Optimizing a Community's Fresh and Brackish Water Supplies With an Aeration, Ion-Exchange, and Reverse Osmosis Treatment Portfolio

Steven J. Duranceau and Jayapregasham Tharamapalan

Steven J. Duranceau, Ph.D., P.E., is associate professor of environmental engineering in the civil, environmental, and construction engineering department at the University of Central Florida in Orlando. Jayapregasham Tharamapalan, Ph.D., is director with JTSR Solutions LLC in Oviedo.

The City of Sarasota (City) owns and operates its drinking water utilities and provides service to consumers within the City's service area. The City's water supply originates from two sources: the Verna Floridian wellfield, located 22 mi east of the City, and the downtown brackish wellfield in the City's northwest area. The City's water treatment facility (WTF) is comprised of two primary water treatment processes: a spiral-wound reverse osmosis (RO) process, and an ion exchange (IX) process, which is regenerated using chlorinated seawater from the Sarasota Bay that is delivered to the WTF by a separate intake system. The capacity of the WTF is 12 mil gal per day (mgd) from a combination of 4.5 mgd from the RO component of the water treatment facility, 5.2 mgd from the IX component of the water treatment facility, and 2.3 mgd of blended bypass water from the Verna wellfield [1]. A schematic of the WTF is as shown in Figure 1.

Approximately 7.9 mgd of water can be withdrawn from the Verna wellfield based on existing permits from the City. The groundwater is treated using tray aerators atop a structure located at the Verna wellfield. Chlorine is added to the aerated groundwater and the water is then stored in a 1-mil-gal (MG) ground storage reservoir prior to gravity flow over 22 mi to the 10th Street Service Reservoir. From this reservoir, about 5.6 mgd is withdrawn for treatment at the City's IX process located at the 12th Street WTF, while another 2.3 mgd bypasses the IX process for final blending. The RO process at the WTF treats 6 mgd of brackish groundwater that is withdrawn from a network of eight wells at the downtown wellfield (Lower Hawthorn Aquifer) in the northwest area of the City. This groundwater is pretreated with sulfuric acid, scale inhibitor, and cartridge filtration. Despite the fact that the WTF has a capacity of 12 mgd, the overall production at the facility is currently limited to 10.5 mgd in order to be able to comply with the sulfate secondary drinking water standard. At production levels higher than 10.5 mgd, the WTF's product water to its customers will exceed the secondary maximum contaminant level (MCL) limit of 250 mg/L for sulfate because the RO permeate production levels are not enough to dilute the treated Verna supply. The primary source of sulfate in the City's water supply comes from the Verna wellfield water that is aerated and segregated for final blending with the RO and IX permeate.

