When All You Have Is Lemons, Try Making Lemonade!

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In early 2007, the South Florida Water Management District promulgated a Water Availability Rule that severely limited the future permitted water allocations from the Biscayne Aquifer, which has been the historic water supply source in Southeast Florida. The city's system-wide potable water treatment facilities' capacity is 44 million gallons per day (MGD), while the source water, after adoption of the Water Availability Rule, is limited to 29 MGD. This represents a stranded existing capacity of 34 percent.

As a step toward using stranded treatment capacity, the city looked into tapping the Upper Floridan Aquifer for water at its Melaluca Floridan well site. The Sawgrass Water Treatment Plant is a nanofiltration softening plant that treats Biscayne Aquifer water. Simply treating the brackish Floridan water with reverse osmosis (RO) can increase the plant's hydraulic capacity, but it requires significant capital and ongoing operational costs.

The Floridan Aquifer water beneath the Melaluca Floridan well site exhibited exceptionally high total dissolved solids (TDS) of 8,000 milligrams per liter (mg/L) in the Upper Floridan, unlike the 3,000 mg/L TDS water found beneath the city's Springtree Water Treatment Plant. Treating the 8,000 mg/L TDS water represents almost a threefold increase in RO energy over that required at other Broward county utilities. The city looked into reducing the TDS of the Floridan water by blending it with concentrate from the nanofiltration membrane softening plant.

The big-picture objective of this study was to blend nanofiltration concentrate (NFC) having a 2,000-mg/L TDS with Floridan Aquifer (FAQ) brackish water having an 8,000 mg/L TDS. The blended water logically would contain less TDS and therefore would require less energy to treat. Also, the additional benefit of harvesting a portion of the NFC that was being wasted down a deep injection well was viewed as positive.

The specific purpose of the study was to test brackish water reverse osmosis (BWRO) over a range of operational conditions, adjusting the feedwater blend with various chemical additions to determine the scaling/fouling potential for each scenario. The RO process was piloted using different blend ratios of FAQ brackish water and NFC while varying parameters such as feedwater blend, recovery, pH, anti-scalant, sodium bisulfite, and dispersant (11 scenarios).

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Methodology

Pilot testing was conducted at the Sawgrass Water Treatment Plant. The NFC was fed from the disposal line and the FAQ water was supplied via truck (2,000 gallons) from a Floridan well located a mile away from the plant at the Melaluca Floridan well site. Water from the truck was stored in an on-site 10,000-gallon tank.

Midway through the study to prevent bio-fouling from algae, a 5-micron filter was installed on the Floridan water line. Both NFC and FAQ supply lines fed into a common pilot feed line. Chemical addition (acid addition and anti-scalant) occurred after blending and before the 5-micron cartridge filter, which was located upstream of the RO membranes. The acid injection system used a feedback loop to main-

