RECLAMATION
Managing Water in the West

Fouling Challenge for a Robust, Remote Controlled Ultrafiltration/ Reverse Osmosis System

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An automated and remote controlled, Ultrafiltration/Reverse Osmosis (UF/RO) system is evaluated for robustness and adaptability to severe changes in feed water quality at the Bureau of Reclamation's Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico. A maximum RO system recovery of 83 percent was achieved on the highly scaling well water. Average RO permeate quality remained acceptable with a maximum conductivity of 168 microSiemens per centimeter, despite wide-ranging feed conductivity due to recycling RO concentrate to the RO feed tank to increase recovery and as backwash supply for the UF system. During fouling challenges with separate solutions of natural humic and fulvic acid, blue-green algae, kaolin powder, and sodium alginate, the system recovered easily upon decline in fouling load or with hot water cleanings. Methods are presented for monitoring the onset of, and degree of, fouling in real time using the traditional process sensors. In addition, recommendations are proposed for automating UF maintenance.

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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.

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Abbreviations and Acronyms

µmhos/cm	micromhos per centimeter
µS/cm	microSiemens per centimeter
AHI	Advanced Hydro, Inc.
Ave.	average
BGNDRF	Brackish Groundwater National Desalination Research Facility
EPA	U.S. Environmental Protection Agency
FNC	future naval capability
ft	feet
gal/d	gallons per day
gal/ft^2	gallons per square feet
gal/min	gallons per minute
hp	horsepower
IP/Ksp	ion product divided by the solubility product
kW	kilowatts
kWh/kgal	kilowatthours per thousand gallons
kWh/m^3	kilowatthours per cubic meter
L/m^2	liters per square meter
L/min	liters per minute
LSI	Langelier Saturation Index
m	meters
m^2	square meters
m^3	cubic meters
m^3/d	cubic meters per day
mbar/min	millibars per minute
MF	microfiltration
mg/L	milligrams per liter
mL/min	milliliters per minute
ND	not detected
NDP	net driving pressure
NOM	natural organic matter
NPF	normalized permeate flow
NTU	nephelometric turbidity units

Abbreviations and Acronyms (continued)

ºC	degrees Celsius
ONR	Office of Naval Research
PBI	polybenzimidazole
PVC	polyvinyl chloride
PVDF	polyvinylidene difluoride
r/min/m^3	revolutions per minute per cubic meter
Reclamation	Bureau of Reclamation
RO	reverse osmosis
SI	saturation index
SP	salt passage
St. Dev.	standard deviation
TDS	total dissolved solids
TMP	transmembrane pressure
UF	ultrafiltration
UMFI	Unified Membrane Fouling Index
VFD	variable frequency drive

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1 Introduction

According to the U.S. Environmental Protection Agency (EPA, 2013), 77 percent of community water systems serve populations of less than 10,000 people, which amounts to 70 million people in the Western United States who receive their water from medium, small, and very small community, transient, or nontransient treatment systems. Most of the systems in the West (84 percent) use groundwater. In large tracts of the West, the groundwater has total dissolved solids (TDS), iron, and manganese above secondary standards; as well as radon, uranium, arsenic, and other contaminants that are close to, or exceed, EPA maximum contaminant level concentrations. Person(s) in charge of operation and maintenance of treatment systems for these difficult waters often have other critical responsibilities. Most people would likely agree that the best situation would be to locate a highly trained treatment process operator onsite who has experience and knows what to watch for and how to respond to changes; however, with remote systems, it is not always practical. Industrial water reuse, remotely produced water treatment, and military applications often have the same requirements for flexibility and reliability, with a low level of operator involvement, as small communities. These applications could use a reliable, robust, automated, and remote controlled treatment system.

Aspects of a treatment system that contribute to robustness include the construction materials that are used; conservative process design; redundancy in instrumentation, and control features. Requirements for remote operation and flexibility include a full monitoring and control system to detect feed water changes and process response to those changes, automated controls that allow smart programming or a trained remote operator to modify operations appropriately, an intuitive human interface, and a secure communication system. Finally, the programmer needs evaluation parameters, target values, dead band levels, alert levels, and actions for the system to take at each level for rising and falling values.

This report focuses on process monitoring during variable feed water conditions, as well as the magnitude of change in evaluation parameters, with the goal of providing assistance in setting evaluation parameter values for initiating operation changes to accommodate changing conditions.

1.1 Background

In 2009, the U.S. Department of Defense Office of Naval Research (ONR) began investing in future naval capability (FNC) for shipboard desalination for small- and large-scale applications. During the first few years, the FNC funded development of key technologies to enable reduced footprint, enhanced energy efficiency, and remote operations. Research performed under Federal programs often reaches the public as dissertations, patents, or in peer reviewed literature as papers associated tangentially with the funded project. Table 1 lists categories of projects funded through the FNC program with references to papers and patents proceeding from the funded work.

Table 1. Summary of Technology Innovations Arising from the ONR FNC Program

Research Area	Primary Investigator	Technology	References
Fouling resistance	Advanced Hydro, Inc.	Membrane coating	Agnihotri, Huang, and Li (2012) and Miller, D.J. et al. (2013)
	Ohio State University	New formulation	Zhao and Ho (2013)
	Ceramem Corporation	Coated ceramic	Goldsmith and Bishop (2010)
	Porogen Corporation	Fouling resistant hollow fiber	Bikson, Etter, and Ching (2013)
Membrane	NanoH_2O, (now LG NanoH_2O)	Nanocomposite seawater membrane	Kurth et al. (2012)
	Sri International	PBI hollow fiber membrane	Jayaweera, et al. (2014)
	Separation Science Technologies/Bureau of Reclamation	Chlorine resistant, thin film membrane	Murphy, Riley, and Porras Mendoza (2014)
Spiral separation	Palo Alto Research Center	Serpentine separator	Lean, Seo, and Völkel (2012)
Monitoring and control	University of California – Los Angeles	Smart system control	Gao et al. (2014a.; 2014b.)

Note: PBI = polybenzimidazole

Remote communities need the same type of robustness the Navy needs for shipboard desalination systems: minimal chemical requirements, energy efficiency, and low maintenance. The Bureau of Reclamation's (Reclamation) Science and Technology Program provided funding to evaluate the potential for developing robust, remote controlled water systems for small, rural communities. As part of this effort, one of the systems designed and built under the ONR FNC program was tested at the Reclamation Brackish Groundwater National Desalination Research Facility

(BGNDRF) in Alamogordo, New Mexico, to evaluate its performance under changing water conditions, a variety of fouling feed waters, and onsite operator neglect.

1.2 Goals for the Project

The test system should run continuously with little operator interaction.
The ultrafiltration (UF) system should produce filtrate with a turbidity <0.1 nephelometric turbidity units (NTU) for the reverse osmosis (RO) system, despite changing feed water quality. It should recover from fouling episodes with minimal onsite operator involvement. The RO permeate should meet drinking water standards, and the membranes should maintain productivity and salt passage characteristics through fouling episodes.

2 Equipment and Test Facility

Testing was carried out at Reclamation's BGNDRF using the system developed by Advanced Hydro, Inc. (AHI) under the ONR FNC shipboard desalination program.

2.1 The System

Sea.PURe™ is a nominal, 5,000-gallon-per-day (gal/d), ultrafiltration/seawater RO system. This RO system meets the size and weight restrictions for the FNC's 4,000-gal/d size. The specific restrictions are 2.3 square meters (m^2) wide by 1.5 meters (m) high (5 feet [ft] by 5 ft by 5 ft) and 910 kilograms (2,000 pounds). A photo of the Sea.PURe™ system is shown in figure 1. Innovative features of the system are summarized below and expanded upon in subsequent sections:

- A patented fouling resistant membrane coating that expands with hot water (40 degrees Celsius [°C]), allowing most fouling material to be washed out of the system

- Open architecture UF design that allows for any UF or microfiltration (MF) modules to be accommodated

- RO system concentrate repurposed for UF system backwash

- Remote control operation with user configurable, UF system backwash cycles that have options for alternating flow directions, cross flow velocity, and air scour

The UF system is fed by a 2-horsepower (hp) Goulds pump, with a second identical pump for backwash (the two center pumps in figure 1). Both pumps are controlled by a single 2.2-kilowatt (kW), 3-hp Danfoss AquaDrive variable frequency drive (VFD). The RO system uses a 0.5-hp Goulds forwarding pump (on the right) and a 15-hp Leeson motor with a 68-liter-per-minute (L/min) Cat Pump controlled by a 11-kW, 15-hp Danfoss AquaDrive VFD under tanks in the back. The pump on the left is a spare replacement pump for any of the three centrifugal pumps. UF feed is degritted with a Lakos centrifugal separator and dual Lakos TwistIIClean screens. Two chemical feed pumps are used for chemical cleanings (citric acid and sodium hydroxide). A third antiscalant .feed pump was added for this application. Low-pressure pipe is schedule 80 polyvinvyl chloride (PVC), and high-pressure pipe is 360 stainless steel.


Figure 1. Sea.PURe™ system set up at the BGNDRF (left) and a side image from AHI (right) (Advanced Hydro, Inc., 2013).

2.1.1 Membranes

As configured for this test, the system used three Dow SFP-2660 UF modules. These membranes are polyvinylidene difluoride (PVDF), hollow fiber modules with a nominal pore diameter of 0.03 micrometer [μm], configured for outside-in flow path. Total membrane area is 99 m^2. The RO system was filled with four LC HR-4040, DOW FILMTEC, polyamide thin-film composite membranes in series. These membranes are rated for 11 cubic meters per day (m^3/d) (2,900 gal/d) with a stabilized salt rejection of 99.7 percent.

AHI coated both types of membrane with a patented, polydopamine based treatment. The treatment process and formula were developed through a Reclamation Desalination and Water Purification Research Program cooperative agreement with the University of Texas at Austin (Ju and Freeman, 2008), and further advanced under Phase 1 of the ONR FNC program (Agnihotri, Huang, and Li, 2012; Miller, D.J. et al., 2013). The coating forms a brush-like surface that expands with high temperature. Treated UF membrane was found to release foulants more readily than untreated membrane without the use of chlorine backwashes (chlorine would remove the coating). Hot water was used for enhanced backwashes, and citric acid and sodium hydroxide were used for chemical cleaning when necessary.

Because the treated UF membrane worked so well as a pretreatment to the RO system, it was difficult to determine if the benefit sufficiently justified not treating the RO membrane as well. However, it was hypothesized that the treatment may aid in preventing irreversible fouling from scale formation on the RO membrane surface.

2.1.2 Open Architecture and Footprint

Free and open competition is such a critical issue for Federal acquisitions that open architecture design was of paramount importance for the ONR FNC program. AHI embraced the concept by allowing space and connectibility for any UF or MF module that would fit within the space allowance.

2.1.3 RO Concentrate Backwash

The Sea.PURe™ system is designed for seawater desalination using the seawater concentrate for backwash, which allows for a smaller, 100-percent recovery, UF system (Advanced Hydro, Inc., 2013). Liberman and Liberman (2005) advocated direct osmosis - high salinity cleaning solution. They recommended periodically injecting a 25-percent sodium chloride solution into the RO feed to create a reverse flow of permeate back through the membrane, lifting fouling material and causing osmotic shock to biofilms. Periodic extreme changes in ionic strength would have the same benefit for UF membrane. Seawater concentrate would be closer to 7.5 to 8 percent salinity, which would still be sufficient for a moderate cleaning effect. The higher ionic strength would also then continue, after each backwash, to the RO system for a similar cleansing effect.

A significant benefit to using the RO concentrate for backwash is that no UF filtrate is wasted. All production capacity can be used for feeding the RO system. The limit of backwashing frequency and duration is determined by the volume of RO concentrate. For seawater systems operating at 40- to 50-percent recovery, at least 50 to 60 percent of the UF filtrate flow is available for backwash. At BGNDRF, however, operating at up to 80-percent recovery by recycling part of the RO concentrate to the feed tank limited the available volume for backwashing.

2.1.4 Remote Control System

Once stable operation has been achieved onsite, the system is capable of remote control from anywhere with Internet service using screen-sharing software. Figure 2 shows the main process monitoring screen and human-machine interface. Solid blue lines show the direction of flow during normal operation, dashed lines show optional backwash direction from P2, and the dotted lines show optional direction for RO concentrate.

Table 2 lists process control input parameters for each process stream. Control outputs are automated valves to control direction of flow, actuation and speed of three chemical feed pumps (acid, base, and antiscalant), and four process pumps. The control strategy is to keep the RO system running continuously, at constant UF filtrate and RO permeate flow, by adjusting pump speed. The RO permeate flow target is set to meet the maximum system production rate of 25 m^3/d (6,700 gal/d). The UF system is set to produce enough filtrate to maintain the RO feed tank level. RO concentrate fills the UF backwash tank and then overflows to drain. The RO feed tank is sized at 190 liters (50 gallons) to keep the RO system supplied while the UF system is in backwash mode.