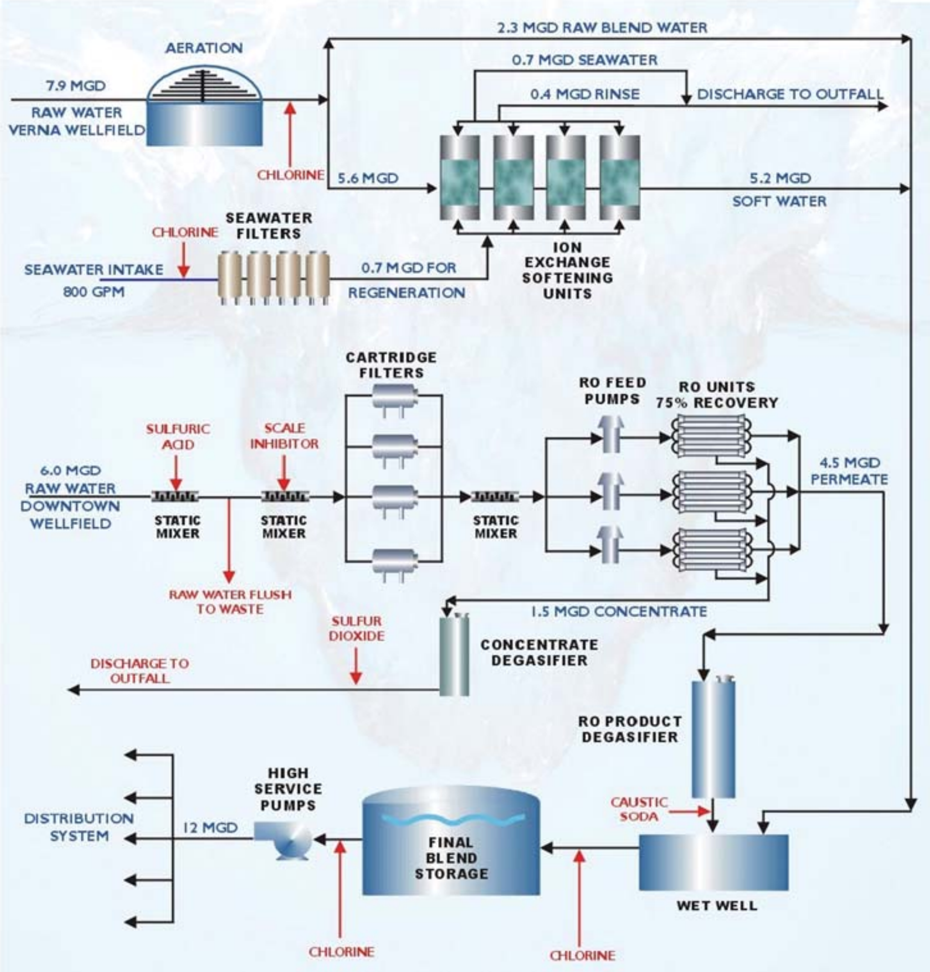

Figure 1. Schematic of the City of Sarasota Water Treatment Facilities

(Courtesy of the City of Sarasota Public Works and Utilities)

Purpose and Motivation

The purpose of this research was to conduct an evaluation to assess the water supply and treatment system for the City in order to develop long-range water quality goals and forecast system alternatives to meet the future needs of the City's drinking water community. The evaluation was implemented in two phases: *Phase 1* focused on the City's brackish water RO process with emphasis on the elimination of sulfuric acid as a pretreatment chemical and subsequent assessment of secondary water quality impacts; *Phase 2* focused on investigating methods to enhance treatment of water supplied by the City's Verna fresh groundwater supply, with emphasis on aeration, nanofiltration (NF), and ion-exchange integrated process evaluations.

Specific objectives for Phase 1 included:

1. Develop a protocol for the elimination of sulfuric acid pretreatment without compromising the RO membranes. The protocol encompassed: (a) a pilot testing plan to reduce the dependence on acid; (b) the implementation of an acid elimination plan for the full-scale RO plant in conservative pH increments; and (c) the installation of a "canary" scaling monitoring device to continuously screen for scale formation during the staged acid elimination plan.
2. Evaluate the secondary impacts of sulfuric acid pretreatment elimination on RO membrane permeate post-treatment processes, including turbidity formation assessments.
3. Develop empirical models for the RO process that uses polyamide membranes to predict the mass transfer of solutes in terms of total dissolved solids and sodium.
4. Develop a tool to allow effective trending and monitoring of performance of RO membrane processes using the Homogeneous Solution Diffusion (HSD) Model.

Specific objectives for Phase 2 included:

1. Evaluation of sulfide efficiency improvements for a City-initiated retrofit improvement of the Verna wellfield tray aeration process.
2. Pilot testing to evaluate pretreatment options for NF process to treat a highly fouling groundwater that is aerated for sulfide control. Pretreatment options prior to the NF process included: (a) bag filters and cartridge filters as minimum on the NF pilot; (b) sand filtration; (c) sand filtration followed by an ultrafiltration (UF) membrane process; (d) UF membrane process without any additional prescreening; and (e) predisinfection to control biofouling followed by dechlorination.
3. Develop a tool to allow effective trending

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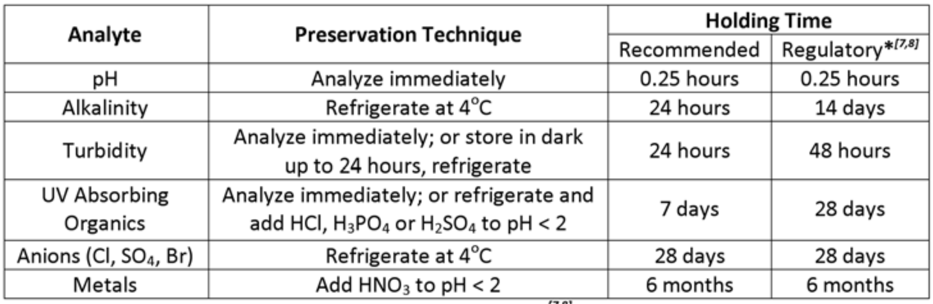
Table 1. Water Quality Sampling and Handling Requirements



Analyte	Preservation Technique	Holding Time	
		Recommended	Regulatory*[7,8]
pH	Analyze immediately	0.25 hours	0.25 hours
Alkalinity	Refrigerate at 4°C	24 hours	14 days
Turbidity	Analyze immediately; or store in dark up to 24 hours, refrigerate	24 hours	48 hours
UV Absorbing Organics	Analyze immediately; or refrigerate and add HCl, H_3PO_4 or H_2SO_4 to pH < 2	7 days	28 days
Anions (Cl, SO_4, Br)	Refrigerate at 4°C	28 days	28 days
Metals	Add HNO_3 to pH < 2	6 months	6 months

***Refer to USEPA. 1992. Rules and Regulations. 40 CFR Parts 100-149 [7,8]**

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and monitoring of performance of NF membrane processes using the HSD Model.

