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Supplementing Drinking Water Sources by Brackish Water Desalination

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Abstract

The City of Palm Coast has traditionally relied on the surficial or intermediate Floridian Aquifer for meeting its drinking water demand. In order to reduce over-usage of this environmentally sensitive source, the deeper brackish water Floridian aquifer was identified as an alternate source. A 2½ - month pilot study was conducted to evaluate the feasibility of using reverse osmosis to treat the brackish water to acceptable drinking water quality. The results of the study indicate that the brackish water source can be effectively treated to safe and aesthetic drinking water quality standards. The City can further minimize finishing chemical costs by blending brackish water RO permeate and untreated surficial aquifer in a 3:1 ratio.

Background of the Study

The two main sources of water were the environmentally sensitive (and relatively clean) surficial aquifer. The surficial aquifer is desirable from the treatment point of view due to its low dissolved solid content. However, increased growth and subsequent demand for drinking water in this rapidly growing community has spurred the need for

utilizing alternative drinking water sources. The alternative source identified was the deeper brackish water aquifer. The brackish aquifer is characterized by high dissolved solids and chloride content. The high chloride in this source necessitates the use of reverse osmosis desalination as opposed to nanofiltration softening.

CPH Engineers Inc., was the chief contractor for the project and responsible for the management and oversight of the pilot operations. The City provided trained personnel from the Palm Coast Utilities to help in daily monitoring, sampling and maintenance of the pilot unit and upkeep and security of the pilot site. Though the initial planning and preparatory groundwork for the pilot started much earlier, the actual pilot study commenced on 12/16/04 and ended on 3/1/05

The main design objectives of the pilot study were to

1. optimize the usage of both the surficial and brackish water sources,
2. minimize the usage of chemical feeds for pre-treatment and post-treatment, and
3. to have a finished water quality as close to the historical distribution system water quality to avoid corrosion related problems.

Description of Pilot Study

The pilot study was conducted at the same site as the planned site for the City of Palm Coast's third water and wastewater treatment plant. The site is located on US Highway 1 and 3 miles north of the Palm Coast Parkway and US 1 intersection. The site was cleared to provide access to drilling equipment, pilot equipment and access vehicles for sampling and maintenance.

The brackish aquifer well (Well #1) was a 12-inch production well drilled to 400 feet depth. The shallow aquifer well (Well #2) was a 4-inch observation well drilled to 80 feet depth. Both the wells were capped and airtight connections to the pilot unit were constructed to prevent external contamination or aeration of the RO feed waters.

The total dissolved solids (TDS) of the brackish aquifer were approximately 1800 mg/L and varied from 1700 – 1900 mg/L. The major TDS ions were chlorides, sulfates, total alkalinity, sodium, calcium, magnesium and silica. Many metals like aluminum, antimony, barium, beryllium, cadmium, chromium, copper, iron, manganese, mercury, nickel, selenium, silver, strontium, thallium and zinc were detected in very low

concentrations or were below the method detection limit. The regulated organic compounds were below the detection limit. Hydrogen sulfide in the brackish aquifer varied from 4.0 – 8.1 mg/L as S indicating hydrogen sulfide treatment would be required for the permeate and concentrate streams. The silt density index of the brackish aquifer was consistently below 1, which indicated the suitability of the source water for RO treatment.

The range of the shallow aquifer TDS was 390 – 420 mg/L. The major TDS ions were alkalinity, calcium and silica. Chlorides and sodium were relatively low compared to the brackish aquifer. The source water quality is shown in Table 1.

The pilot reverse osmosis system (contracted from Harn R/O, Florida) consisted of pretreatment acid and scale inhibitor chemical injection, cartridge filtration, well boost pump, high pressure feed pump, pressure vessels, RO membrane elements, instrumentation, controls, and inter-stage booster pump. The design utilized pressure vessels that contain the equivalent of seven membrane elements per pressure vessel staged in a 2-1, two-stage array.

Several pre-pilot computer aided design simulations were conducted for evaluating the membranes on the two sources and analyzing the design for pre-treatment, scaling, operating pressures and quality of permeate. The City desired that pre-treatment with acid addition be limited due to safety concerns and operational simplicity. Therefore, the pilot operations were designed to have only pre-filtration and antiscalent addition as pre-treatment. Based on these design and operational requirements, an appropriate membrane designed for brackish water desalination and capable of significant removal of monovalent ions was selected. The selected system configuration for the pilot study was a two-stage process with a 2:1 configuration. The first stage had two pressure vessels with 7 elements each and the second stage had one pressure vessel with 7 membrane elements. The concentrate stream for the first stage served as the feed stream for the second stage. The permeate streams from the first and second stages were mixed to produce the final permeate stream. The system recovery was 75 – 80% for all cases. The feed flow was set at 24 gpm, which corresponded to a flux of 15.5 gsfd.