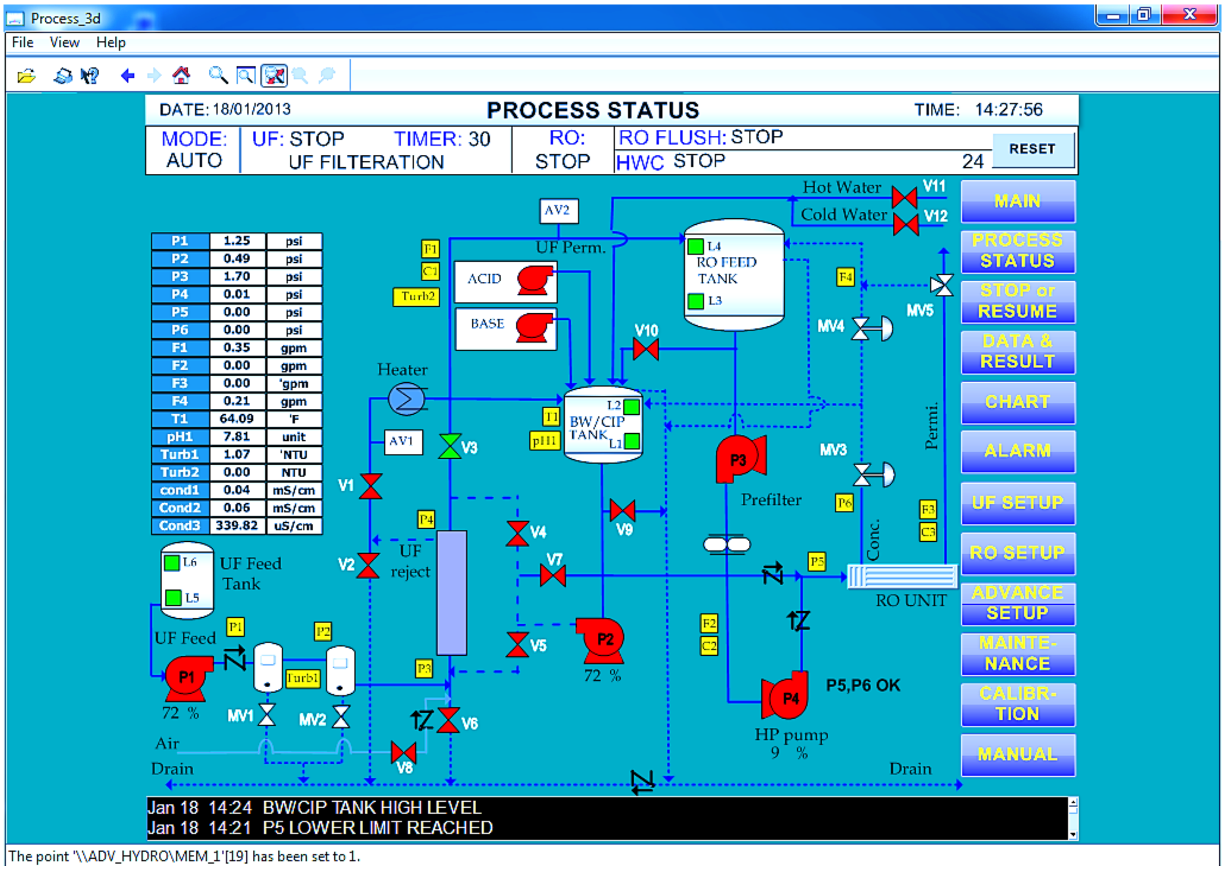

Figure 2. Main Process Monitoring & Human-Machine Interface.

Table 2. Process Control Inputs

Location	Parameter	Pressure	Flow	Turbidity	Conductivity	Temperature	pH
	Feed	X					
	Inlet strainer	X		X			
	UF feed	X					
	UF filtrate		X	X	X		
	UF retentate	X					
	UF backwash/ clean-in-place					X	X
	RO feed	X	X		X		
	RO permeate		X		X		
	RO concentrate	X					
	RO concentrate recycle		X				

There are a variety of options for the UF backwash cycle besides frequency. It can be backwashed from the top end of the module, through the fibers, and back out the top (in at V4 and out at V2) or through the top and out the bottom (in at V4 and out at V6), with or without air scour, at a specified flow rate which sets the duration. Figure 3 shows the flow paths for the two directional options and the forward flush. Two different backwash cycle methods can be specified on the backwash setup screen. A ratio is set to specify how often to use each method (for example, 1:1, as used for this test, alternates methods every cycle). The maximum frequency depends on the available concentrate flow. With brackish water, it is necessary to recycle part of the RO concentrate to the RO feed tank to attain higher recovery rates. For this test, with 80-percent recovery, the maximum backwash frequency was three times per hour.

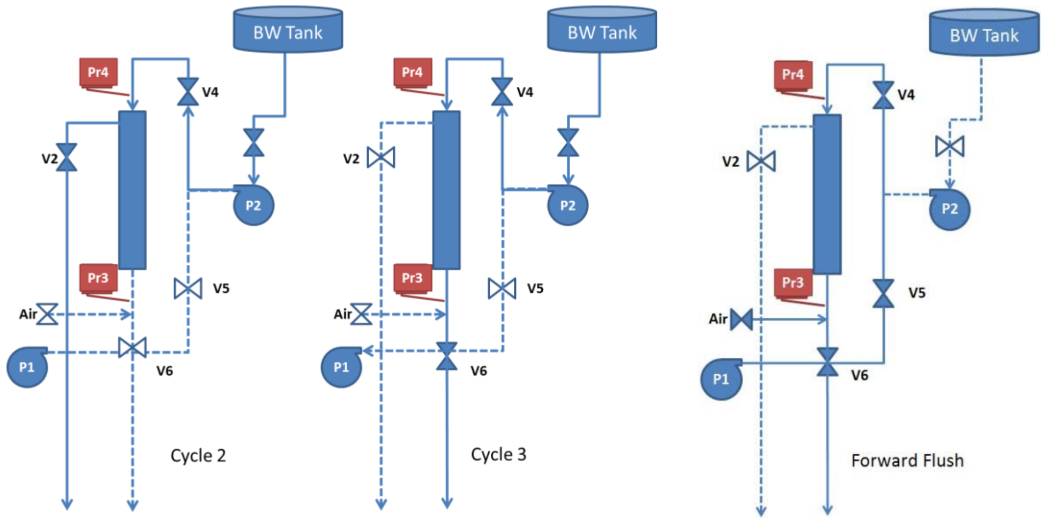

Figure 3. Back flush cycles 2 and 3 and forward flush cycle for the UF elements.

2.2 BGNDRF

The BGNDRF is located in Alamogordo, New Mexico, 85 miles north of El Paso, Texas, and 16 miles east of White Sands National Monument. The facility is a 40-acre research service facility. Private parties, universities, and Federal and State Government agencies carry out research projects at the facility on brackish water treatment, concentrate management, saline agricultural methods, and harvesting of alternative energy from wind and sun. There are six test bays inside the facility and four larger test pads outside. Each test area has access to four wells at different depths that provide brackish groundwater with a range of dissolved solids composition. Table 3 provides a summary of the well water compositions. More detailed information on the facility is available at http://www.usbr.gov/research/AWT/BGNDRF. The testing for this project started with Well 2 but, due to technical difficulties, was moved to Well 4, and then completed with Well 3.

Table 3. BGNDRF Well Water Analyses (November 2013)

Parameter Name	Reporting Units	Well 1	Well 2	Well 3	Well 4
Water temperature	ºC	39.8	20.4	20.4	20.3
Dissolved oxygen	mg/L	2.46	6.09	2.33	5.04
Alkalinity, bicarbonate	mg/L $CaCO_3$	98	250	190	210
pH	pH units	7.64	7.23	7.3	7.24
Color	Color units	10	ND	ND	10
Conductance, specific	µmhos/cm	3,300	5,900	4,400	5,000
Bromide	mg/L	ND	0.38	0.25	ND
Chloride	mg/L	37	530	690	650
Fluoride	mg/L	1.6	0.66	ND	ND
Hardness, total	mg/L $CaCO_3$	700	2,600	1,900	2,000
Langelier Saturation Index (LSI)	SI	0.6	0.6	0.5	0.5
Nitrogen, nitrate	mg/L N	ND	6.5	2.6	3.9
Perchlorate	mg/L	ND	0.16	0.47	0.39
Phosphorus, total	mg/L P	ND	ND	ND	0.065
TDS	mg/L	2,650	5,240	3,510	4,080
Sulfate	mg/L	1,700	2,900	1,600	2,000
Turbidity	NTU	ND	0.65	3.7	38
Aluminum	mg/L	ND	ND	ND	0.051
Arsenic	mg/L	ND	0.0013	0.001	0.00042
Barium	mg/L	0.038	0.01	0.011	0.012
Boron	mg/L	0.38	0.93	0.14	0.27
Calcium	mg/L	200	530	440	480
Chromium	mg/L	ND	ND	ND	0.0024
Cobalt	mg/L	ND	0.0029	0.0024	ND
Copper	mg/L	0.018	0.02	0.0072	0.038
Iron (dissolved)	mg/L	ND	0.031	ND	0.440
Iron (total)	mg/L	0.028	0.085	0.044	3.000
Magnesium	mg/L	48	310	190	210
Manganese (dissolved)	mg/L	0.052	0.0054	0.01	0.021
Manganese (total)	mg/L	0.057	0.0062	0.011	0.024
Nickel	mg/L	ND	0.004	0.0036	0.0027
Potassium	mg/L	8.6	2.9	3.3	3.3
Selenium	mg/L	0.001	0.008	0.0077	0.0068
Silicon dioxide	mg/L	24	23	20	18
Sodium	mg/L	540	600	340	400
Strontium	mg/L	6	8.2	6.8	7.2
Uranium	mg/L	0.0025	0.015	0.0087	0.0085
Zinc	mg/L	0.018	0.024	0.0043	0.027

Note: mg/L = milligrams per liter, ND = not detected, µmhos/cm = micromhos per centimeter

3 Evaluation Methods

The test plan called for four stages of evaluation: (1) startup, (2) increasing RO system recovery, (3) fouling, and (4) high recovery. The high recovery stage was concluded with cleaning and reevaluation of post-cleaning performance.

3.1 Overall Evaluations

In addition to the specific system performance metrics described below, the overall system was evaluated on responsiveness to changing conditions, ease of use, reliability, and power consumption (ease of use was subjective). Reliability was evaluated on the number of incidents related to equipment function. Power consumption was calculated for the UF system based on the 2-hp pump motor size, estimated 85-percent combined pump and motor efficiency, pump speed, and flow; and considering that both the UF feed pump and backwash pump are the same type of pump and are controlled by the same VFD with 98-percent efficiency. The RO power is based on flow and pressure, considering the RO feed pump/motor size is 15 hp with 92.4-percent efficiency driven by a VFD with 98-percent efficiency.

3.2 UF System Evaluation

The UF system was evaluated on its ability to provide continuous flow, of acceptable quality, to the RO system, despite the fouling challenge. There are two aspects of such an evaluation: (1) the degree to which the UF membranes resist fouling, and (2) the effectiveness of the backwash cycle in recovering performance.

3.2.1 Feed Water Quality

Turbidity of the feed solution is measured after the cyclone separator and before the screen filters. Variation in turbidity during each of the fouling challenges was due to accumulation in the cyclone separator; adsorption on the sides of the tank, which periodically sloughed off and plugged the injection line; and exhaustion of foulant solution.

Conductivity measurements of the UF filtrate were used to monitor changes in incoming water quality and the degree of change from backwash events.

3.2.2 Fouling

Degree of fouling was evaluated through:

1. Maximum transmembrane pressure (TMP) during the production cycle

2. Rate of change in TMP over the production cycle

3. Rate of change in pump speed per unit volume required to maintain filtrate flow to the RO system

4. Unified Membrane Fouling Index (UMFI) (Huang and Jacangelo, 2008)

TMP is the difference between the pressures of the UF feed and filtrate measured by two different sensors. The maximum is the highest TMP before the backwash cycle begins. The rate of change in TMP and pump speed during each production cycle was calculated at the end of the test. The UMFI is calculated from the change in specific flux over a production cycle. The specific flux (J_s) is the filtration rate divided by the TMP. The basis point (J_{so}) is taken for each set of conditions when the system is performing steadily. The slope of the line formed from plotting the inverse specific flux against accumulated filtrate volume is the UMFI. The intersection with the Y axis is the degree of irreversible fouling not recovered since the basis point. This may be reversible with cleaning but not with the backwash cycle. In the equations below, Q is the filtrate flow at time "t" and at the basis point "o".

$$\frac{J_s}{J_{so}} = \frac{Q_t/TMP_t}{Q_o/TMP_o} = J_s'$$

$$\frac{1}{J_s'} = 1 + UMFI * V_s$$

Huang and Jacangelo (2008) describe the theory behind the UMFI and show how it is theoretically the same for constant pressure and constant filtrate flow. Normalization against a basis point removes the necessity for module area, membrane resistances, physical attributes of the particulates, etc. The model assumes that cake formation is the primary long-term mode of fouling in full-size systems after a period of time, that the foulants are of similar concentration as would be found in natural water systems, and that foulants do not permeate the membrane.