Methods and Materials

Water Quality Analysis

In Table 1, the sample collection and analysis protocol is listed for several of the water quality parameters evaluated in this research project. The recommended holding times for samples were adopted for this research study wherein turbidity, pH, temperature, conductivity, and total sulfide measurements were taken immediately after sample collection on site. Samples that are stored for analysis later were refrigerated at 4°C. Alkalinity and total organic carbon (TOC) analysis were carried out within 24 hours of sampling. Methods used for the measurement of each constituent were in accordance with the procedures set out in *Standard Methods for the Examination of Water and Wastewater* [2,7,8].

Phase 1 Approach

The City and University of Central Florida (UCF) developed a plan to eliminate the use of sulfuric acid as pretreatment to the City's RO process using a three-step approach. This approach adopted in this study to evaluate and eliminate use of acid in pretreatment process involved: (1) pilot testing the plan to reduce the dependence on acid, (2) implementing the plan on the full-scale system with conservative pH increments, and (3) continuous screening for scale formation potential by using a "canary" monitoring device.

Reverse Osmosis Pilot-Scale Acid Reduction Methods

The RO pilot skid contained two stages, in a 2-1 array, with 12 elements in the first stage and six elements in the second stage. Hydranautics CPA2-4040 and ESPA2-4040 spiral-wound polyamide membrane elements were used in the first and second stages, respectively. The pilot unit used the same type of membranes as the RO plant, with the membrane element surface area on the pilot unit being 85 ft^2 each, as compared to 400 ft^2 for the membranes on the full-scale plant. The pilot setup mimicked the City's RO water treatment process. The raw feed water to the RO pilot skid was about 21.1 gal per min (gpm), and at 75 percent recovery, the pilot skid produced 15.8 gpm of water. Process data was automatically recorded on the pilot at 10-min intervals to facilitate data analysis and pilot performance evaluations. A planned stepped reduction in acid feed was implemented. The approach has been through small dosage reductions or an increase of pH of the RO feedwater until the acid feed was completely eliminated and the feedwater returned to an ambient pH level. The steps include pH steps of 5.8 (original pH with acid feed), 6.3, 6.6, and 7.1 (ambient pH). During the acid elimination phase, scaling conditions may take place, as there is no longer a pH suppressant. The scale inhibitor Aquafeed®1025 was fed to the RO pilot at a dose of 2 mg/L.

Reverse Osmosis Full-Scale Acid Reduction Methods

Acid elimination on the 4.5-mgd RO plant, which consists of three 1.5-mgd trains, was carried out in smaller pH increments than the pilot study. The steps include pH steps of 5.8 (original pH with acid feed), 6.05, 6.3, 6.5, 6.7, 6.9, and 7.1 (ambient pH). The more conservative approach to acid elimination on the full-scale system was selected primarily as a precautionary measure, and also because the acid feed injection system could be more easily controlled in the full-scale plant.

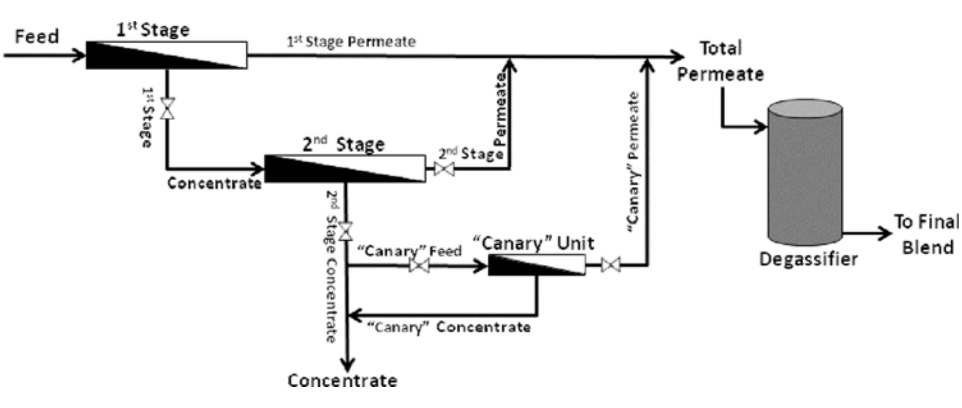

Figure 2. Schematic of the "Canary" Unit Setup[5,6]