Table 1: Average historic, surficial source, brackish source, RO permeate and RO concentrate water quality.

Parameter	Units	Historic Distributed WQ	Brackish Well #1	Surficial Well #2	System RO Permeate	System RO Concentrate
Arsenic	mg/L	0.003	< 0.07	< 0.07	< 0.07	< 0.07
Bromide	mg/L		0.190	< 0.078	< 0.078	
Calcium	mg/L	33	173	110	0	856
Copper	mg/L	0.0014	< 0.0071	< 0.0071	< 0.0071	< 0.0071
Heterotrophic Plate Count	cfu/ml		150.0	15.0	< 1	
Iron	mg/L	0.003	< 0.16	0.18	< 0.16	< 0.11
Lead	mg/L	0.0011	< 0.0092	< 0.0092	< 0.0092	< 0.0092
Magnesium	mg/L	9	98	5	0	492
Manganese	mg/L	0.0038	< 0.0022	0.0274	< 0.0022	0.0076
Nitrate (as N)	mg/L	0.004	< 0.014	< 0.014	< 0.014	< 0.014
Nitrite (as N)	mg/L	0.003	0.015	0.014	0.014	0.015
pH (Field)	pH Units	8.24	7.3	7.1	6.3	7.8
Silica as SiO_2	mg/L		21	36	0	101
Sodium	mg/L	33	304	21	14	1411
Sulfate (as SO_4)	mg/L	17	390	5	5	1900
Sulfide (as S)[**]	mg/L		6.67	0.02	7.75	4.28
Total Alkalinity (as $CaCO_3$)	mg/L	80	150	283	7	740
Total Chlorides	mg/L	48	675	36	21	3056
Total Coliform	cfu/100ml		< 1	< 1	< 1	
Total Dissolved Solids	mg/L	230	1778	410	44	8350
Total Organic Carbon[**]	mg/L	10.0	6.9	7.2	< 0.73	31.0
True Color	CPU	11	16	17	1	84

[**] The laboratory quality controls were not met for the TOC and sulfide

analysis

In order to avoid corrosion, red water and dissolution of existing films or chemical scales in the City's distribution system due to introduction of chemically incompatible waters, it was necessary to produce chemically balanced blended water. This was most easily achieved by blending the RO permeate stream with water from the surficial aquifer. Simulations were conducted to evaluate the optimum blend of the brackish aquifer's RO permeate and the surficial aquifer that would produce water quality that was similar to the existing distribution system water quality. In all the blending discussion, 100 % of the RO permeate stream is used for blending. It should not be inferred that only 72 % of the RO permeate stream is utilized.

It can be observed from Figure 1 that the blend of 25% surficial aquifer and 75% RO permeate is suitable to achieve a blended calcium hardness that is historically similar to the existing distribution system water quality. Similarly as shown in Figure 2, a blend ratio of 25 % surficial aquifer to 75 % RO permeate stream also produces optimum alkalinity. As lower concentrations of sulfates and chlorides are desired, chloride and sulfate water quality is improved by blending as the blended water at 1/3 ratio of surficial aquifer raw water to RO permeate stream produces lower chlorides and sulfates than the historical distribution system water quality.

The pilot was operated in three phases for assessment of water quality and operational criteria for different modes of operation. The different phases were:

Phase 1: two months of operation with Well #1 as feed source for RO treatment at 80% recovery and post-RO blending of permeate with Well #2.

Phase 2: one week of operation with Well #1 as feed source for RO treatment at 75% recovery and post-blending of permeate with Well #2.