The effectiveness of the backwash cycle was evaluated by the degree of irreversible fouling, as measured by the difference between initial and post-cleaning values for each of the above metrics. The quality of UF filtrate was evaluated periodically with a hand-held turbidimeter.

3.3 RO System

The RO system is evaluated through changes in normalized permeate flow (NPF) and salt passage (SP) with increasing recovery rate and through fouling challenges. The NPF is the permeate flow normalized for net driving pressure (NDP) and temperature differences through the temperature correction factor.

$$NDP = P_{app} - \Delta\pi - \frac{1}{2}\Delta P - P_p$$

Where:

- $\Delta\pi$: osmotic potential of the feed/concentrate mixture
- $\frac{1}{2}\Delta P$: one half the pressure difference across the vessel
- P_p: product backpressure, which in this application is zero as the product exits into a tank at atmospheric pressure

Bulk osmotic potential is calculated according to the equation below from the feed water composition and instantaneous recovery rate, which is the permeate flow divided by the feed flow. When concentrate is not recycled to the RO feed tank, this is also the overall recovery rate.

$$\Delta\pi = \Delta nRT$$

Where "Δn" is the difference between the log mean of the number of moles of ions in the feed-concentrate solution and the permeate stream. Molar concentration is calculated from the composition and conductivity of the feed solutions using the average molar mass and ratio of conductivity to TDS for each well, as listed in table 4. The magnitude of the permeate concentration is small enough to be considered insignificant with high rejection brackish water membranes and brackish source water. "R" is the universal gas constant, and "T" is temperature in degrees Kelvin.

Table 4. Well Characteristics Required for Estimating Osmotic Potential

	Well 1	Well 2	Well 3	Well 4
Ratio of conductivity to TDS $\left[\frac{\mu S/cm}{mg/L}\right]$	1.25	1.13	1.25	1.23
Average molar mass (grams per mol)	57.6	51.7	48.4	50.8

NPF is calculated according to following equation:

$$NPF = Q_p * \frac{NDP_r}{NDP_t} * \frac{TCF_r}{TCF_t}$$

Where Q_p is the RO permeate flow. Subscript "r" indicates the reference data point at each step change in flow and/or recovery, while "t" is the data point at a particular time afterwards. The temperature correction factor used is from AHI:

$$TCF = \exp\left\{1250 * \left[\frac{1}{298.15} - \frac{1}{(T + 273.15)}\right]\right\}$$

Where "T" is the temperature in centigrade at time "t".

Instantaneous recovery is the ratio of RO permeate to RO feed. With recycling of the concentrate to the RO feed, the overall recovery is calculated as:

$$Rec_{overall} = \frac{Q_p}{\left(Q_f - Q_{recycle}\right)}$$

The log mean concentration factor used for calculating SP and osmotic potential of the feed-concentrate solution is calculated using the instantaneous recovery, rather than the overall recovery, because the feed conductivity is taken after recycle mixing:

$$CF = \frac{LN\left[\frac{1}{1 - Rec_{instantaneous}}\right]}{Rec_{instantaneous}}$$

SP normalized for temperature and flow is then calculated as:

$$SP = \left[\frac{C_p}{C_f * CF}\right] * \frac{TCF_r}{TCF_t} * \frac{Q_{p(t)}}{Q_{p(r)}}$$

Subscript "p" is the permeate stream, "f" is the feed stream, "r" and "t" are as defined above. Conductivity "C" is used to estimate concentration of permeate and feed streams.

3.4 Recovery Tests

From previous work (Chapman, 2013), it is known that recovery greater than 25 percent will result in scaling when using the Well 2 groundwater without antiscalant. Upon startup, the system was operated for 20 days at 45 L/min

(12 gallons per minute [gal/min]) feed flow at 23- to 25-percent recovery to ensure the connections were sound and that water quality would be as expected from Well 2. After 9 days, Well 2 went off-line due to a power failure. The project was switched between Wells 1, 3, and 4 until pump issues were resolved, and, eventually, Well 3 was used for the remainder of the testing. The antiscalant projection software, Avista Advisor (version 3.21; Avista Technologies, 1999), was used to project maximum recovery, antiscalant selection, and dosing. Table 5 describes the level of saturation from the two primary wells over the range of recovery rates used during the testing, and recommended antiscalant dose.

Table 5. Saturation Indicators for Wells 2 and 3

	Well 2		Well 3					Maximum
	Raw	25%	Raw	25%	50%	80%	85%	With Vitec® 7000*
LSI	0.59	0.84	0.4	0.53	1.03	2.16	2.53	≤2.5
S&DSI	0.25	0.41	0.22	0.51	0.91	1.73	2.02	
$CaSO_4$ IP/Ksp	1.03	1.47	0.64	0.94	1.58	4.68	6.54	7
$BaSO_4$ IP/Ksp	1.87	2.60	1.51	2.07	3.28	9.24	12.75	300
$SrSO_4$ IP/Ksp	0.88	1.19	0.54	0.73	1.13	3.09	4.21	35
Ca F_2 IP/IP maximum	0.40	0.94	ND	0	0	0	0	1,000
Calcium carbonate precipitation potential	37.3	82.2	13.9	35.1	91.1	451.5	692.6	≤900
Silica (mg/L)	24	31	20.0	26.3	39.9	99.1	133	120
Iron and manganese	0.01	0.02	0.05	0.07	0.10	0.22	0.29	3.94
Recommended dose of Vitec® 7000 (mg/L)				4.08	2.74	2.44	5.44	

*Avista Technologies Vitec® 7000 Data Sheet plus maximum recovery for Well 4 is 24 percent due to iron and manganese saturation.

Note: S&DSI = Stiff and Davis Stability Index, IP/Ksp = ion product divided by the solubility product.

A 10-percent solution of Avista's Vitec® 7000 antiscalant was prepared with RO permeate and dosed at approximately 0.5 milliliter per minute (mL/min) into the filtrate flow (22.7 L/min) entering the RO feed tank for an average dose of 1.85 mg/L of antiscalant. This is less than the recommended dose identified above; however, the lower dose was justified because antiscalant was injected into the RO feed tank, where it would be blended with recycled RO concentrate with concentrated antiscalant, and the antifouling coating on the RO membrane was expected to provide some degree of protection.

3.5 Fouling Tests

Fouling challenges were conducted for 10 days while the system was operating at a target of 80-percent recovery using Orchid Pro (20 mg/L), blue-green algae (20 mg/L and 10 mg/L), Kaolin powder (10 mg/L), and sodium alginate (20 mg/L). The following sections summarize each of these substances and its relevance to the study.

3.5.1 Orchid Pro

Orchid Pro is a natural fertilizer produced by Turf Pro USA. As described by the company (Turf Pro USA, 2014), Orchid Pro is a cold water extract of natural humate that contains trace elements, microorganisms, a full spectrum of humic and fulvic acids, organic carbon, and lignin, with 3% chelated iron. The solution is dark brown. These compounds are derived from plant matter and are classified as allochthonous natural organic matter (NOM). Characterization of NOM through Fluorescence Excitation-Emission Matrix analysis was used by Lozier and collaborators to describe different types of NOM and determine their contribution to low-pressure membrane fouling (Lozier et al., 2008). PVDF UF membrane (also used in this study) was found to be less susceptible to fouling from allochtonous NOM than other membrane formulations that were evaluated (Huang, 2005). The molecular mass range for humic/fulvic/umlic acids from lake sediment is mostly under 10,000 daltons with 20 to 30 percent under 700 daltons (Ishiwatari, 1971; Lozier et al., 2008).

Orchid Pro was injected into the UF feed tank as a 2.5-gram-per liter (g/L) solution at a rate of 170 mL/min to attain an average feed concentration of 20 mg/L as the commercial product. The turbidity increased from an average of 3.3 NTU for the raw well water, to an average of 7.3 NTU the first day, and 8.5 NTU the second day.

3.5.2 Blue-green Algae

Chlorella blue-green algae (broken cell) was purchased from Bulk Supplements in Henderson, Nevada (Bulk Supplements, 2014). The powder was mixed with raw water in a kitchen blender at high speed for 1 minute, then diluted with raw water to a concentration of 2.5 grams per liter, and, finally, injected at 170 mL/min into the UF feed tank for a target concentration of 20 mg/L of the powdered algae. The turbidity of the UF feed with blue-green algae at 20 mg/L averaged around 13.5 NTU. After dosing the first batch of blue-green algae, the concentration was cut in half due to intensive fouling. At 10 mg/L, the average turbidity was 5.6 NTU.

Blended blue-green algae could be classified as autochthonous NOM because it is derived from cell tissues with associated polysaccharides and proteins. This type of NOM was the most problematic foulant of the types evaluated by Lozier and collaborators (Lozier et al., 2008; Amy, 2008).

3.5.3 Kaolin Powder

Food grade kaolin powder, $Al_2Si_2O_5(OH)_4$, was purchased from the Frontier Co-op through Amazon's Web site (Amazon, 2014). It is a fine, whitish-green powder with a density of 2.6 grams per cubic centimeter (Wenk and Bulakh, 2004). Kaolin powder is used to make white ceramic goods; as a coating agent for paint; as a filler for paper; as an ingredient in soap, facial products, and baby powder; as an antacid in Kaopectate; and as a clotting agent in bandages. The mineral absorbs heavy metals, toxins, and oils. It does not dissolve in water but forms a slowly settling suspension. It was chosen for this study as a fine particulate to simulate runoff conditions in surface water treatment.

Kaolin powder was blended with well water in the kitchen blender on high speed for only 20 seconds, which was sufficient to form a suspension. It was dosed to produce a feed solution to the UF system of 10 mg/L of kaolin. Turbidity ranged from 5.2 to 31 NTU, with an average of 8.3 NTU.

3.5.4 Sodium Alginate

Sodium alginate, or alginic acid, was purchased from Modernist Pantry. An extract of brown seaweed, this product is capable of absorbing 200 to 300 times its weight in water, forming a gelatinous liquid. It is used as a food thickener and impression material for life casting. In high concentrations, the gel can be molded and cured by air drying. It was chosen for the fouling study to simulate water quality during natural algal blooms.

The alginate powder was blended in small quantities into well water to avoid solidification and then injected into the UF feed tank to produce a concentration of 20 mg/L of alginate powder. Turbidity during alginate runs ranged from 2 to 23 NTU, with an average of 6.3.

4. Results

Results are presented first for the overall responsiveness to changing conditions and ease of use. Then, more specific results are presented for the RO and UF systems during the fouling challenge, cleaning after the fouling challenge, and, finally, the power consumption.

4.1 Responsiveness to Changing Conditions

Figure 4 shows the variation in feed conductivity and UF feed pump speed over the duration of testing. Operation with different wells is indicated by the arrows and well numbers at the top. The fouling challenge period is indicated by the shaded rectangle. An increase in pump speed is an indication of fouling. The speed increases to maintain constant flow, while overcoming increasing resistance. As presented in table 3, the composition and TDS are significantly different for each of the four wells used in testing. The variability in the band of conductivity measurements over a given cycle is caused by backwashing the UF system with RO concentrate. The band increases in amplitude when the RO system recovery is increased, causing higher concentration of the salts in the UF backwash. Figure 5 is a close-in view showing how the UF filtrate conductivity changes over a backwash cycle. The lower level of conductivity is representative of the incoming well water. The high points are the RO concentrate backwash rinsing through the system. Higher conductivity lasts for approximately 4 to 5 minutes and then tapers off back to the well water conductivity.

The UF process control logic for this system adapts to fouling by increasing the pump speed to maintain constant filtrate flow, which keeps the RO feed tank filled. Filtrate flow stays very close to the target set point between backwash cycles, as can be seen in figure 6. UF filtrate flow rate was decreased the afternoon of June 23 and with subsequent changes in RO recovery rate. RO recovery is increased by recycling some RO concentrate to the RO feed tank; consequently, less UF filtrate is needed to meet the RO feed flow demand. The increase in TMP in the shaded area covers the fouling challenge period, where the UF system had higher resistance from buildup of fouling material added to the UF feed tank. To provide a clearer picture of the variation over the fouling challenge, figures 7-9 show the change in TMP and turbidity for the UF system over the period of challenge testing.

Figure 10 shows the change in pump speed and feed pressure to the spiral separator over a series of backwash cycles with blue-green algae in the influent feed water at a concentration of 20 mg/L. UF filtrate flow and flux (22.8 L/min, 0.23 L/m^2) (6 gal/min, 0.056 gal/ft^2) were constant over this period. Because the UF effluent discharges to atmospheric pressure, increases in TMP are directly related to the pump speed, resistance through the spiral separator, screen, and UF modules. When there is an extreme blockage, the pump will ramp up to its maximum 3,450 revolutions per minute (r/min) in an attempt to maintain flow. At three points in figure 10 (two backwashes before 4 a.m., and one backwash after 8 a.m.), the pump had to ramp up to overcome increased resistance due to blockage of the screen and/or UF membrane with blue-green algae. When the blockage was finally cleared by the self-cleaning mechanism, the flow suddenly increased until speed controls regained the target set point (as happened after 8:30 a.m. in figure 10).