Continued on page 48

Figure 1: Pilot Process Flow Diagram

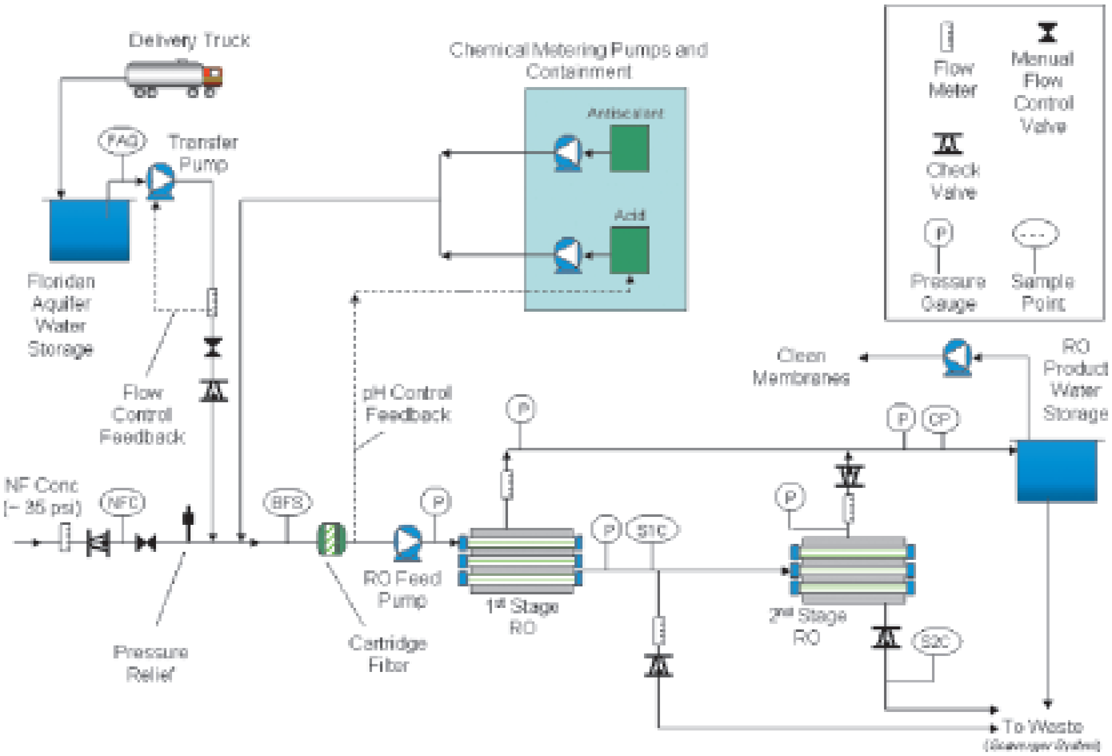


Table 1: Concentrate Recovery Pilot Operational Conditions

Scenario ID	Start Date	Runtime (hours)	Feedwater Blend (%NFC:%FAQ)	Stages	Baseline Recovery	pH	Chemical Addition
FIRST TANKER TRUCK – FAQ CONTAMINATION							
1	2/20	84	60%:40%	2	70%	6.3	AV: 4 mg/L
2	2/24	See below	60%:40%	2	70%	5.0	AV: 4 mg/L
SECOND TANKER TRUCK – FAQ CONTAMINATION							
2	3/18	153	60%:40%	2	70%	5.0	AV: 4 mg/L
Autopsy, Membrane Replacement, Single-Stage Piping							
3	5/8	31	40%:60%	1	55%	6.5	KL: 5 mg/L
THIRD TRUCK WITH PLASTIC TANK							
4	6/3	See below	30%:70%	1	55%	6.5	KL: 5 mg/L
Membrane Replacement							
4	6/11	149	30%:70%	1	55%	6.5	KL: 5 mg/L
5	6/17	See below	30%:70%	1	55%	5.5	KL: 5 mg/L
6	6/23	40	60%: 40%	1	55%	5.5	KL: 5 mg/L
7	6/30	152	0%:100%	1	55%	5	KL: 5 mg/L
5	7/7	See below	30%:70%	1	55%	5.5	KL: 5 mg/L
5	7/11	193	30%: 70%	1	55%	5.5	KL: 5 mg/L
8	7/16	See below	30%:70%	1	35%	5.5	KL: 5 mg/L
8	7/22	186	30%:70%	1	35%	5.5	KL: 5 mg/L
9	7/31	88	30%: 70%	1	55%	5.5	KL: 5 mg/L Bisulfite
Membrane Replacement							
10	9/15	329	15%/85%	1	55%	5.5	KL: 5 mg/L
11	9/28	364	25%/75%	1	55%	5.5	KL: 5 mg/L Dispersant
Autopsy							

Continued from page 46

tain a set pH for a given run.

The general process flow diagram for the proposed pilot facility is presented in Figure 1. The process train consisted of a 2:1 array (seven element: four element) of RO membranes which had the flexibility to be configured as single-stage, if desired.

The membranes selected for pilot test were Film-Tec BW30-4040. These membranes have a diameter of four inches and each element has a surface area of 78 ft^2 (7.2 m^2).

A summary of the experiments performed at the Sawgrass Water Treatment Plant is presented in Table 1. Beginning in May, single-stage operation, running only the final stage, was used in order to minimize the amount of FAQ water transported and stored on location at the Sawgrass Plant. Recovery of 55 percent in the final-stage operation reflects similar operating conditions as 70-percent recovery for a two-stage operation.

Pilot Success Criteria

At the start of each test run (defined by a set of operating conditions), the initial specific flux, feed pressure and normalized water transport coefficient (WTC) were benchmarked in order to evaluate subsequent changes in conditions caused by membrane scaling/fouling. Fouling was defined as a decrease in the WTC by 15 percent from its original value over the course of 1,000 hours (six weeks), which translates approximately into a 3-percent decrease within a single week. Similar percentage changes were applied to the flux (decreases with fouling) and feed pressures (increases with fouling).

Results and Discussion

Feedwater Quality

In order to evaluate the effect of feedwater quality on system performance, samples of the NFC and FAQ water were collected by operations staff and sent for analysis. Key constituents varied significantly between the two feedwaters, as indicated in Table 2.

High TDS increases the pressure required to move water through the membrane, increasing the energy use. High levels of total organic carbon (TOC) can foul BWRO membranes, increasing the frequency of cleaning and membranes replacement. The NFC has approximately 40 times the amount of TOC found in the FAQ water. Industry standards recommend limiting influent TOC to 5 mg/L for conventional groundwaters.

The dissolved and total iron levels in the NFC are two orders of magnitude higher than the industry standard of 0.05 mg/L of influent dissolved iron to minimize fouling. Constituents such as barium sulfate or silica (sparingly soluble salts) can scale the membranes and are a function of the recovery of the system. Prior to beginning testing, the waters were evaluated for scaling potential and to select antiscalants to manage scaling.

Blended Water Quality Parameters of Concern

The blend percentage of NFC and FAQ waters was varied throughout the pilot study in order to determine optimal ratios for a sustained operation. The TDS of the blended water increased when a higher percentage of FAQ water was used. Conversely, the concentrations of TOC and iron decreased when the percentage of FAQ water increased. The silt density index was monitored routinely for both source waters, as well as the blend stream. The blend stream after cartridge filter had a silt density index in the range of 2 to 3.