Phase 3: one week of operation with Well #2 as feed source for RO treatment at 75% recovery and post-blending of permeate.
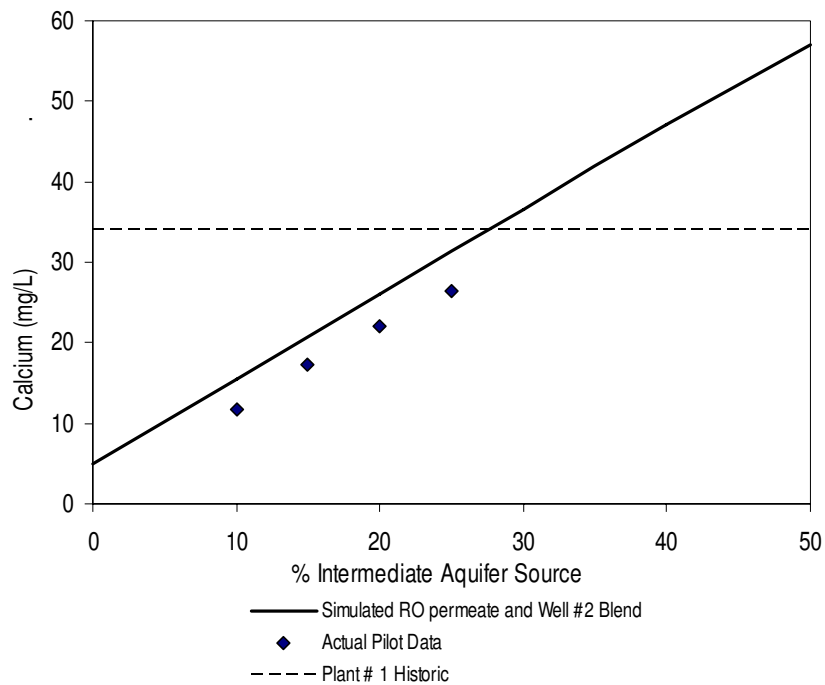
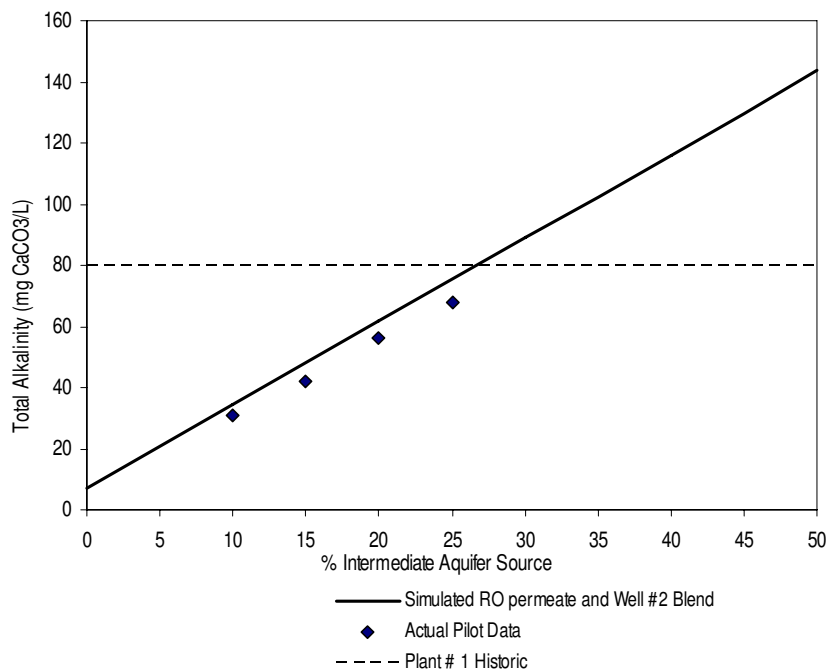Figure 1: Simulated and actual blend calcium for pilot RO softening