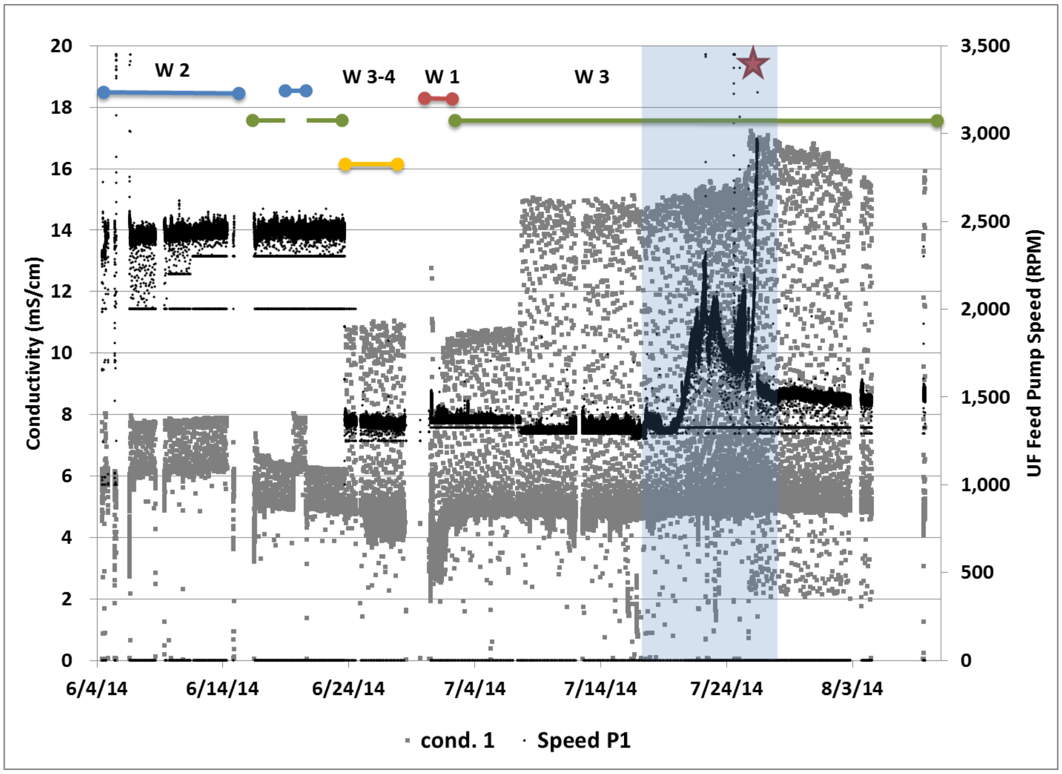

Figure 4. Feed conductivity and UF feed pump speed.

The alternating back-flush cycles may help the system to overcome fouling buildup by changing the direction of backflush flow with every cycle. During this test, the backflush cycle was alternated between cycle 2 and cycle 3, as illustrated in figure 3. After each backflush, there is a forward flush with air scour.

The RO system was operated at constant speed from the high-pressure, positive displacement, RO feed pump (P4 in figure 2). Constant speed allows the pressure to rise with increasing resistance due to fouling or changes in osmotic differential between the bulk feed and permeate. In this mode, the NDP increases with increasing resistance, allowing for a more or less consistent NPF. The system also has the option to allow the pump speed to change to maintain constant pressure or constant permeate flow.

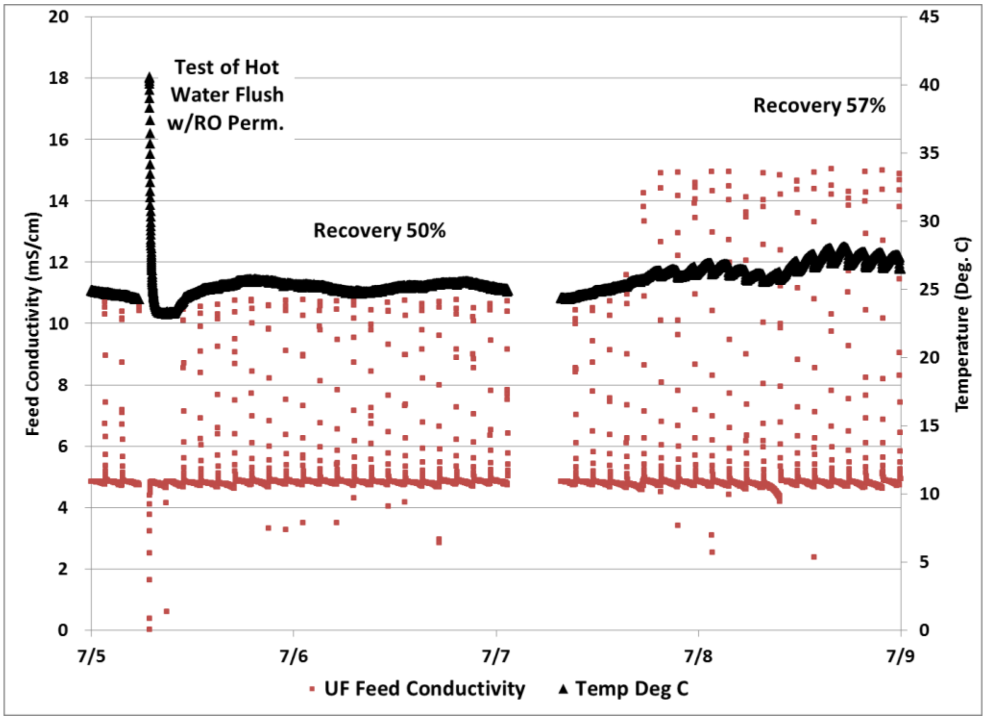

Figure 5. Variation in UF feed conductivity with RO concentrate backwash during the increasing recovery period.

4.2 Ease of Use and Reliability

The system was very easy to use. Once the operating parameters were set, the system could be restarted in two steps from the Human-Machine Interface (HMI). Only one unexplained equipment issue arose when one of the VFDs required rebooting, which shut down the system for 1 hour until a person onsite could intervene. Three other equipment issues were related to the feed source:

(1) The feed water was nearly saturated with calcium sulfate. At three points during the testing, valve 10 and the backwash high tank level sensor (which controls filling of the backwash feed tank) malfunctioned due to calcium sulfate scale buildup. Using concentrate for backwash is a good option to consider when source water is scarce or for seawater applications; however, in practice, it should be evaluated for scale formation potential and nucleation period. Supersaturated backwash is not problematic unless it is in the system past the nucleation period, when

crystals begin to form. After that point, precipitation is catalyzed more readily. Another option would be to use noncontact level sensors and an easily accessible screen to keep crystals out of valves and prevent them from entering the UF system in the backwash process.

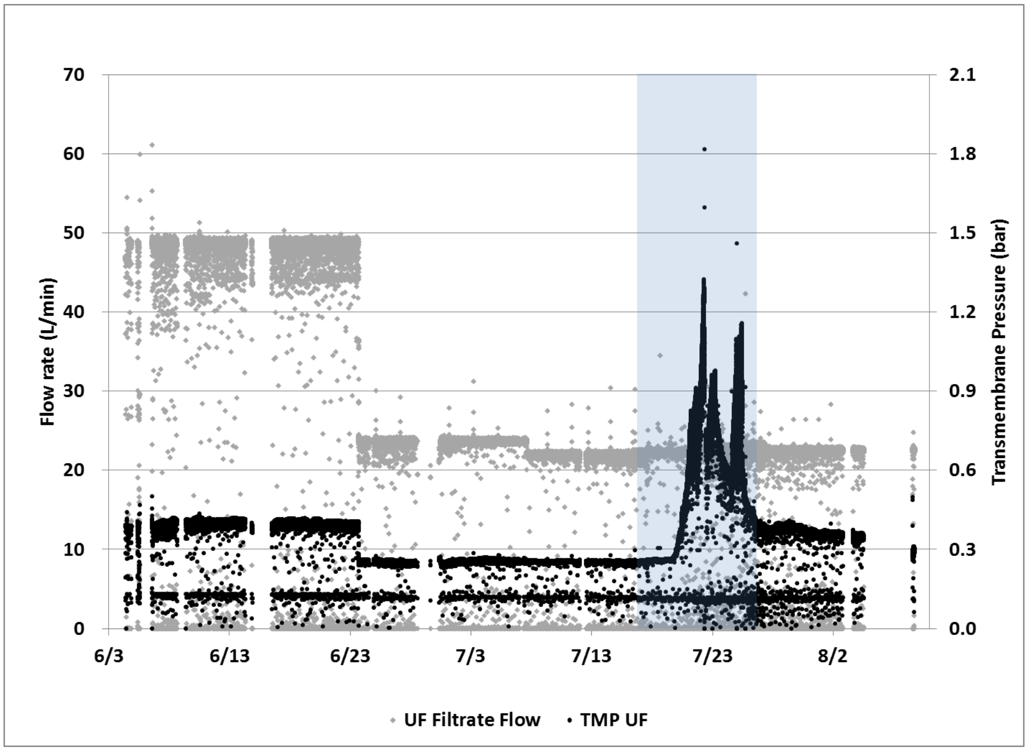

Figure 6. UF system filtrate flow and transmembrane pressure. Shaded column covers the fouling challenge period.

(2) The feed turbidimeter required programming to clean more frequently during the blue-green algae fouling challenge.

(3) The prefiltration screens had to be taken out of service during the blue-green algae fouling challenge due to clogging at the time indicated by a star in figure 4. The screen maintenance alarm was based on the pressure difference across the screens, but the increase in pressure was only for one data point before the cycle completed, and the condition was over. During the worst instance, around 8:30 a.m. (shown in figure 10), the high pressure lasted for only 3 minutes. The alarm must be "latched" so that if the event occurs and resolves, the remote operator will still see it and be able to respond. The issue was noticed by the remote operator

when the pump speed reached its maximum level. New screens were plugged instantly, so the problem was permanently resolved by removing the screens from the vessels and allowing the UF membranes to handle the increased load of algae.

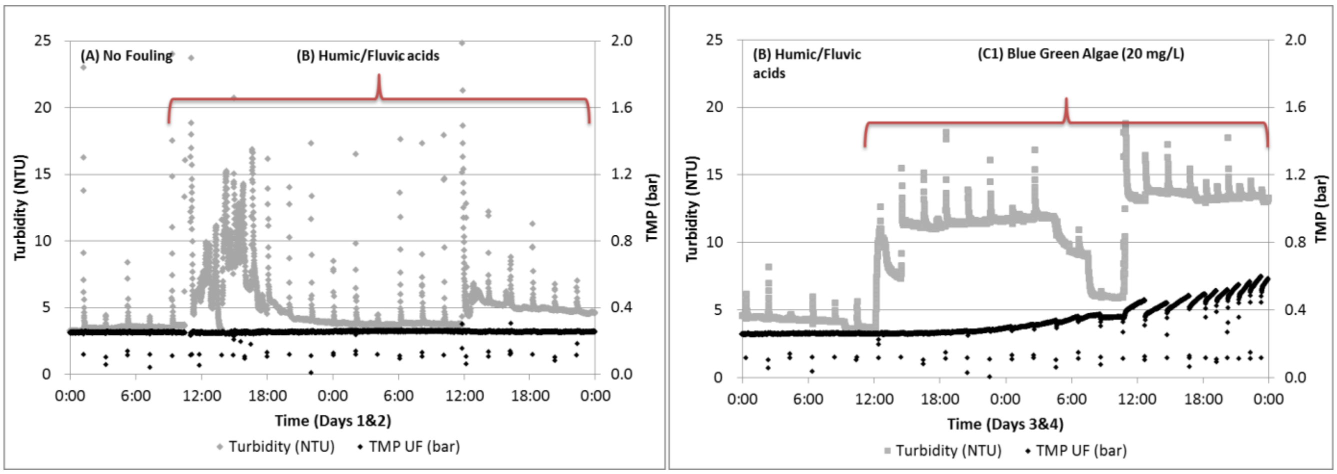

Figure 7. Fouling challenge: days 1-4. Humic/fulvic acid injection caused no change in TMP, but it did increase turbidity that was removed by the UF system. Fouling with blue-green algae began to increase the TMP after 12 hours.