Baseline Condition – 100% Floridan Aquifer Water

Figure 2 illustrate the results of the RO test with 100-percent FAQ. This scenario was operating in a single-stage configuration, resulting in 55-percent recovery. These results suggest that operating an RO system at the given operational parameters with 100-percent FAQ should be feasible to achieve the

Continued on page 50

Table 2: Feedwater Quality of NFC and FAQ

Constituent	Units	NF Concentrate (NFC)		Floridan Aquifer (FAQ)	
		Average	Count	Average	Count
Total Dissolved Solids (TDS)	mg/L	2068	8	8605	8
Total Organic Carbon	mg/L	90.1	7	2.3	7
Laboratory Specific Conductance	µmhos/cm	1849	7	9659	7
Field Specific Conductance	µmhos/cm	2352	8	13351	8
Iron	mg/L	7.71	8	0.089	7
Dissolved Iron	mg/L	4.62	7	0.0360	7

Figure 2: Specific Flux for 100% Floridan

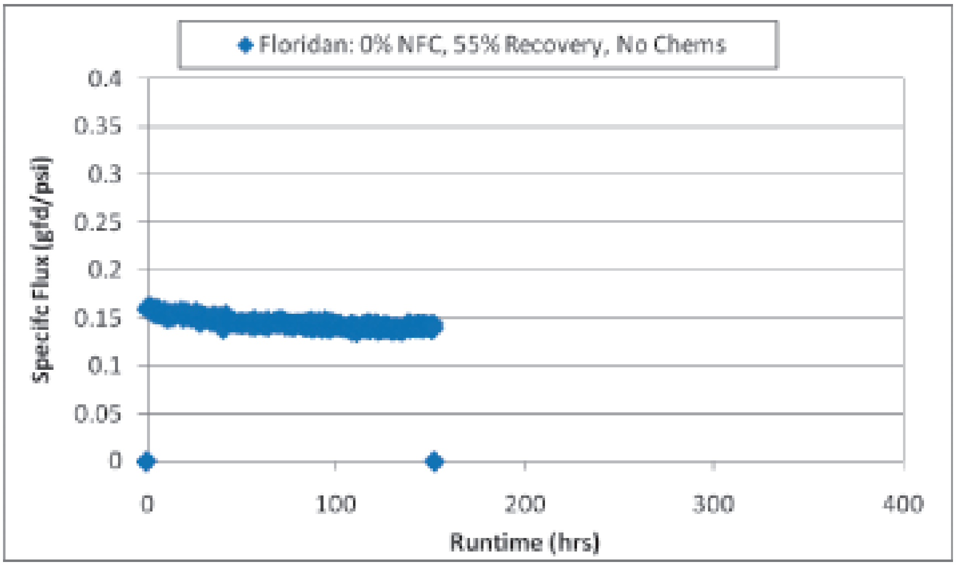


Figure 3: Specific Flux for 30% NFC Blend

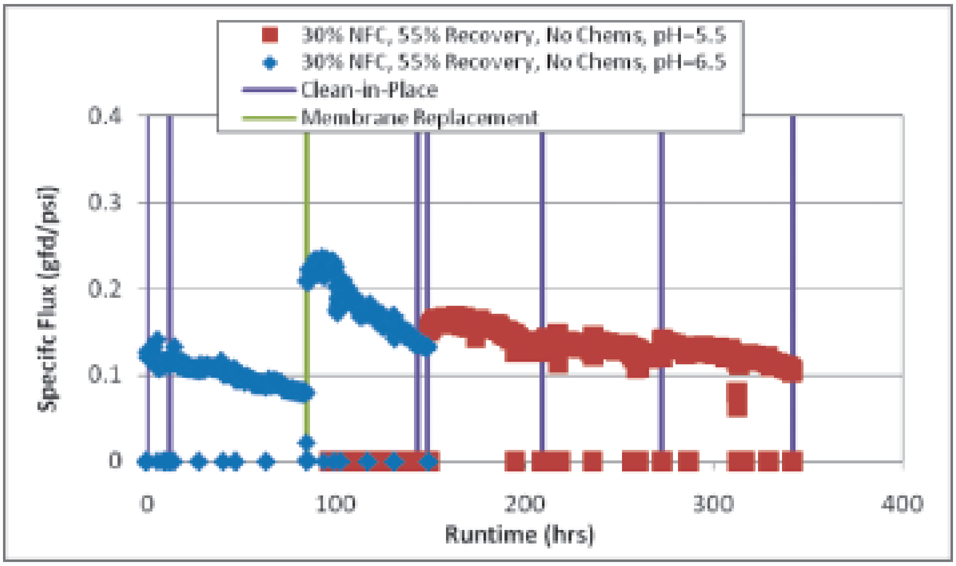


Figure 4: Specific Flux 15% NFC and 30% NFC at pH 5.5

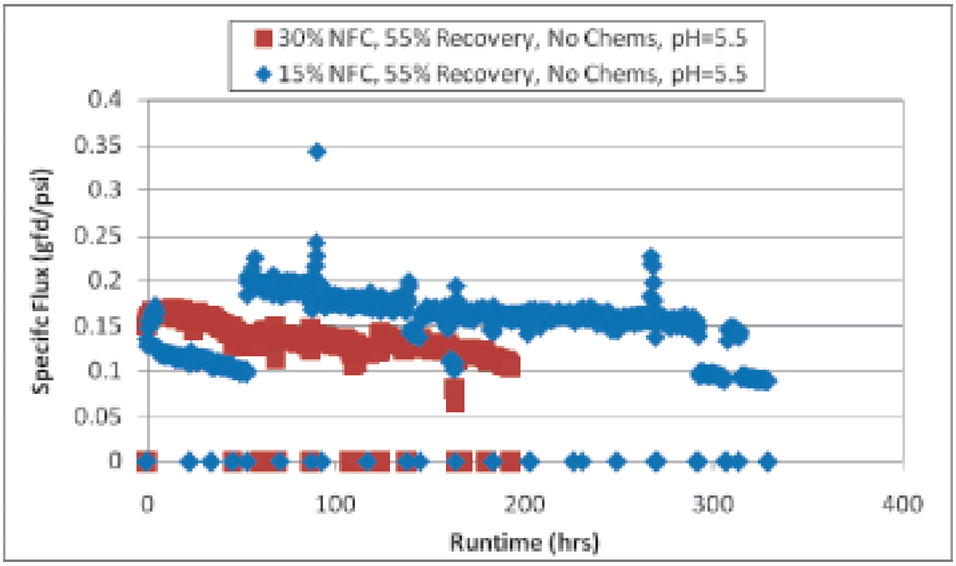


Figure 5: Specific Flux 30% NFC at 35% and 55% Recoveries

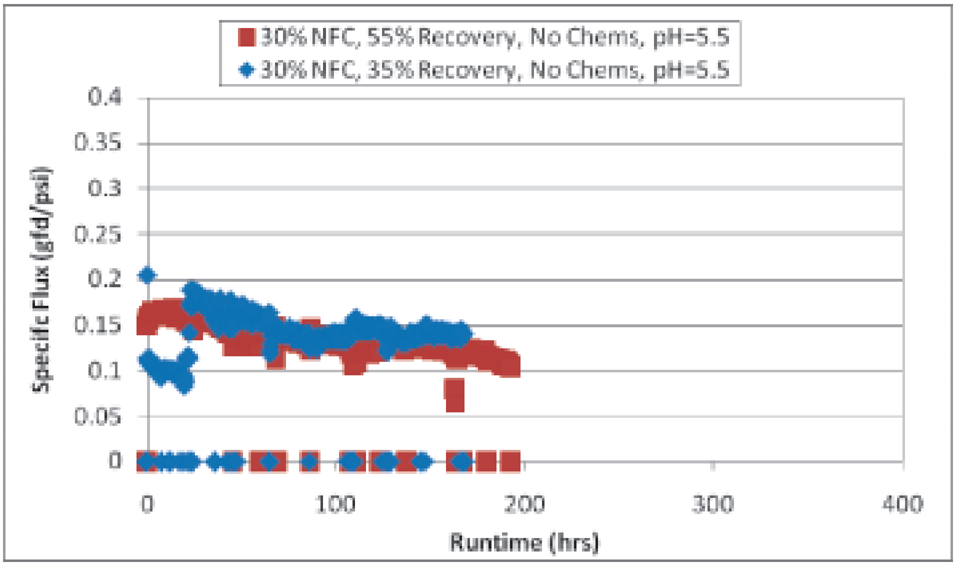


Table 3: TOC and Iron Concentrations

	NFC	NF Stage 2 Feed	Average for Blend (30% NFC/ 70% FAQ)	Average for Blend (60% NFC/ 40% FAQ)
TOC	90 mg/L	41 mg/L	26 mg/L	55 mg/L
Iron	9 mg/L	4.1 mg/L	2.6 mg/L	4.45 mg/L

Continued from page 49

cleans-in-place (CIPs) interval goal. Longer testing (> 1,000 hours) is required to determine if long-term issues are present.

NFC Blends with Floridan Aquifer Water

Figure 3 illustrates test runs where 30 percent of the feedwater was NCF and recovery was 55 percent. Two scenarios are presented on this graph: Blue diamonds represent runs with a feed pH of 6.5 and red squares represent runs with a feed pH of 5.5. Also indicated on these figures are CIPs and membrane replacements. Frequent CIPs were required because of membrane fouling.

These figures illustrate several points:

1. The first runs, illustrating severe fouling, used a feed pH of 6.5 at a blend ratio of 30-percent NFC to 70-percent FAQ water and recovery of 55 percent. When the feed pH was decreased to 5.5, at the same blend ratio and recovery, the fouling rate decreased significantly.
2. The decrease in permeability and increase in differential pressure observed with the 30-percent NFC blend at a pH of 5.5 were still higher than tolerable for design of a full-scale system, and would require too-frequent CIPs.