Figure 2: Simulated and actual blend total alkalinity for pilot RO softening
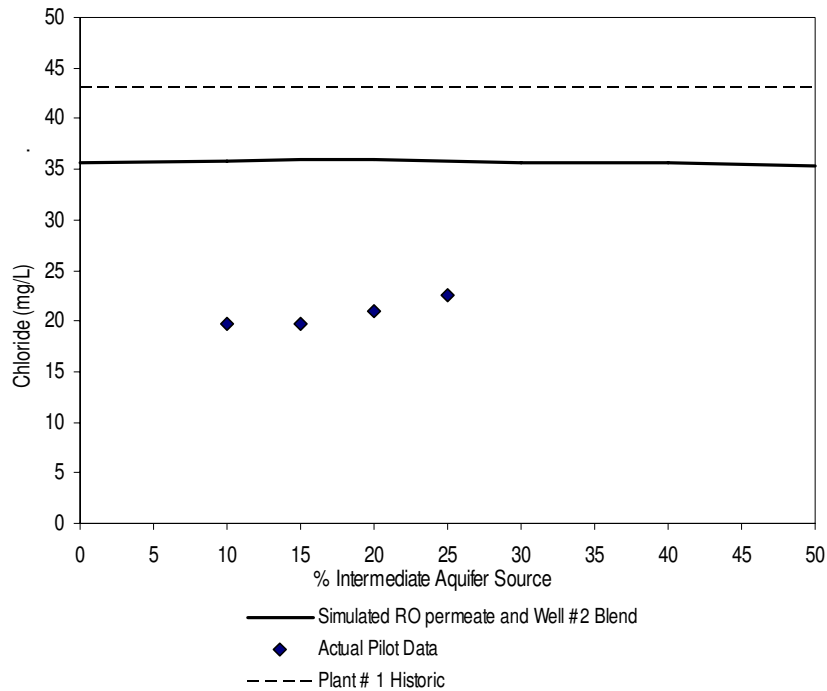
Figure 3: Simulated and actual blend chloride for pilot RO softening

Phase 1 operational conditions were determined as optimum by manufacturer recommendations and computer simulation. Hence, Phase 1 operation was conducted for two months, which was the longest period of operation for any phase. Operational conditions for Phases 2 and 3 were conducted to evaluate the operational flexibility of the RO plant. A one week period of operation was utilized in Phase 3 and again in Phase 3. Under Phase 1, the pilot unit was operated continuously (with scheduled stops for generator maintenance) for a period of two months. The system recovery was set at 80%. The operational and system parameters for the three phases are shown in Table 2.

During Phase 2, the system recovery was reduced to 75%. During this phase the flux was increased such that the permeate production would be similar to Phase 1.

In Phase 3 the feed water source was switched to Well #2 (intermediate aquifer source). The system recovery was 75% as this is the highest non-scaling recovery that can be achieved due to high silica in the intermediate aquifer source. The intermediate aquifer is not envisioned as a permanent source for RO treatment. However, it is included as part of the pilot study since the City desired to have the flexibility of using both the sources during initial start-up.

Table 2: Average operational parameters for pilot phases

Parameter	Average		
	Phase 1	**Phase 2**	**Phase 3**
Run Time	2 Months	1 Week	1 Week
Temp	23.5	23.2	21.9
SDI	0.7	0.6	0.7
Flows (gpm)			
Feed	23.5	25.7	23.9
System Permeate	18.7	19.3	17.9
System Concentrate	4.8	6.4	6.0
Well #2 Blend	6.3	6.3	
Total Treated (Permeate + Blend)	25.0	25.6	17.9
Pressures (psi)			
Stage 1 Feed	98	108	76
Stage 2 Boost Feed	148	121	113
System Concentrate	136	107	98
System Permeate	6	6	4
Conductivities (umhos/cm)			
Feed	2940	2919	663
System Permeate	86	70	12
System Concentrate	12088	9765	2289
Total Treated (Permeate + Blend)	235	229	
System Parameters normalized and corrected to 25 C			
System Recovery	0.80	0.75	0.75
System Salt Passage	1.12	0.93	0.83
System Flux (gsfd)	15.4	16.0	15.5
System Pressure Differential (psi)	29	28	31
System Water Transport Coefficient (gfd/psi)	0.28	0.28	0.24

The pilot was operated on a continuous basis for a period of 2.5 months. Out of 2.5 months the system operated normally for 93% of the time. The pilot was not operational for 4% of the time due to planned shutdowns for generator maintenance and plumbing changes to the system. The remaining 3% of the time the pilot was shutdown to repair and replace a malfunctioning generator. There was no shutdown due to actual pilot malfunction or breakdown. The operating parameters for the pilot under the three phases are listed in Table 2. The system recoveries for the period of pilot operation are shown in Figure 4. The recoveries and fluxes were stable during the first two months of operation (Phase I). Rapid variations are seen in the recoveries and fluxes during the smaller phases (Phase II and Phase III). This is due to a relatively rapid frequency for changing recoveries that resulting in a non-steady conditions. The recoveries were changed back to

Phase I conditions to conduct sampling for acute toxicity tests for the concentrate stream. This change is reflected in the graphs for recoveries and fluxes. The decline in the normalized water transport coefficient indicates that the system will have achieved a 15% flux decline in 100 days (Figure 5). This implies that the cleaning frequency for the pilot system would be over 3 times annually.