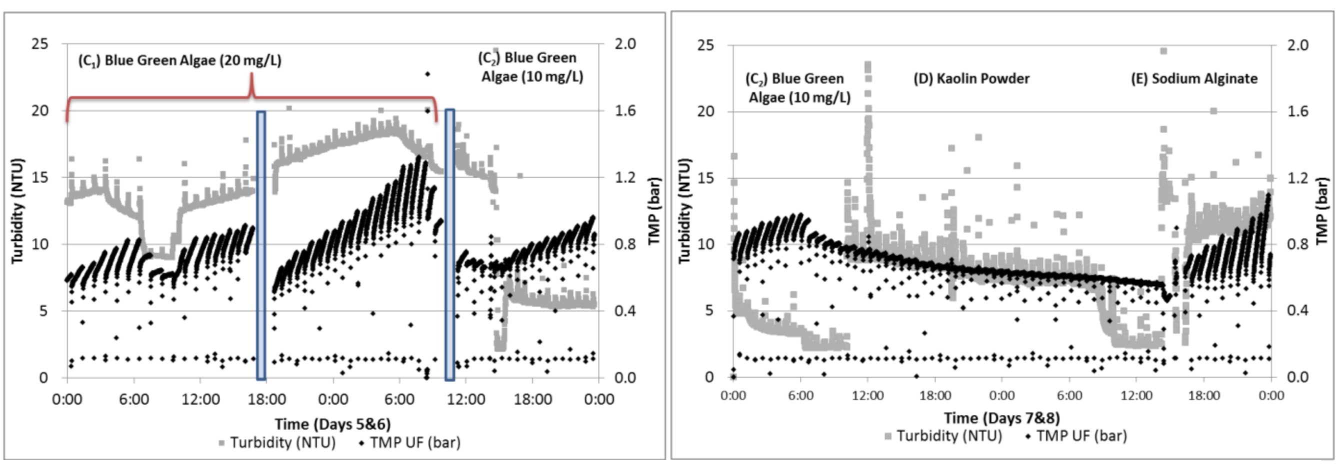

Figure 8. Fouling challenge: days 5-8. Once the buildup of blue-green algae took hold in the UF modules, it significantly increased the TMP over production cycles. Backwash frequency was reduced to 30-minute intervals shortly after noon on day 5. Two hot water cleans were conducted during the 20-mg/L, blue-green algae injection period (blue bars). The loss of fouling material after 6 a.m. on day 5 resulted in a reduction in TMP that was similar to the reduction with the hot water clean . Kaolin powder had a cleansing effect on the system, even though turbidity was higher than for the 10-mg/L, blue-green algae solution. Sodium alginate fouling was similar to the 20-mg/L, blue-green algae.

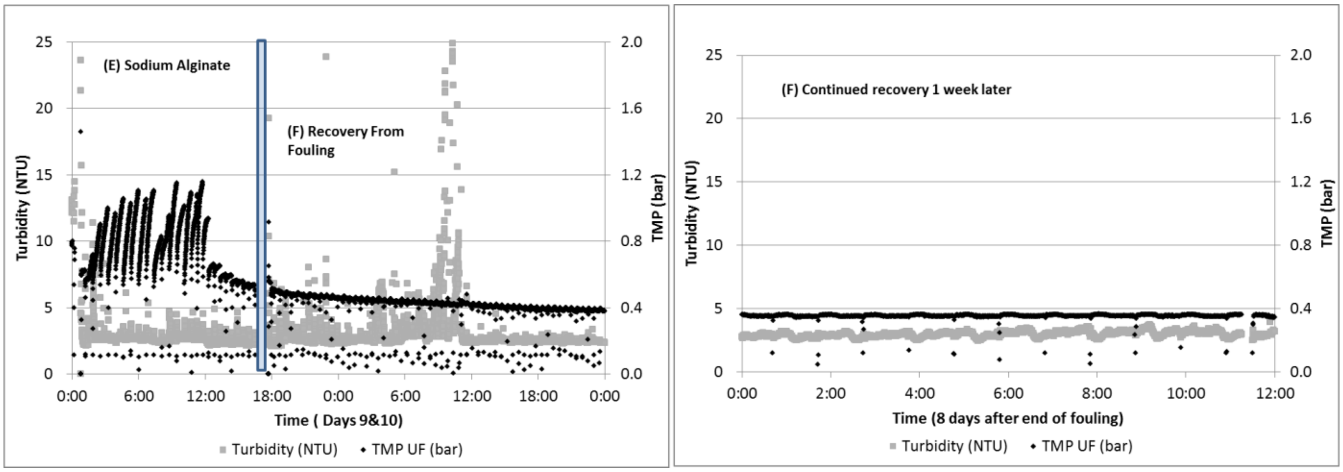

Figure 9. Fouling challenge: days 9-10 and 1 week later. The system began to recover from fouling as soon as the fouling challenge was complete. A hot water clean was performed at the end of the challenge. Residual turbidity was due to accumulation in and on the walls of the UF feed tank, which worked its way out over time. After 1 week, the system was almost back to prefouling condition with hot water as the only cleaning agent.

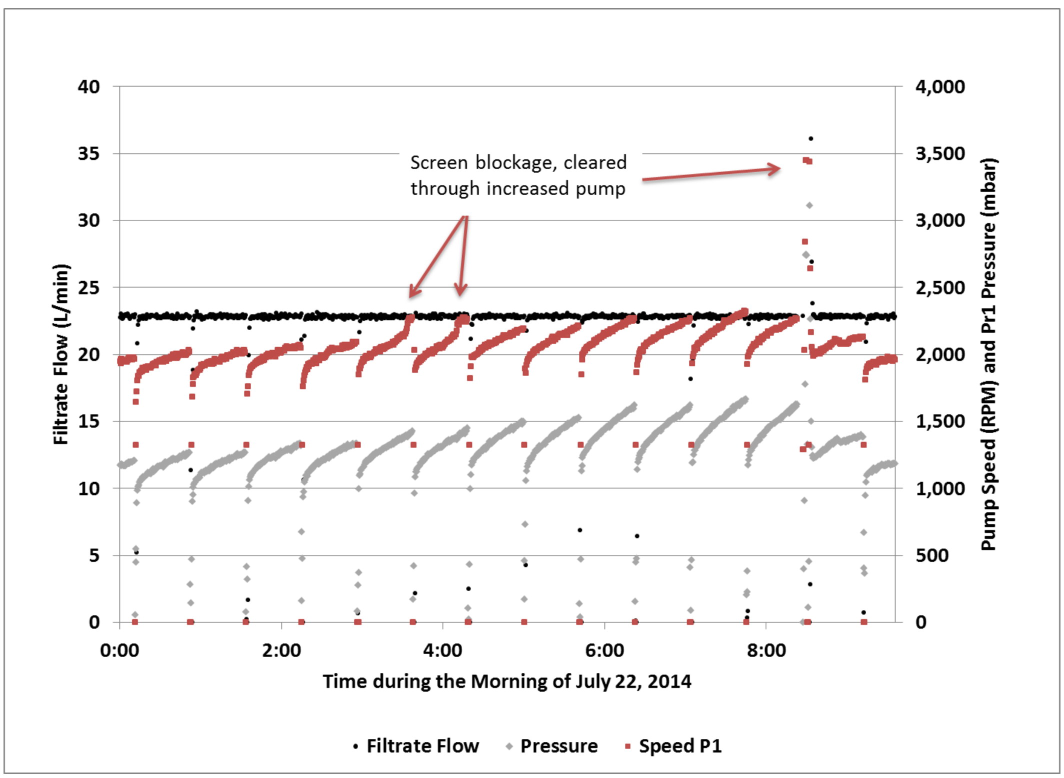

Figure 10. UF system pretreatment separator inlet pressure and pump speed during algae challenge. Two cycles before 4 a.m. show increases in pump speed caused by screen plugging.

4.3 RO System

Figures 11 and 12 show RO system flow and pressure parameters. NPF and NDP are normalized at each level of recovery. RO feed flow was constant because of the mode of operation with constant pump speed. As described above, this resulted in fairly constant NPF. The feed pressure and NDP increased with recovery rate and after the fouling challenge when recovery was over 80 percent. The steady increase in NDP at the end of the challenge, with increasing recovery, indicates that scale was building up in the RO system. The cleaning process at the end of the test brought the NDP back in line with previous levels, though, as discussed below.

Figure 13 shows SP and recovery. The SP started out near 99.7 percent, which is the level claimed on the manufacturer’s specification sheet for stabilized salt rejection (Dow, 2014). SP increased by a few points with the highest recovery, which could be due to high ionic strength that overwhelmed the charge repulsion characteristics. Added concentration to the feed water from UF backwashing with RO concentrate added approximately 3 milliSiemens per centimeter of conductivity to the RO feed tank, which showed up in the feed conductivity for up to 10 minutes after each backwash. The added salt loading resulted in an increase in permeate conductivity of approximately 40 μS/cm, which tapered off over 20 minutes.

Figure 14 shows greater detail about the response of SP and NPF to the fouling challenge and subsequent passive cleaning. Letters in figure 14 correspond to fouling events described in table 6. Red arrows indicate hot water cleaning of the UF system, which requires shutting down the RO. The green arrow indicates a shutdown to remove screen filters. NPF fluctuates with diurnal temperature changes and with the change in NDP caused by the fluctuation in concentration with backwash cycles.

SP decreased during the fouling challenge, most likely due to adsorption of organic matter from the humic and fulvic acids, which are too small to be removed by UF membrane. On the other hand, the foulant material may have reacted with calcium, or other components of the well water, while in the RO feed tank and then formed a coating on the membrane surface, which hindered salt transport. Detailed analysis was not performed on the RO permeate to determine if the reduction in SP was specific to any particular ion. SP returned to prefouling levels by the end of the fouling challenge; however, it then increased by one-third after the chemical cleaning, which corresponded to a decline in rejection rate from 99.6 percent to 99.1 percent. Other spikes in salt passage were due to system shutdowns due to loss of feedwater (7/16, 7/26), programming change (7/17), and scale buildup in the backwash tank (7/23, 7/25).

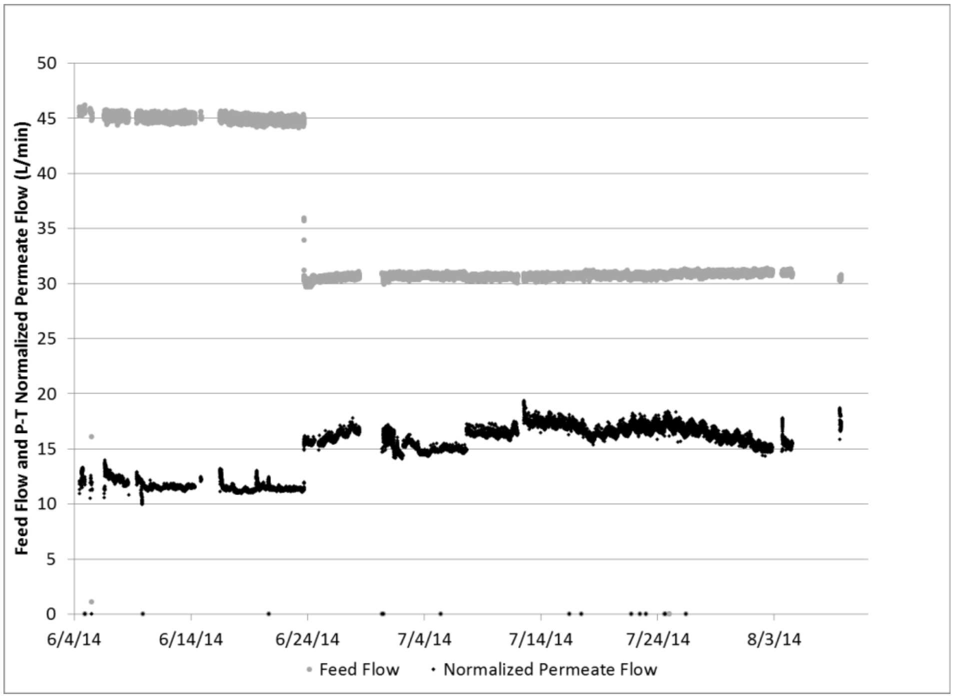

Figure 11. RO system productivity performance parameters – feed flow and pressure-temperature normalized permeate flow.

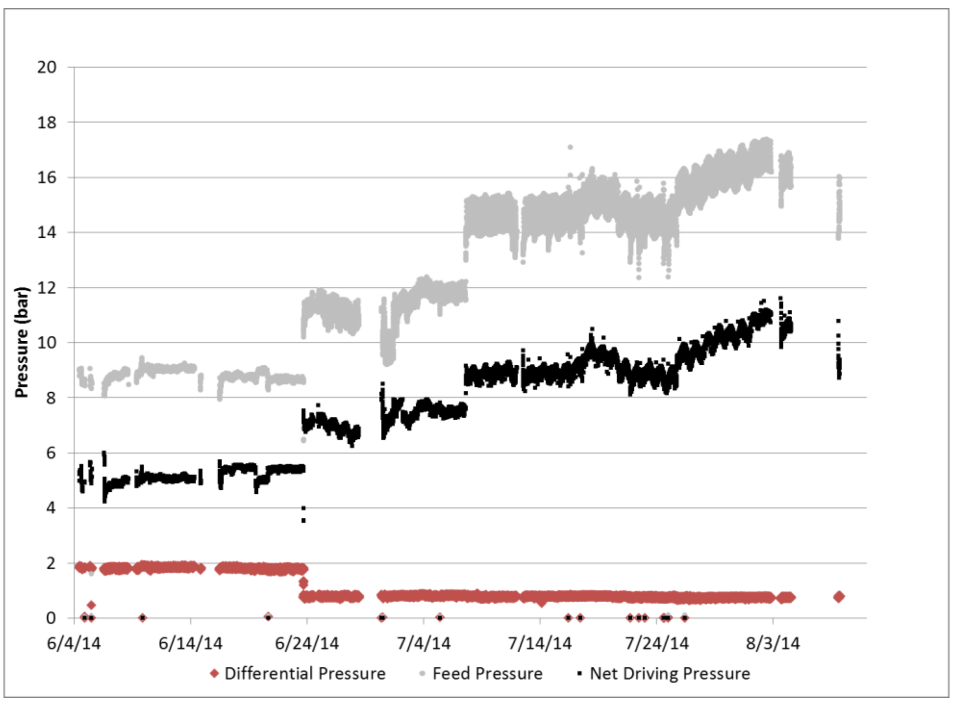

Figure 12. RO system performance parameters - pressure.