Reverse Osmosis Full-Scale "Canary" Monitoring Assembly

In order to provide a robust monitoring program during the acid elimination phase, a two-membrane element pressure vessel, called the "canary" unit, was installed as a third stage on one of the three RO trains. The "canary" unit was installed at the tail end of the second-stage membrane process and tapped onto two pressure vessels out of a total of fourteen pressure vessels in the second stage of Train C. The "canary" pressure vessel incorporated two Hydranautics ESPA2 spiral-wound polyamide membrane elements, which are also used in the second stage of the full-scale RO trains. The "canary" assembly was monitored for pressure and flow rates three times daily by the City's operators via an instrumentation panel coupled to the "canary." The recovery rate on the "canary" was altered via adjustments to the feed and concentrate valves. The configuration of the "canary" unit is shown in Figure 2.

Phase 2 Approach

Phase 2 focused on investigating methods to enhance treatment of water supplied by the City's Verna fresh groundwater supply, with emphasis on aeration, NF, and ion-exchange integrated process evaluations. The study to pilot-test membrane softening process using NF membranes included evaluation of the most economical pretreatment option for the NF process. Pretreatment options that were evaluated included combinations of cartridge filters (CF), bag filters (BF), sand filters (SF), and UF membrane processes.

Verna Studies

The City initiated a retrofit of its Verna Tray aerators with a new design. Water sampling evaluations were conducted prior to and after construction of tray aerator improvements to evaluate sulfide efficiency improvements of the Verna wellfield tray aeration process.

Nanofiltration Pilot-Scale Pretreatment Studies

The NF pilot skid contained two stages, in a 2-1 array, with 12 elements in the first stage and six elements in the second stage. Hydranautics ESNA1-LF-4040 spiral-wound polyamide NF membrane elements were used in both the first and second stages. On the pilot unit, each of the pilot membrane elements had a surface area of 85 ft^2. The raw feed water to the RO pilot skid was about 20 gpm, and at 85 percent recovery, the pilot skid produced 17 gpm of water. Process data was automatically recorded on the pilot at 10-min intervals to facilitate data analysis and pilot performance evaluations.

Field and Laboratory Quality Control

To assess the consistency of the precision of the analytical instrumentation, duplicate measurements were taken. For field and laboratory measurements, duplicates were taken every five samples. Quality control requirements for field data were followed according to the analytical methods listed in the laboratory quality assurance procedures for the UCF Environmental Systems Engineering Institute (ESEI) housed within the civil, environmental, and construction engineering (CECE) department (Real-Robert, 2011). Quality control measures for laboratory data collection were performed according to the standard of care. [2,4,5]

Results and Discussion

Phase 1 Findings

Pilot Plant Demonstrates Acid Elimination Potential

The pilot study for acid elimination was carried out between March 25 and August 6, 2010, while the actual elimination on the 4.5-mgd RO plant was carried out in steps between June 2, 2011, and May 20, 2012. An assessment of the raw water variability was conducted to evaluate the impact of well rotation on water quality and that of refurbished wells that were added into the well rotation system. Membrane performance was assessed by normalizing permeate flow and is presented in Figure 3. In tandem with monitoring the normalized mass transfer coefficient (MTC), sometimes called specific flux by operators, the feed pressure and differential pressure across the pilot was also monitored as presented in Figure 4.

Full-Scale Reverse Osmosis Process Acid Elimination Successful

The results of this phase of the study are illustrated in Figures 5 and 6. The productivity of the full-scale RO membranes post-acid elimination was lowered by about 0.03 gal/ft^2 day psi to 0.20 gal/ft^2 day psi as the result of an increase in the calcium carbonate scaling potential. However, chemical cleaning with low pH cleaners eliminated this potential issue; hence, it was deemed favorable for the City to remove the acid feed from the RO system and operate at a recovery rate of 75 percent.