The permeate water quality analysis indicated greater than 99% removal for most contaminants in the source water. Chlorides and sodium comprised the major portion of the dissolved solid content in the permeate water. The sulfide content in the permeate is high as expected since RO or NF membranes do not reject H_2S. However, the analytical technique used by the professional laboratory for sulfides was inaccurate and therefore an exact measure of the sulfide concentration in the permeate is not known. It can be safely assumed that based on the source-water pH of 7.3 at least 50% of the sulfides from the source will be present in permeate. There was little difference in permeate water quality at 75% and 80% recovery with Well #1 as the RO source.
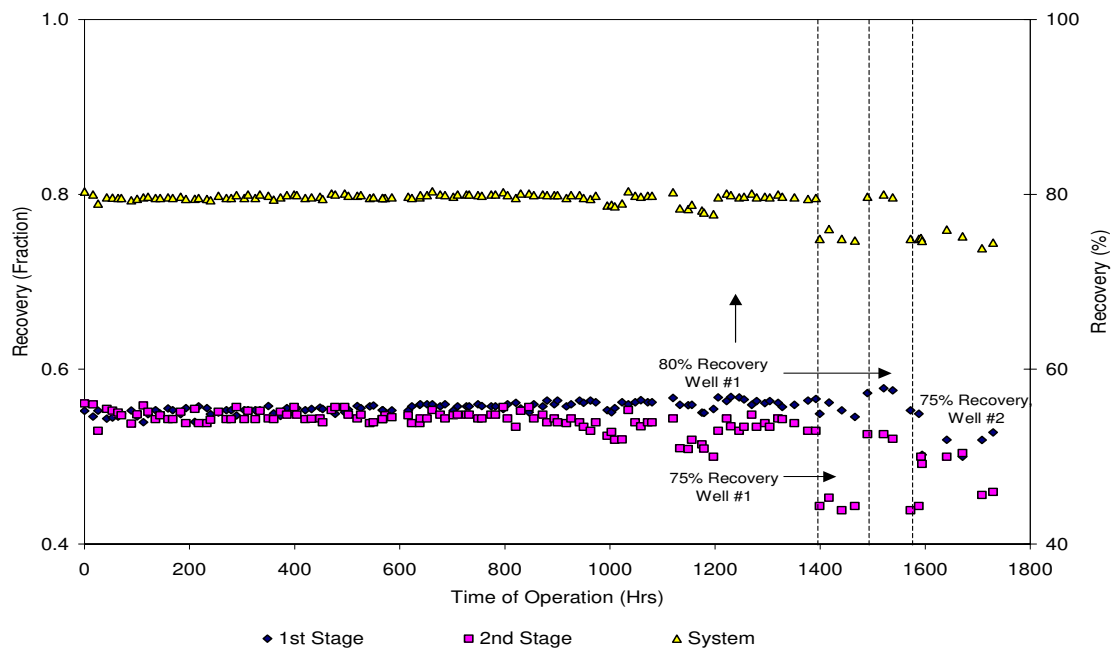

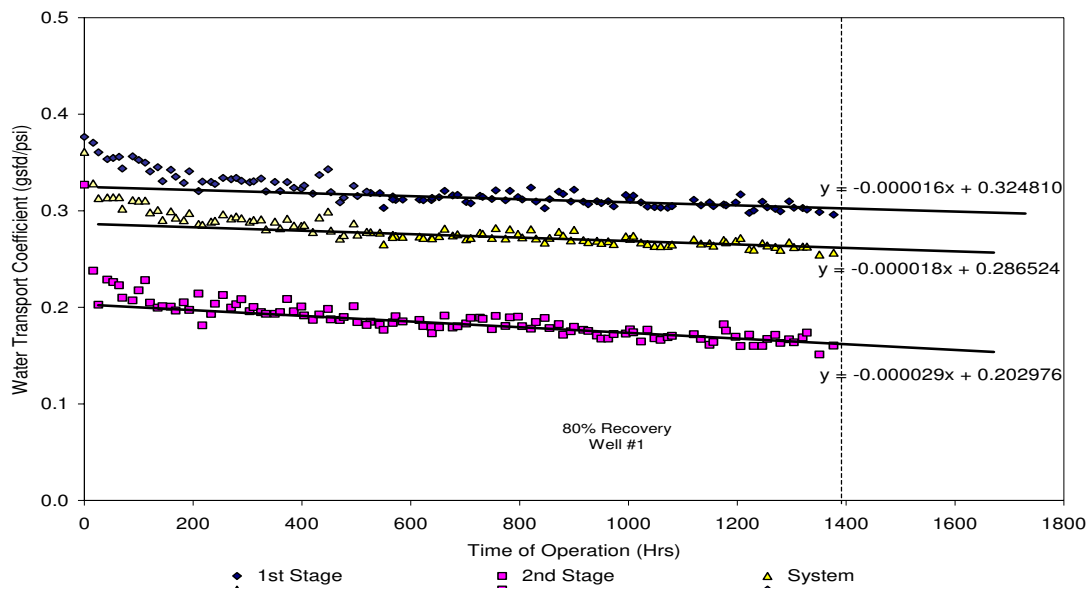Figure 4: System, Stage 1 and Stage 2 recoveries during pilot study