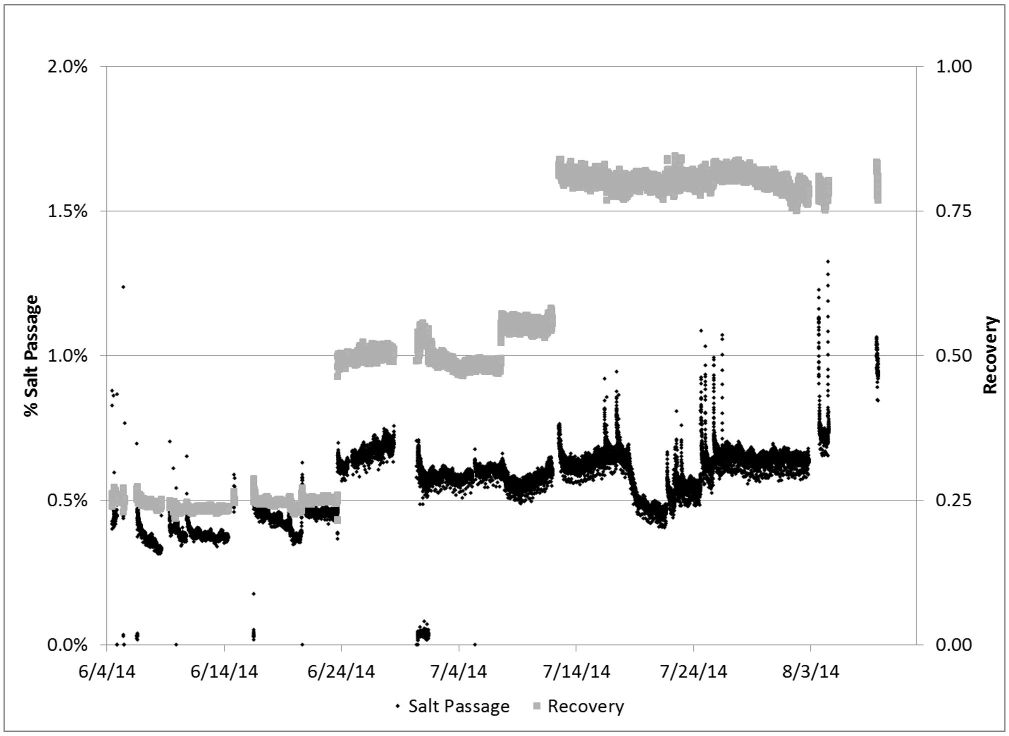

Figure 13. Normalized salt passage and recovery.

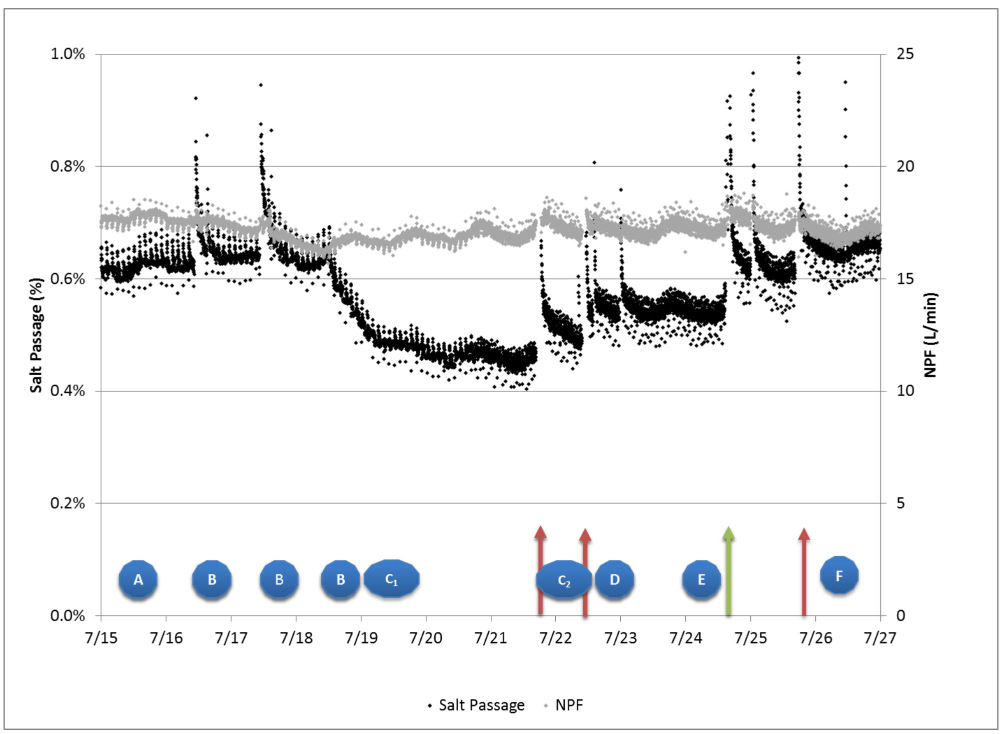

Figure 14. Percent salt passage and NPF during fouling challenge.

Table 6. Fouling Events and Their Effect on UF System Performance

Foulant Additive	Dose (mg/L)	Rate of Change in TMP (mbar/min)		UMFI (m^{-3})		Maximum TMP (bar)		Rate of Change in r/min (r/min/m^3)	
		Ave.	St. Dev.	Ave.	St. Dev.	Ave.	St. Dev.	Ave.	St. Dev.
A – none	0	-0.005	0.07	-0.004	0.007	0.32	0.07	0.35	10.79
B – humic/ fulvic acids	20	-0.001	0.03	-0.002	0.003	0.26	0.01	2.93	6.95
C1 – blue-green algae	20	2.99	2.41	0.493	0.400	0.74	0.31	124	99.6
C2 – blue-green algae	10	3.12	1.42	0.392	0.188	0.85	0.09	121	53.8
D – kaolin powder	10	1.04	0.53	0.033	0.040	0.66	0.06	41.5	11.9
E – sodium alginate	20	8.32	3.79	1.32	0.59	0.93	0.16	293	121
F – none	0	-0.15	0.19	-0.051	0.065	0.38	0.01	15.4	24.1
G – after cleaning	0	0.43	0.20	0.083	0.026	0.31	0.01	-14.2	8.0

Note: mbar/min = millibars per minute, m^{-3} = per cubic meter, r/min/m^3 = revolutions per minute per cubic meter, Ave. = average, St. Dev. = standard deviation.

Whenever an RO system is stopped for any length of time without flushing the feed channel, direct osmosis begins. In this case, direct osmosis caused periodic spikes in permeate conductivity and apparent SP. Actually, the increase is due to pure water permeating back into the feed stream, rather than an increase in the rate of salt permeating to the product side of the membrane. Even with the SP near 1 percent after cleaning, the RO permeate remained acceptable for drinking water purposes (near 100 µS/cm conductivity), which corresponds to approximately 90 mg/L of TDS.

4.4 UF System

Table 6 lists the fouling events with average values and standard deviation of the UF system evaluation metrics. Figure 15 shows the range and variation of these metrics over the duration of the blue-green algae fouling challenge, and figure 16 shows the range and variation for the kaolin powder challenge. The chart for sodium alginate would be similar to the blue-green algae response, while the response to the humic/fulvic acid challenge would be flat lines at the values listed in table 6.

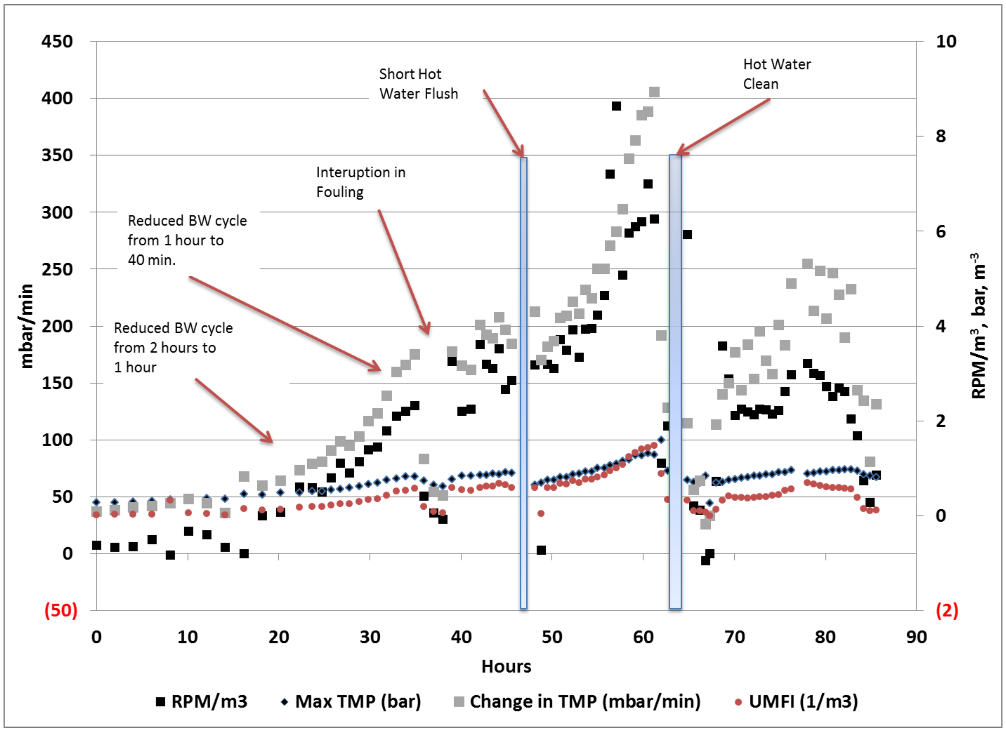

Figure 15. Evaluation metrics during blue-green algae fouling (C1 and C2).

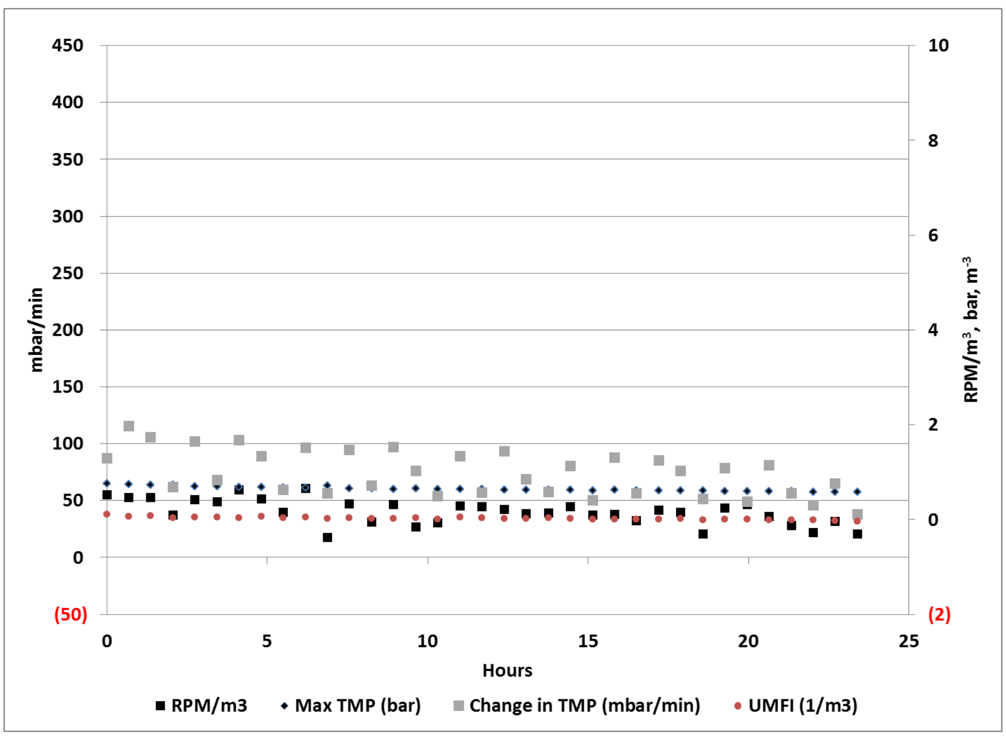

Figure 16. Evaluation metrics during kaolin powder fouling.