The successful implementation of the "canary" pressure vessel within the RO full-scale process documented that very minimal scaling would occur. The final blend consists of the degasified RO permeate, IX soft water, and Verna raw water that bypasses the IX. In Table

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Table 2. Comparison of Total Permeate Quality at pHs 5.8 and 7.1[5,6]

Parameter	Units	Total Permeate	
		pH = 5.8	pH=7.1
pH		5.47 ± 0.04	6.46 ± 0.13
Temp	°C	29.3 ± 0.6	27.7 ± 0.2
Turbidity	NTU	0.08 ± 0.00	0.08 ± 0.02
Conductivity	µS/cm	77.4 ± 0.5	95.0 ± 5.1
TOC	mg/L	< 0.1	< 0.1
SO_4^{2-}	mg/L	2.8 ± 0.2	4.6 ± 0.2
Cl^-	mg/L	13.5 ± 0.8	18.0 ± 0.7
Alkalinity	mg/L as $CaCO_3$	13.0 ± 0.7	16.6 ± 5.8
Si	mg/L	0.46 ± 0.01	0.52 ± 0.03
K	mg/L	0.34 ± 0.02	0.39 ± 0.02
Na	mg/L	12.9 ± 1.8	15.4 ± 0.8
Ca Hardness	mg/L as $CaCO_3$	< 2.5	< 2.5
Total Hardness	mg/L as $CaCO_3$	< 6.8	< 6.8
TDS	mg/L	44.3 ± 2.5	56.8 ± 3.6
TSS	mg/L	0	0
Total Sulfide	mg/L as S^{2-}	2.61 ± 1.05	3.43 ± 0.27

Table 3. Unit Price of Sulfuric Acid to City

Timeframe	Price/Ton ($)	Timeframe	Price/Ton ($)
Sept-1997 to Sept-2007	60.00*	Apr-2010 to Mar-2011	139.50
Oct-2007 to Jun-2008	78.80	Apr-2011 to Oct-2011	134.50
Jul-2008 to Dec-2009	138.00	Nov-2011 to Dec-2012	159.50
Jan-2009 to Mar-2010	343.91	*Based on the previous 10-year avg of City bid purchases	

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2, the total permeate water quality at pH 5.80 (i.e., before the acid elimination) and at pH 7.10 (i.e., after acid elimination) are tabulated for comparison. The higher pH is the result of the degassing of the dissolved carbon dioxide and hydrogen sulfide gases [3].

Table 2 summarizes the total permeate water quality. The higher sulfide content means that hydrogen sulfide (H_2S) stripping efficiency on the degassifier will be lower for the same air-to-water ratios. This is noted in the higher turbidity values of the degassified permeate water at pH 7.10 compared to pH 5.80. The degassified permeate turbidity at pH 7.10 is 0.38 + 0.05 NTU, while the turbidity at pH 5.80 was lower at 0.08 + 0.02. The higher pH is the result of the degassing of the dissolved carbon dioxide and hydrogen sulfide as the water passes through the degassifier. Hence, alkalinity is also lower in the degassified permeate water as compared to the alkalinity of the total permeate from the RO plant [3].

Cost Analysis

The primary driver for the RO process acid reduction research was the fluctuating bid prices that the City received from its supplier. Table 3 presents the unit bid price of sulfuric acid to the City between September 1997 and December 2012. In 2009, the supplier's price of acid to the City was a high of $343.91/ton, representing an annual cost of $215,000. In 2010, the expenditure was about $122,000, and in 2011, before acid elimination started on July 5, 2011, the total expenditure was about $47,000. Thereafter, during the phased acid elimination between July 6, 2011, and Feb. 20, 2012, the total expenditure on acid was about $20,000. The average acid consumption between 2009 and June 2012 is shown in Table 4. The typical use of sulfuric acid in the RO plant is about 0.46 tons per MG of permeate produced. The cost savings as the acid elimination progressed is tabulated in Table 5. If the average permeate production at the RO plant is 3.5 mgd for the period of July–December 2012, the projected savings realized from the acid elimination project by the end of 2012 will be about $123,000 at prevailing acid bid prices.

Phase 2 Findings

Verna Aeration Improvements and Performance

As part of the City's strategy to improve the overall water quality of its water supply, the City embarked on a project to improve the aeration system at the Verna wellfield. The original deep tray aeration system, with four tiers of trays, was found to be inefficient in stripping the sulfides in water because the distribution of water over the trays was not uniform and not all of the available tray area was utilized to maximize aeration. The retrofitting works to improve aeration at Verna started in fall 2011 and was completed in July 2012. Sulfide testing was carried out prior to June 2010 and after August 2012 when the Verna tray aeration system was retrofitted, and the results are summarized in Table 6. The higher sulfide content of the raw Verna water in June 2010 compared to August 2012 is due to well rotations, and the City could not bring the same