Based on the fouling observed under these conditions, two parameters were altered to evaluate the effects on fouling: 1) decreasing the recovery [a lower recovery concentrates less foulants onto the membrane surface] and 2) lowering the percent of the NFC in the blend.

Figure 4 illustrates a blend with 15-percent NFC. This resulted in a much lower fouling rate at of 55-percent recovery, with a pH of 5.5 and flux of 11 gallons per foot per day. Summarizing the findings of these runs:

1. The fouling rate was much lower using 15-percent NFC and much closer to the baseline run of 100-percent FAQ water. The pH of this run was 5.5.
2. At 15-percent NFC blend, the differential pressure is nearly flat, indicating minor scaling. The specific flux decreased, however, indicating some form of fouling and resulting in a higher-frequency CIPs than targeted.

Figure 5 illustrates blends of 30-percent NFC to 70-percent FAQ water with two different recovery rates: 35 percent and 55 percent. A reduced recovery rate did not affect the rate of decrease of the specific flux, but it did affect the rate of increase of differential pressure. Reducing the recovery is an aspect to investigate further if other evaluations prove unsuccessful, but this change must be balanced with other cost factors and loss of water production.

Foulant Evaluations

As seen in the previous figures, the rate of fouling was fairly high whenever NFC blend equaled or exceeded 30 percent. Originally it was anticipated that by diluting NFC with FAQ water, the blend would have properties similar to the feedwater at the Sawgrass Water Treatment Plant. For instance, assuming that TOC and iron are rejected completely by nanofiltration membranes and the recovery in Stage 2 of the Sawgrass nanofiltration system is 54 percent, the concentration of TOC and iron in the Sawgrass Stage 2 feed should be less than half of the NFC concentration, shown in Table 3.

Table 3 illustrates that the TOC and iron concentrations in the Sawgrass Plant's nanofiltration Stage 2 feed are higher than the 30-percent NFC to 70-percent FAQ blend and are similar to the 60-percent NFC to 40-percent FAQ blend. This level of TOC and iron does not cause excessive fouling in nanofiltration Stage 2, but it does cause excess fouling in the BWRO pilot study. Since it is not simply the concentration of TOC and iron that leads to excessive fouling, it is speculated that other reactions occur when the NFC and FAQ waters are blended and treated with the BWRO.

In order to further explore potential causes of the fouling, a number of additional experiments were conducted. Tests included an evaluation of dissolved oxygen (DO) on the particle count in the FAQ water, which was unavoidably introduced during transport. Sodium metabisulfite (SMBS) was added to FAQ water to remove the DO, reducing the potential for oxidization of compounds in the NFC water. Finally, organic dispersant was added to the combined feedwater. These experiments are summarized as follows:

Air Exposure Evaluations

While air exposure to the FAQ water was shown to be an unlikely source of fouling based on the bench test results, it was still possible that the DO in the FAQ water was reacting with compounds in the NFC to cause fouling. Specifically, there was concern over the oxidation of iron in the NFC by DO. Iron in an anoxic environment typically is present as ferrous iron and is soluble in water, but the oxidized form, ferric iron, is insoluble and can cause significant fouling.

In order to de-aerate the FAQ water, sodium metabisulfite ($Na_2S_2O_5$) was added to it. Figure 6 illustrates the results of this run compared to runs with the same operational parameters but no chemical addition. The blend, recovery, and pH were 30-percent NFC to 70-percent FAQ, 55 percent, and 5.5, respectively.

1. The initial specific flux of the SMBS scenario is lower than the "no chemical" scenario, but this situation likely is due to residual fouling before the SMBS run, which occurred after the "no chemical" runs. The same phenomenon can be seen in the differential pressure.
2. The permeability and differential pressure of the SMBS scenario appear to be stable. A longer runtime with the SMBS scenario would provide more definitive data, but it does appear that the addition of sodium bisulfite has a positive effect on the rate of fouling.