The UMFI is calculated from the slope of the curves in figure 17 for an equivalent number of backwash cycles during each of the fouling challenge stages. The background data is portrayed with the calculated UMFI to illustrate the significance of the UMFI value. The UMFI before and after the fouling challenge, during fouling with humic/fulvic acids and kaolin powder, and after cleaning is close to zero. However, potentially reversible fouling is apparent from the deviation from unity at the start of each backwash cycle. The percentage of fouling that is irreversible after final cleaning is approximately 12 to 15 percent.

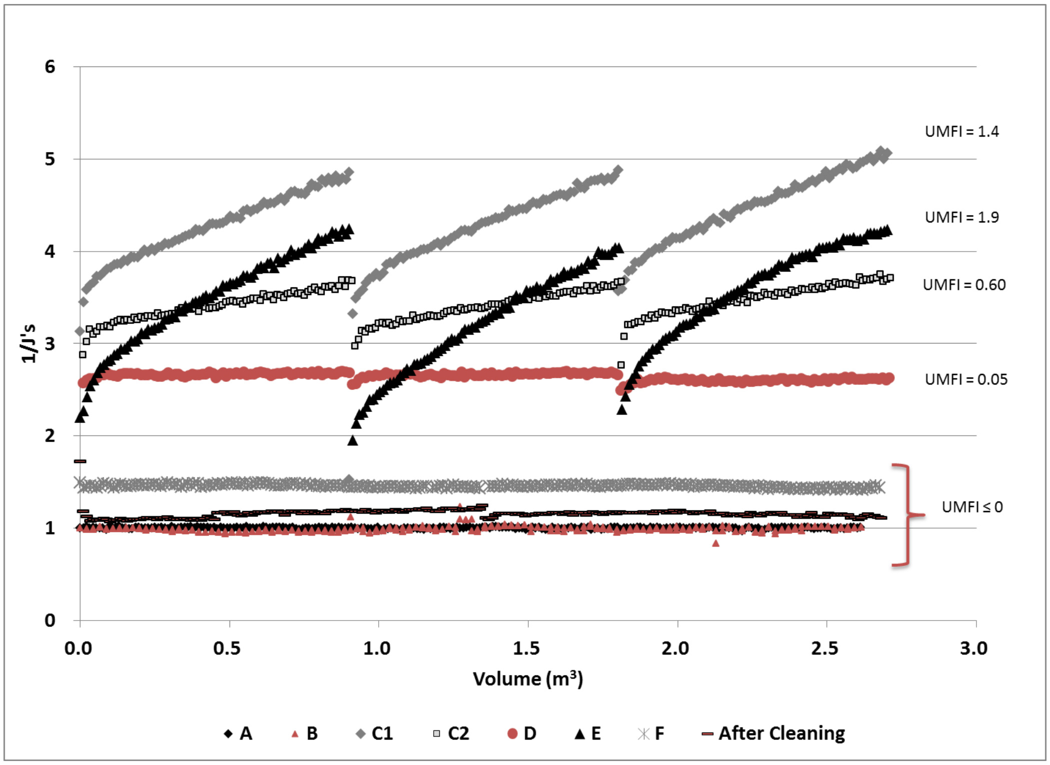

Figure 17. Change in the inverse of specific flux with production.

The backwash cycle was modified seven times during the test to address changes in water quality. Table 7 lists each change and the value of the different performance metrics just before each change. On June 24, 2014, the change was made to accommodate lower feed flows and higher RO system recovery with low fouling groundwater. The last change was made to prepare for long-term storage. The decision to change the backwash cycle was made through human logic based on a combination of the rate of change in TMP and the maximum TMP.

Table 2. Modifications to the Backwash Cycle with Performance Parameter Values

Change No.	Date and Time	Backwash Modification	Maximum TMP (mbar)	ΔTMP (mbar/ min)	UMFI (m^{-3})	Δ Pump Speed ($r/min/m^3$)
1	6/24 23:00	Baseline 2-hour interval; reverse flush at 3,199 r/min; and forward flush at 1,324 r/min	262	(0.02)	(0.01)	1.10
2	7/20 19:17	1-hour interval	360	0.06	0.01	5.68
3	7/21 13:21	40 minutes	857	4.03	0.59	184
4	7/21 17:00	Hot water clean	900	3.62	0.59	153
5	7/22 8:30	Short hot water clean	1290	8.94	1.48	294
6	7/25 11:18	30 minutes	1,158	15.6	2.52	526
7	7/25 18:42	Reverse flush at 1,199 r/min	507	1.29	0.00	63
8	7/27 8:56	1 hour	389	(0.10)	(0.25)	8.6
9	8/8 15:56	Reverse flush at 2,799 r/min	310	(0.17)	(0.03)	17

4.5 Cleaning

During the fouling challenge, the system was cleaned with a 1-hour hot (40 °C) RO permeate flush once during the blue-green algae fouling challenge and again at the end of the fouling injection period. At the end of high recovery RO testing, the whole system was cleaned with citric acid (2 hours, pH 3.5, 35 °C), then the UF system was also cleaned with caustic (NaOH, pH 12, 2 hours, 35 °C). Table 8 lists before and after cleaning metrics.

Table 8. Power Consumption

Condition	UF System kWh/m^3 (kWh/kgal) UF Filtrate	RO System kWh/m^3 (kWh/kgal) RO Permeate
25% RO recovery/no recycle	0.22 (0.84)	3.87 (14.60)
50% recovery	0.08 (0.31)	3.20 (12.12)
75-83% recovery with fouling	0.23 (0.87)	3.42 (12.95)
75-83% recovery without fouling	0.11 (0.42)	3.40 (12.87)
Average for total RO permeate	3.73 (14.13)	

Note: kWh/m^3 = kilowatthours per cubic meter, kWh/kgal = kilowatthours per thousand gallons

4.6 Power Consumption

Table 8 lists average power requirements for each system during each phase of testing and for the whole system as an average over the testing period. The RO power use was constant at each recovery rate interval. UF power consumption was affected by changes in flow rate and fouling load.

5 Discussion

5.1 Robustness

The Sea.PURe™ system demonstrated a high level of robustness during the test period, despite changes in feed water composition and fouling challenge. While the UF system exhibited fouling with blue-green algae and sodium alginate, it recovered sufficiently within the range of allowable backwash frequency settings.

A comparison of the system with the criteria suggested above appears below:

- **Materials of construction:** The float switch that fills the UF backwash tank became encrusted with scale twice toward the end of the test period. Noncontact level sensors would help with determining the level, but it would still be necessary to add a screen or clog/crust proof valve to prevent solids from entering the UF system during backflushing. Other materials held up well to the brackish water environment.

- **Conservative process design:** The UF system is capable of delivering three times the filtrate needed for this test with high recovery RO. Seawater recoveries between 35 and 45 percent would not require recirculating concentrate to the RO feed; thus using the full production level of the UF system. Backwashing the UF with RO concentrate is not a conservative feature for highly saturated brackish water, but it would be beneficial in a seawater application. The RO system did not have a single issue during the test period. The turbidity to the RO was always well under 0.1 NTU, even during the most difficult fouling solutions.

- **Redundancy in instrumentation and control features:** The system does not have redundant sensors. Loss of any of the flow or pressure sensors would shut down the system, although it could be operated in manual mode. The RO feed turbidimeter was not sensitive enough to register the UF filtrate turbidity. The applicable turbidity range should cover at least the double digit milliNTU level.

- **Adaptable controls:** The UF process control is flexible in that backwashes can be conducted in a variety of modes, with or without air scour, at a user modifiable interval and duration. Pump speed can be maintained at a fixed rate, or it can be set to maintain a given filtrate flow. The RO system can also run at a fixed pump speed or to target a desired permeate flow and recovery rate.

- **Algorithm for determining changes in feed conditions:** Other than tracking filtrate and RO permeate flow, the system does not adjust to feed water conditions. The remote operator monitoring system performance accomplishes this; however, with additional testing, the next generation of control programming could easily incorporate backwash cycle control with existing inputs and outputs.

5.2 Automated Monitoring to Evaluate Fouling

UF process monitoring and control programs need to query a series of yes/no questions to determine if UF filtrate is performing well and then take appropriate actions. Figure 18 describes a series of simplified inquiries that is repeated continuously, usually with timers to wait long enough for the process to stabilize after any adjustments. Two remaining issues/questions are: (1) what data should be used to determine if the system is performing well or struggling; and (2) if the system is struggling, what action should be taken?

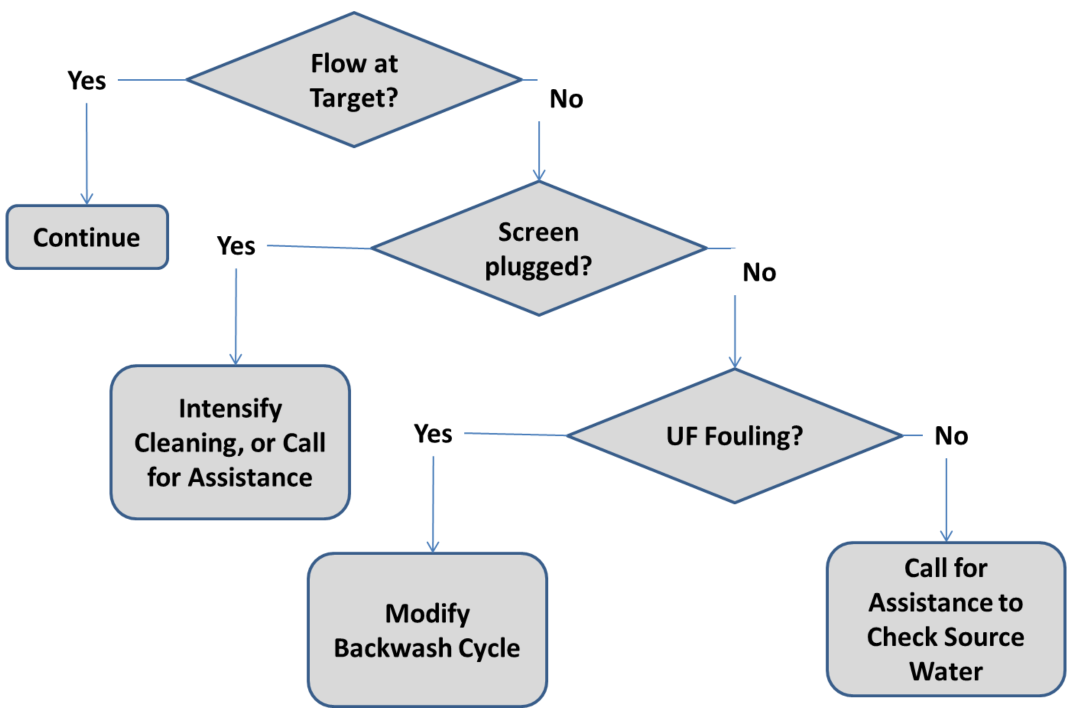

Figure 18. Simplified decision tree for UF control.

A computer algorithm to determine whether the membrane is fouling can use any of the inputs to the process discussed above: change in TMP, pump speed, maximum TMP, or calculated UMFI. Change in TMP or pump speed can be determined by recording the first reading when the target flow is reached, and recording the last reading at the end of the production cycles, and then determine the rate of change over time or with flow. The UMFI requires a further calculation to divide the filtrate flow by the instantaneous TMP at the same two points. Maximum TMP is also easy to capture with simple logic. It is important to catch these data points when the flow is at the target level; otherwise, there may be division by zero errors or very large value results.

As can be seen in figures 15 and 16, each of the evaluation factors respond in the same manner to changes in filterability; however, the magnitude of the change is different. The change in pump speed and TMP (in mbar/min) has the greatest range of response over the change in conditions depicted. Pump speed is responding to increased resistance in the system. Change in TMP is incorporated into the UMFI through the normalized specific flux, so it is not surprising that they are strongly correlated to each other. Figure 19 plots each of these parameters against change in pump speed per unit volume during the fouling challenge. UMFI and change in TMP have the strongest correlation to the change in pump speed and track each other very closely during the clean and fouling periods. Maximum TMP increases with the other parameters, but it is not correlated to them in a linear manner; rather, it levels off as it reaches one bar.

The open symbols in figure 19 are the UMFI versus pump speed change after the fouling period, when the spiral separator was clogged with remaining fouling material. The UF membranes appeared to be recovering during this period, based on all other parameters, but the pump was still ramping up to get feed flow through the pretreatment equipment. Figure 9 shows spikes in turbidity after the fouling period, with continued improvement in the TMP. These spikes were caused by the effort of the pump cleaning out the tanks, pipes, and pretreatment system.

Figure 20 shows the comparative magnitude of change in these parameters before each process adjustment was made to manage the fouling situation. The parameters are plotted as a fraction of their highest value over the test period. The first point is the baseline value in a clean state. The first change from 2-hour production cycle to 1-hour production cycle was based on a relatively small change in maximum TMP, while the other evaluation parameters were still very low. The next three changes were preceded by equivalent changes in all metrics. The fourth change was a short, hot water flush that did not reverse fouling but slowed it down for another 10 hours (see figure 15). By the sixth change, reducing the production cycle to 30 minutes, the maximum TMP had plateaued, while the other three metrics continued to increase.