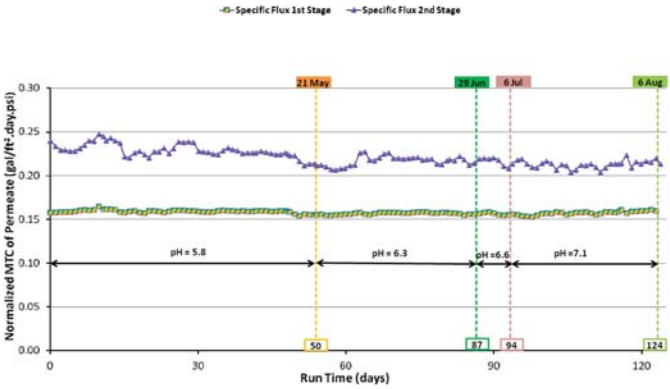

Figure 3. Average Daily Reverse Osmosis Pilot Plant Normalized Mass Transfer Coefficient

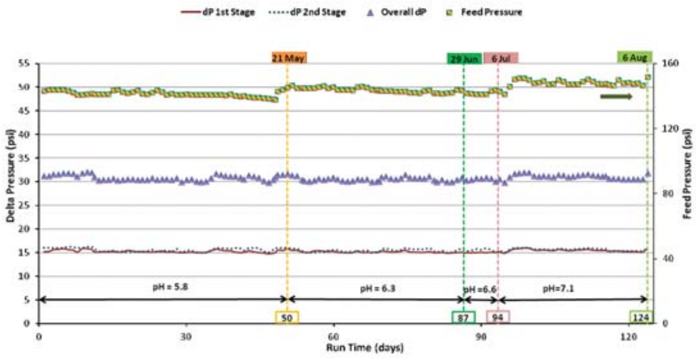

Figure 4. Average Daily Feed Pressure and Differential Pressure on Reverse Osmosis Pilot

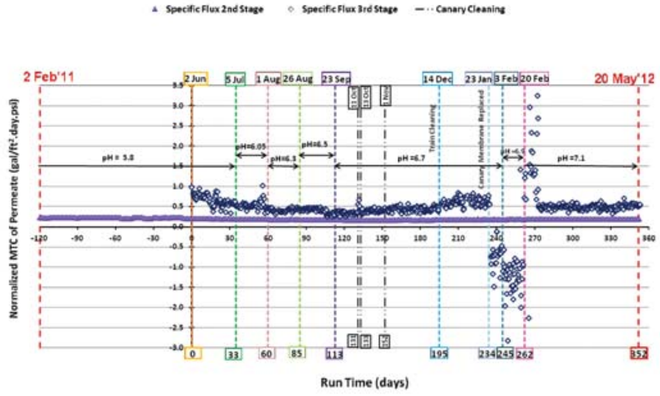

Figure 5. Normalized Permeate MTC of Reverse Osmosis Train C Second Stage and "Canary" Unit

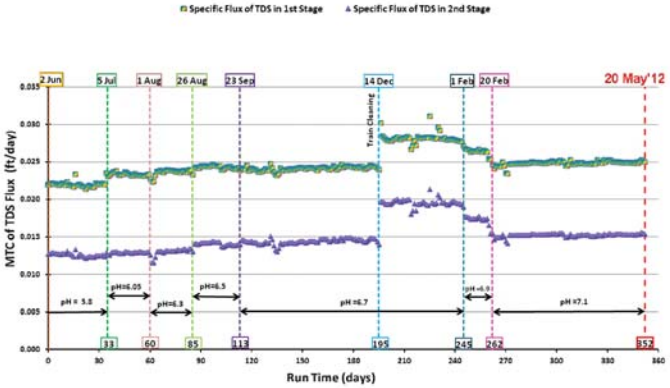

Figure 6. Total Dissolved Solids Solute Mass Transfer Coefficient as a Function of Run Time

sets of wells online in August 2012 for direct comparison.

Table 4. Computation of Average Acid Use per MG of Permeate Production[5,6]

Timeframe	Acid Use (Tons)	Permeate Flow (MG)	Avg Acid Use (tons/MG)
Yr 2009	625	1342	0.466
Yr 2010	653	1396	0.468
Yr 2011 (1/1-6/30)	285	677	0.421
Average per day	1.77	3.88	0.460

Table 5. Projected Savings from Acid Elimination Project[5,6]

Timeframe	Permeate Flow (MG)	Projected ($)	Actual Cost ($)	Savings($)
6 Jul - Oct'11	415	25,700	13,600	12,100
Nov'11 - Jun'12	952.5	69,900	6,400	63,500
Jul - Dec'12	644	47,300	-	47,300

Table 6. Efficiencies of Tray Aerators at Verna Wellfield[5,6]

Sample Type	Old Tray Aerators		New Tray Aerators	
	S^{2-} (mg/L)	Turbidity (NTU)	S^{2-} (mg/L)	Turbidity (NTU)
Raw Verna	5.8	0.3	2.6	0.23
Degassified Verna	3.0	0.9	0.9	2.0
Efficiency	- 48%	+ 200%	- 65%	+ 770%