Figure 6: Specific Flux 30% NFC with Sodium Bisulfite

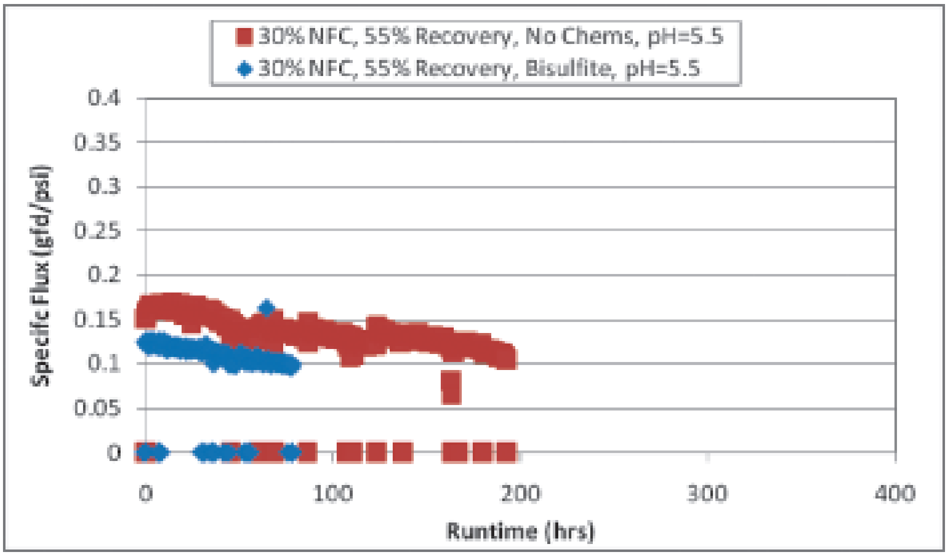
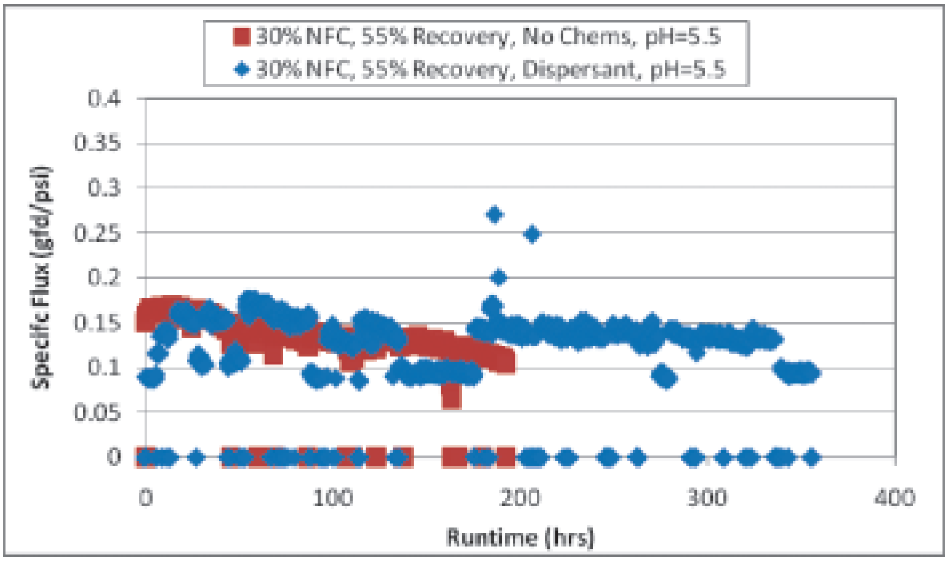


Figure 7: Specific Flux 30% NFC with Dispersant



Dispersant Trials

Dispersant was used to prevent the coagulation and deposition of colloidal organic matter. Figure 7 illustrates the effect of dispersant compared to a "no chemical" scenario. The blend, recovery, and pH were 30-percent NFC to 70-percent FAQ, 55 percent, and 5.5, respectively.

1. The dispersant run occurred soon after a membrane replacement; therefore, the membranes were relatively clean at the start of the run.
2. Both the specific flux and the differential pressure were very stable when compared to the "no chemical" scenario. Both the specific flux and differential pressure were very similar to the baseline run with 100-percent FAQ water, a trend in specific flux is shown in Figure 7.

Based on the runs that utilized SMBS and dispersant, it appears that the fouling rate in the pilot study can be reduced significantly by minimizing the presence of insoluble and non-dissolved iron and/or colloidal organic matter. The use of either of these chemicals would likely allow extended operation of the RO system, assuming a 30-percent NFC to 70-percent FAQ water blend, recovery of 55 percent, and pH adjustment to 5.5.

Autopsies

Two autopsies were performed on fouled membrane elements. The first autopsy was performed by Dow/Film-Tec when two elements were collected on March 27, 2009, after an experimental run and without chemical cleaning to preserve the foulants. The run used a feed blend of 60-percent NFC to 40-percent FAQ water and had 70-percent recovery.

The flow and rejection changes observed with this element were consistent with organic fouling. The salt passage was higher than expected (30-40 µS/cm), which is indicative of a dynamic membrane coating (fouling). Based on the test results, the fouling was most likely caused by iron and organics. The organic foul-

