, or soon thereafter. However, the variability in unforeseen challenges faced throughout the startup of this project and the duration it took to rectify them demonstrated the importance in having a defined startup phase sufficiently long before attempting to acquire data for performance reporting.

- To complement the importance of a sufficiently long startup phase prior to collecting operational data for performance reporting, it is imperative to acquire reliable initial data on the system once the startup phase is complete and the system is in normal operation.

8. SUMMARY OF COMPLETED ACTIVITIES

List of activities completed during the entire period:

- Constructed water-related infrastructure at SDF National Training Center
- Fabricated RO water treatment skid system in Pasadena at Trussell Technologies Workshop
- Installed RO skid onsite
- Started-up RO skid and high rate solar evaporator
- Evaluated performance of RO treatment system
- Evaluated performance of high rate solar evaporator
- Submitted seven quarterly technical progress reports
- Submitted draft final report

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