Verna Well Supply Membrane Pretreatment

A schematic of one of the operating conditions tested for evaluation of an NF system for treatment of the aerated Verna groundwater supply is provided in Figure 7. The NF pretreatment evaluations included cartridge, sand, ultra-, and bag filtration. Preliminary results indicated that cartridge filtration alone would not protect against membrane fouling; sand filtration offered a three-fold reduction in cleaning frequencies. It was determined that UF pretreatment (flux rate of 40-45 gal/ft^2 day) downstream of sand filtration (loading rate of 3 gal/ft^2 day) and prior to bag filtration would arrest particulate fouling; however, algae control was problematic. Representative results of UF pilot testing are provided in Figure 8.

Pilot testing with UF as prefilter to the NF pilot was started on February 1, 2012. The UF pilot incorporated two Toyobo Durasep UPF0860 UF hollow fiber membranes and operated in an inside-outside configuration. Toyobo's UF membrane fibers are composed of hydrophilic polyethersulfone (PES) modified with polyvinylpyrrolidone. During the preliminary evaluation phase of the pilot, two new modules (each 430 ft^2 of surface area) were used to evaluate possible operating flux rates and identify suitable chemically enhanced backwash (CEB) chemicals and CEB frequencies. Preliminary evaluation tests of UF pilot operations were carried out between February 1 and March 27, 2012. During these tests flux rates, forward filtration cycle times, and frequency of CEBs were adjusted. The UF pilot operations between March 8 and March 27, 2012, were without SF as pretreatment to the UF pilot. Enhanced CEBs were performed whenever significant fouling was noted in order to restore the membranes productivity. These enhanced CEBs refer to injection of CEB chemicals with longer soak times than normal CEBs.

Identification of fouling on the UF membranes was established by monitoring the increases in transmembrane pressure (TMP) as logged on the UF pilot's programmable logic control (PLC). Following the preliminary evaluation, pilot testing with new Toyobo test modules was started on March 27, 2012, with both UF membrane modules on the UF pilot being replaced. From the evaluations carried out during the preliminary evaluation phase, a flux rate of 45 gal/ft^2 day, equivalent to filtrate production of approximately 27 gpm and a forward filtration time of 45 min, was adopted. The UF pilot testing was thereafter carried out between March 27 and October 8, 2012. Severe algal fouling of the UF pilots was observed during the course of this research study and a chlorine injection system was introduced to the feed stream of the UF pilot on July 25, 2012; thereafter, a CIP was carried out on the UF pilot on August 10, 2012.

Conclusions

Elimination of Sulfuric Acid Pretreatment at City's Brackish RO Process Was Successful

Phase 1 included a four-month-duration full-scale analogous pilot test where sulfuric acid feed was systematically reduced from a pretreated feed pH 5.8 to an ambient feed pH 7.1. As a result, the full-scale RO process's acid pretreatment acid feed dosage was incrementally reduced and eliminated, while the process was monitored with a custom-designed two-element "canary" device. Throughout the reduction in acid feed, Langelier Saturation Index (LSI) and Ryznar Stability Index (RSI) indices were calculated and assessed. The productivity of the full-scale RO membranes post-acid elimination was lowered by about 0.03 gal/ft^2 day psi to 0.20 gal/ft^2 day psi as the result of an increase in the calcium carbonate scaling potential. However, chemical cleaning with low pH cleaners resolved this issue. The elimination of sulfuric acid pretreatment is estimated to save the City over $120,000 annually at full capacity production of 4.5 mgd, based on 2012 bid prices for sulfuric acid.

Canary Device Deemed Effective

The Canary monitor successfully serves as a monitoring device that allows for the detection of potential scale formation without interruption of the full-scale process operation. This finding is supported by other studies where the monitoring of scale within membrane processes had been previously reported [3,9].

Verna Tray Aerator Improvements Improve Sulfide Removal

The sulfide removal efficiency at Verna following the tray aerator retrofit has increased from 48 percent to 65 percent previously. The turbidity formed as the sulfides are oxidized has also increased close to 770 percent, as compared to about a 200 percent increase previously. The increased turbidity, while it signifies improved aeration, also means that improved filtration is necessary to control the turbidity of the final blended water supplied by the City.