The reduction in all metrics after change six occurs with the end of the fouling period. The last three points represent continued improvement in performance, followed by reductions in backwash cycle intensity. In the improvement stage, maximum TMP is a more visible indicator while in its mid-range. Change in pump speed with volume and change in TMP are very low within their ranges, while the UMFI plateaus at subzero levels.

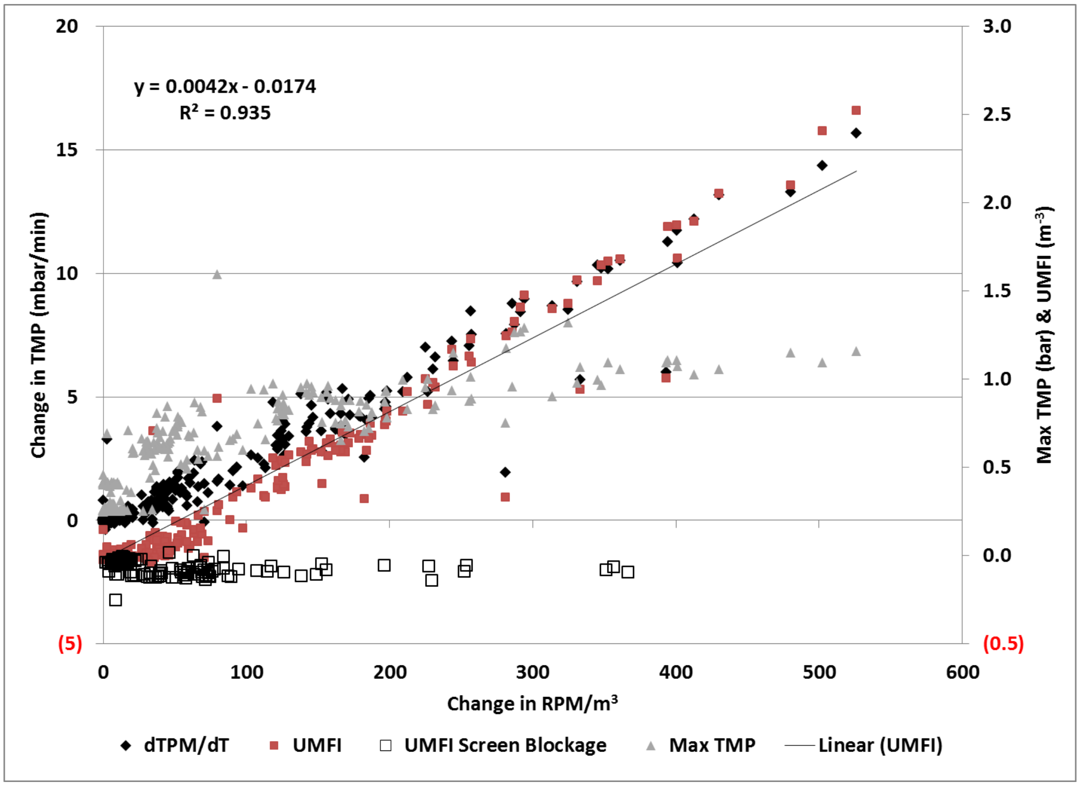

Figure 19. Proportionality between UMFI, change in TMP, maximum TMP, and pump speed.

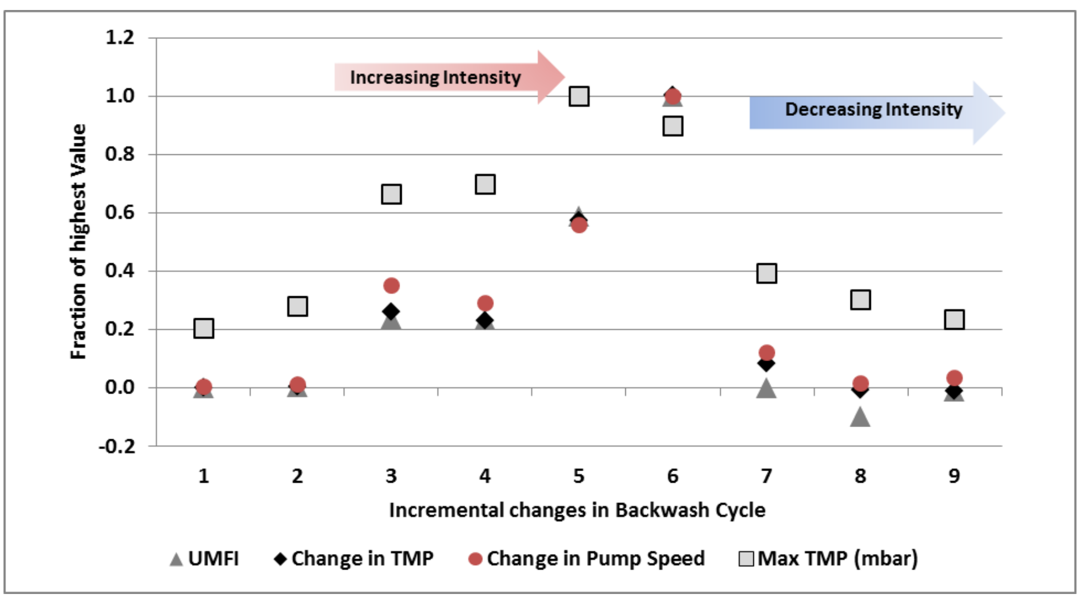

Figure 20. Percent change in evaluation parameters at each change in the backwash cycle.

Perhaps the best control plan would be to use a combination of indicators at different levels of fouling. The maximum TMP requires no calculation; it only requires a maximum function to monitor TMP over the production cycle. However, it apparently reaches its maximum value while the system is still responding to additional fouling through compaction. When the maximum TMP reaches its mid-range, the program should begin to monitor the change in TMP over the production cycle. Monitoring the change in pump speed with volume would also alert the operator (or control function) to increase maintenance for the prescreening equipment if it is not keeping pace with the change in TMP.

5.3 Automated Response to Fouling Indicators

After considering the information presented above, at this point, the question arises: What can be changed in the process to prolong performance through challenging periods? The changes made in this project were related to flow direction, backwash frequency, flushing rate, and initiating hot water flushes or hour-long cleaning cycles. Greater change in fouling indicators drove an increase in backwash frequency, which is also a decrease in fouling accumulation time. Backflush cross flow velocity was decreased to keep the pressures down during the backflush and to transfer part of the cleaning load to the forward flush. Air scour was used during every forward flush during this test. For less fouling conditions, the air scour could be reserved for a first-level intensification of backwash protocol.

Intuitively, it would seem that, for a change to be considered beneficial, the subsequent production cycle should complete at the target flow rate with a lower maximum TMP, and a lower rate of increase in pump speed and TMP; however, as can be seen in figures 15 and 20, none of the changes in backwash cycle during the fouling challenge had that result until the fouling agent was removed, or when it was changed to kaolin powder. Then, every subsequent backwash resulted in a lower value in all indicators. The production cycle is completely governed by the solids loading of the source water. The backwash cycle can only push out the accumulation. The metric for determining the success of the backwash is the condition at the moment the production cycle begins again, the immediate TMP and pump speed when target flow is reached, and initial change in TMP during the first few seconds after target flow has been reached. That data can be captured in the programmable logic controller programming, which cycles much more frequently than the data was recorded during this test (30-second intervals).

Figure 21 compares initial TMP data from the random production cycles throughout the fouling period. The initial TMP was chosen at the point when the target flow reached the average value for the cycle. Cycle 3 backflushes resulted in overall lower initial TMPs than cycle 2. Comparative testing without alternating backflush cycles would be necessary to determine if cycle 3 is always a more effective method, or if alternating directions has other benefits for more completely reaching all areas of the module.

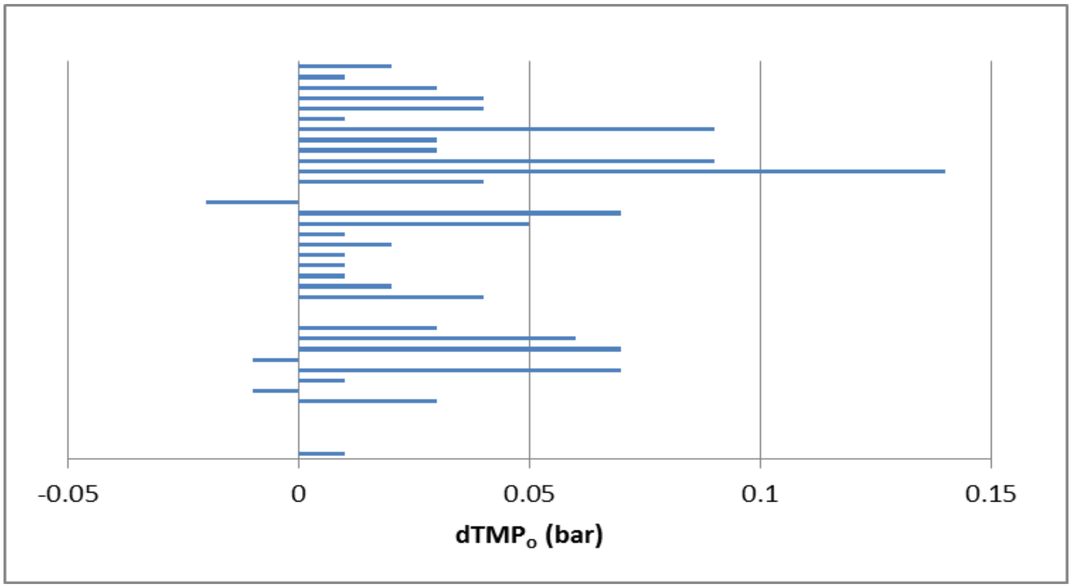

Figure 21. Difference between initial TMP following cycle 2 backflush and subsequent cycle 3 backflush.

To avoid losing the benefit of any one aspect of the backwash cycle, it would be better to alternate modifications. The choices are:

- Flow direction
- Flow velocity
- Duration
- Pulsation
- Air scour

If some feed water quality conditions are getting worse, then the system's response can be considered acceptable if it is holding steady in the performance evaluation metrics, or if the metrics are increased by a small percentage. The next backwash can be the same in the alternate flow path. If performance metrics are greatly increased, then a further modification can be initiated for the next backwash cycle. Specific decision points must be assessed for the system. Maximum values revealed in figure 19 were used in figure 20. They are specific for this system. A control program needs set point values based on the system design and expected conditions. It may be necessary to challenge the system, as in this study, to find the maximum values that can be expected. More testing is needed to evaluate the increased longevity of performance using a variety of performance metrics with different decision point levels to determine the degree of urgency associated with any particular value, as well as to match the degree of intensity of a change in operation to the level of change in performance metric.

6 Conclusions

The AHI Sea.PURe™ system appears to be a robust system in that it did not have any failures that could not be resolved with minor human intervention. The most severe failure was due to scale formation on the backwash tank level control switch, which required about 30 minutes of level sensor and tank cleaning.

The fouling challenges were handled well enough to keep the RO system in operation throughout the test period. There were no problems with the RO system. It kept producing high quality, low TDS permeate throughout the fouling challenge.

Programming for automated UF systems with constant filtrate flow control can effectively use the change in pump speed with cumulative production volume as a test parameter for modifying the backwash cycle. During this test, change in pump speed with volume produced was strongly correlated with change in TMP and UMFI, which were equivalently correlated to each other. Maximum TMP was not correlated with the other metrics, but it leveled out with higher values of the other metrics. Efficacy of backwash cycles can be determined by comparing instantaneous TMP or pump speed at the point when the target flow has been reached. Increments of the expected maximum value can be used as triggers for further modification. Further testing of the automation of backwash cycle modification is necessary to confirm appropriate decision points and dead-band allowances to prevent overmodification.

The concept of remote control for rural water systems worked well in this case. With the addition of automated backwash cycle modification and auto dialing alarms, it should be sufficient for the remote operator to check on the system once or twice a day in most situations. This method can be adapted to any treatment process, not just membrane filtration.

6.1 Further Investigation Needed

Maximum TMP was used as the decision indicator for backwash cycle control in this test with changes made at approximately each factor of the initial nonfouled maximum TMP. Repeating the test using change in pump speed/volume would clarify whether this metric results in stable performance. This would require programming modifications to calculate the metric, as well as some experimentation to determine how to set limits and dead-band levels. The universe of backwash conditions needs to be explored. A table of increasing levels of intensity in the backwash cycle can be developed. An experimental design matrix of conditions can be tested, using the performance metrics that were evaluated in this study, to determine an optimum control plan.

For this test, only feed water turbidity was used as in indicator of water quality. In some situations, turbidity may not change significantly with the fouling capacity of the feed water. In this test, the kaolin powder added turbidity, but it had a beneficial effect on system performance. The sodium alginate was clear and, thus, did not significantly increase turbidity; however, it was a severe foulant. We need to investigate on-line sensors to detect algae bloom situations as they are developing so that preemptive measures can be taken, rather than simply reactive measures.

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