Continued on page 52

Figure 8: Specific Flux, CIPs and Membrane Replacements

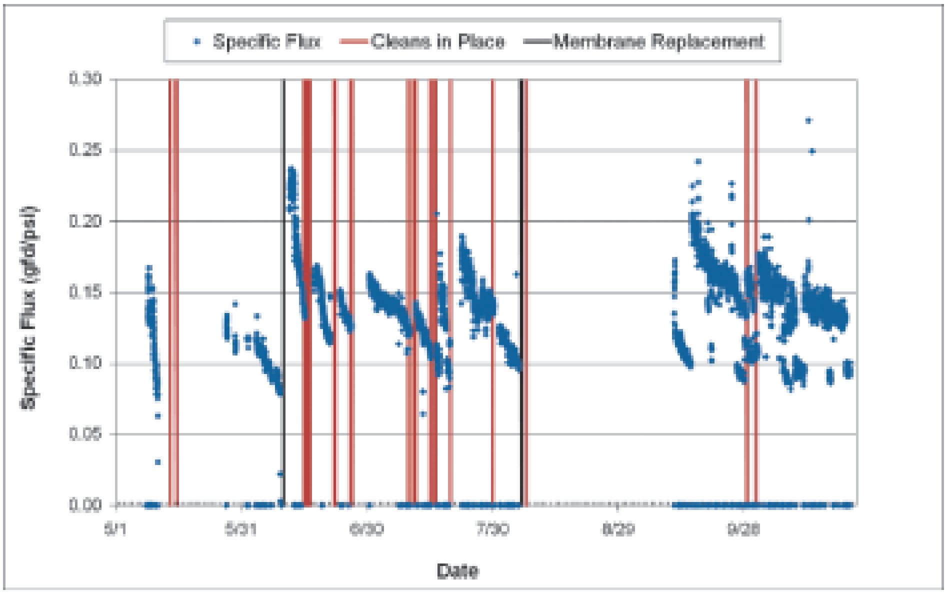


Figure 9: Comparative Cost Analysis

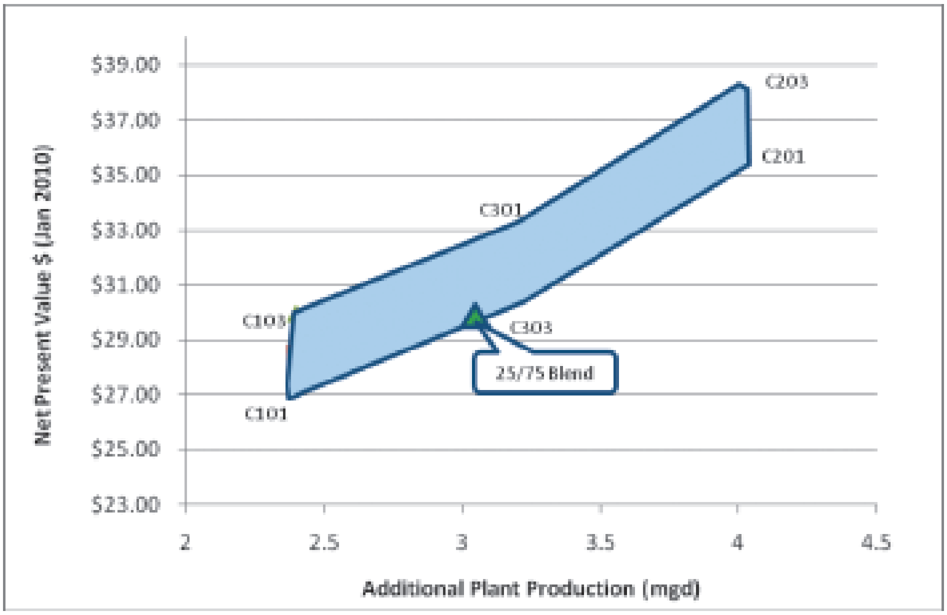


Table 4: Summary of Scenarios with Stable Operation

Scenario	Feedwater Blend	Recovery	pH	Chemical Addition
7	0% NFC/100% FAQ	55%	5	Antiscalant
9	30% NFC/70% FAQ	55%	5.5	Antiscalant Sodium Metabisulfite
10	15% NFC/85% FAQ	55%	5.5	Antiscalant
11	30% NFC/70% FAQ	55%	5.5	Antiscalant Dispersant

Continued from page 51

ing was thought be the most significant type. Extensive cleaning was required to restore the flow of the elements to the *minimum* specification for this element type.

The second autopsy was performed by Avista when an element was collected on October 30, 2009, after an experimental run and without chemical cleaning to preserve the foulants. This run operated with a blend of 25-percent NFC to 75-percent FAQ water and a recovery of 55 percent. Dispersants were used to break up organic materials.

The exposed membrane surfaces of the element were coated evenly with brownish-orange foulant material. Amorphous material dominated the foulant, but some gram positive and negative bacteria were both observed during microscope analysis.

Scanning electron microscopy and energy dispersive x-ray analysis (SEM/EDX) identified significant inorganic material (iron oxides). Organic content of foulant from the element was determined as 43 percent of loss on ignition (LOI), where values in excess of about 35 percent of LOI represent significant organic content.

Fourier-transform infrared (FTIR) analysis confirmed significant amounts of organic matter fouling and identified proteins, carbohydrates, and polysaccharides. The autopsy results agree with earlier conclusions that fouling is caused by the high levels of iron and TOC from the NFC.

Cleans-in-Place

In order to remove the foulants, CIPs were performed. Low-pH cleaning solutions targeted removal of inorganic foulants such as iron. Fouling from organics was removed with high-pH cleaning solutions.

The frequency of CIPs during the pilot study was dictated by the operating parameters for each run. In general, runs that used a higher percentage of NFC were likely to foul quickly and required more frequent CIPs. The use of dispersant, bisulfite, and acid all increased the runtime between CIPs.