Verna Water Supply Nanofiltration Treatment Effectiveness Impacted by Pretreatment

The NF pretreatment evaluations included cartridge, sand, ultra-, and bag filtration. Results indicated that cartridge filtration alone would not protect against membrane fouling; in contrast, sand filtration offered a three-fold reduction in cleaning frequencies. It was determined that UF membrane pretreatment (flux rate of 40-45 gal/ft^2 day) downstream of sand

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filtration (loading rate of 3 gal/ft^2 day) and prior to bag filtration controlled particulate fouling; unfortunately, algae control was problematic. It appears that stable NF operations could be achieved through the use of SF and UF; it controls colloidal plugging problems on the first stage. A chlorine injection with a bisulfite injection to quench the excess chlorine will likely be needed to control biofouling. Additional work continues on this aspect of the project.

Acknowledgements

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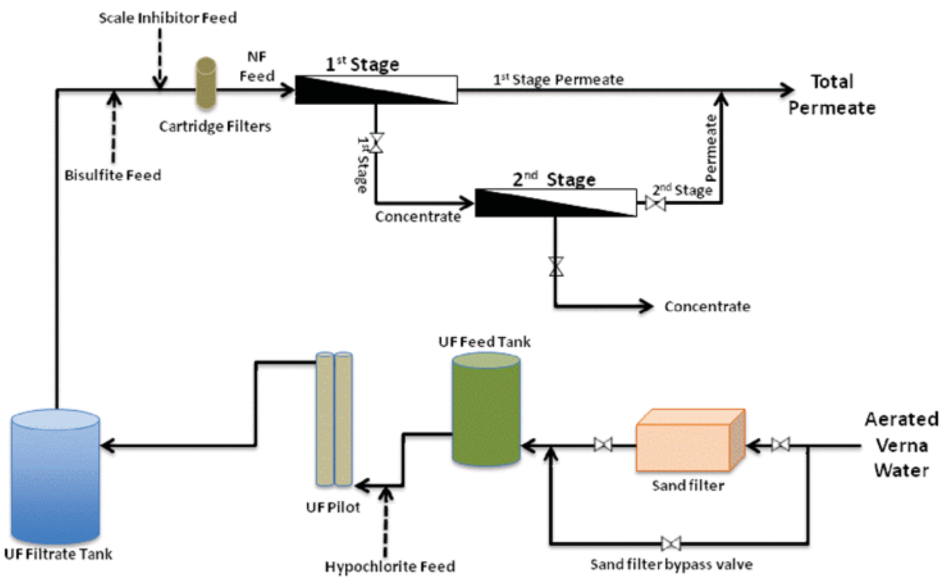

Figure 7. Representative Schematic Layout of Ultrafiltration and Nanofiltration Pilot

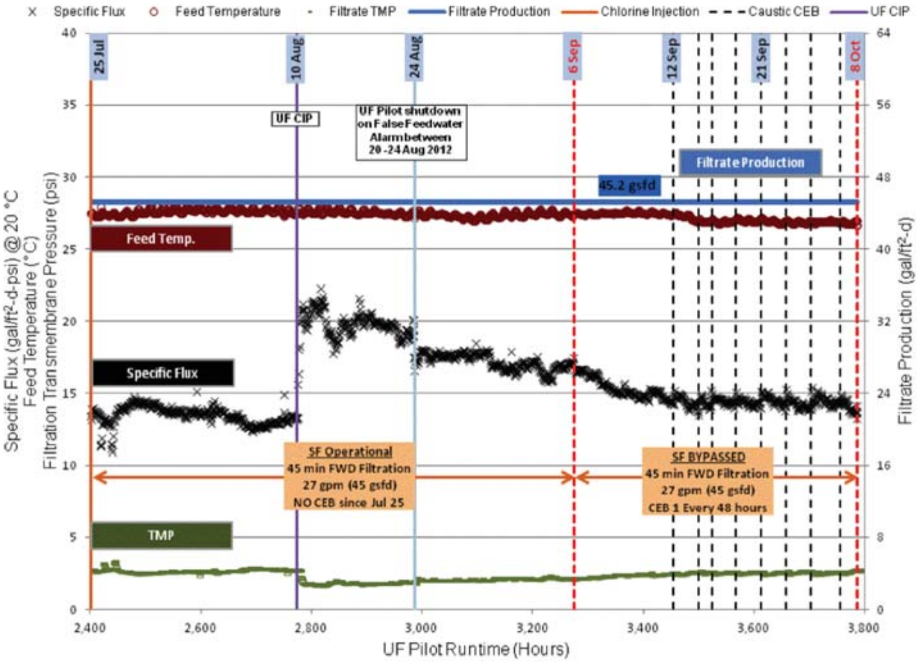

Figure 8. Representative Ultrafiltration Pilot Operations (July 25–Oct. 8, 2012)

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