Because of the nature of fouling present during the pilot study, it was sometimes necessary to perform multiple soaks during a CIP in order to fully recover the permeability and differential pressure to baseline conditions. Some of the fouling that occurred during the study was permanent, thus specific flux and other operating parameters did not return to their baseline conditions. This is demonstrated in Figure 8, where after a CIP, the specific flux did not return to levels seen from a new membrane. As a result, it was necessary to replace the membranes three times during the pilot study.

RO Permeate Quality

The permeate TDS was below the regulatory requirement of 500 mg/L in all samples. The organic carbon was either present at very low levels or not detected in the permeate. Iron concentration increased in the blended feedwater as the percentage of NFC increased, but iron was not detected in the combined permeate, regardless of the feedwater blend and the membrane recovery rate.

Comparative Cost Analysis

The city of Sunrise plans to install Floridan Aquifer wells in the near future. Quantities of water per well and the quality of FAQ water significantly impact the cost of the full-scale RO project. Floridan Aquifer wells in Southeast Florida historically yield 2 million to 3 million MGD. Since the yield of the Floridan Aquifer is a function of the limestone formation, the final yield is unknown until the well is constructed. A compounding problem could be the quality of the Floridan water in this location, which is currently unknown until a test well is installed.

Operational cost is a function of the amount of energy and chemical usage, where energy cost is a function of the TDS of the source water. Capital cost is a function of infrastructure invested, where infrastructure directly depends on the number of wells installed with the corresponding number of treatment process trains.

If two wells are installed with a net production capacity of 2.0 MGD each, then three 1.0-MGD trains (1.0-MGD permeate production per train) can be recommended; if two wells are installed with 2.5 MGD production capacity, then four 1.0-MGD trains can be recommended. Capital costs associated with Floridan Aquifer wells are significantly higher than Biscayne Aquifer wells, making the capital cost more closely associated with well yield.

If the planned Floridan Aquifer well yield is less than 3 MGD, the reverse-osmosis process (80-percent recovery) can not produce the target permeate requirement of 2.33 MGD (set by South Florida Water Management District permit) unless a second well is drilled. A unique option surfaces, however, if the Floridan well yield is less than 3 MGD but more than 2.48 MGD, where a 25-percent NCF to 75-percent FAQ water blend can meet the 2.33 MGD target, deferring more than $1 million in construction costs for a second Floridan well.

If the Floridan Aquifer yield is less than 2.5 MGD, the blend option (25-percent NFC to 75-percent FAQ) may not be able to provide more than 2.3 MGD of permeate. Figure 9 shows a graphical representation of variability of the different baseline possibilities as an area curve, where the blend ratio is represented as a point within this area envelope.

As seen in Figure 9, the unpredictability of the Floridan Aquifer at the planned site creates variability in the overall net present value, depending on the well yield and the water quality; thus the cost estimate is represented as an area curve. The blend scenario for Figure 9 assumes 75-percent FAQ water to 25-percent NFC, 8,000 mg/L of Floridan Aquifer TDS, and an additional permeate production need of 2.33 MGD at the Sawgrass Water Treatment Plant. Based on these computations and analysis, depending on the well yield and water quality, there is an optimal point within the area of consideration where blending proves a cost benefit.

Summary and Conclusions

An unexpected consequence of blending the NFC and FAQ waters was the high rate of fouling observed on the membrane surface. The blended feed to the pilot plant had concentrations of TOC and iron similar to the second stage of the Sawgrass Water Treatment Plant, but the rate of fouling was significantly higher.

The high rate of fouling required that CIPs be performed in the middle of scenarios

Continued on page 54

Continued from page 53

much more frequently than originally anticipated. CIPs were performed using both caustic and acidic solutions to remove foulants and to return permeability and differential pressure to baseline conditions; however, because of the nature of the fouling, the CIPs were not always successful in fully recovering permeability or differential pressure. This situation required replacement of membranes three times during the pilot study. This rate of fouling, especially irreversible fouling, would not be acceptable at full-scale operation.

During the pilot study, 11 different scenarios were evaluated, varying feedwater blend, recovery, pH, and chemical addition. This information is summarized in Table 4, which shows the conditions that provided stable operation during the pilot study.

All of the successful scenarios utilized pH adjustment to maintain a pH of 5.5 or less. This minimized fouling from sparingly soluble salts and from TOC. Chemical addition of sodium metabisulfite (Scenario 9) and organic dispersant (Scenario 11) were used successfully to minimize fouling from insoluble iron and TOC, respectively; however, because of the short runtime of Scenario 9, this solution cannot be recommended without further testing.

High fouling rates also could be avoided by minimizing the percentage of NFC in the combined blend. Based on Scenarios 7 and 10, the maximum percentage of NFC that could be used without the need for additional chemicals was 15 percent.

Other non-cost comparative factors should be taken into account while considering blending. Some of these factors are monthly manual cleans, a high need of operational attention, performance uncertainties of blend ratio under consideration for a second-stage membrane process, and the risk of using multiple Floridan wells at this specific site.

A comparative analysis consisting of both a cost and non-cost suite of parameters should be considered by the city before moving forward with a blending process using FAQ water and NFC or a pure RO process using FAQ water as source water at this site.

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