Figure 5: System, Stage 1 and Stage 2 linear trends of decline in water transport coefficient
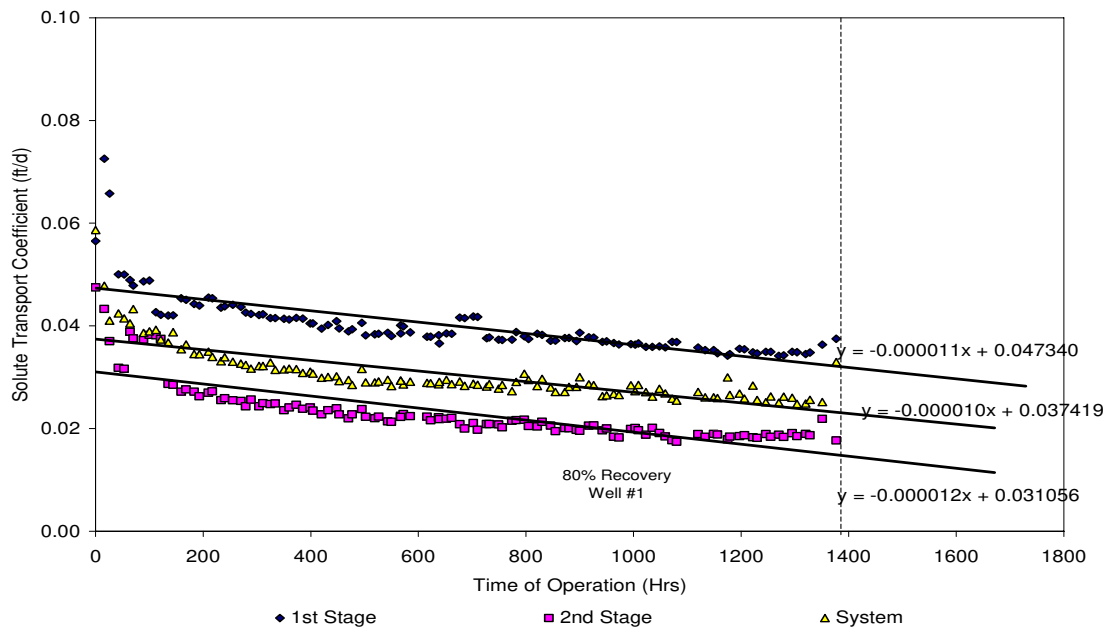

Figure 6: System, Stage 1 and Stage 2 linear trends of decline in solute transport coefficient

The main purpose of evaluating the concentrate water quality was to determine the feasibility of different disposal alternatives. Therefore a comprehensive list of potential contaminants was analyzed in the concentrate stream. As expected, the concentrate stream had high dissolved solids consisting of primarily chlorides, sulfates, calcium, magnesium, sodium and alkalinity. Most of the heavy metals, with the exception of strontium, were either in low concentrations or below the detection level.

Mass balance was conducted around selected water quality parameters for system pilot operations using Equation 1. Due to pilot operations paired data was not always available for conducting mass balance. Only paired data, where available was used for these calculations. Another complicating factor was that most heavy metals were at or below detection limits in both the permeate and feed water. Due to the high degree of error associated with measurements in very low concentrations it is not feasible to have meaningful inference from such data. Therefore, only selected parameters were used in this report. A summary of these mass balances for the selected parameters is given in Table 3. The solute mass balances are indicative of the accuracy of the field and laboratory data. Values between 86 and 116 are typical for pilot studies.

$$\text{System percent mass recovery} = \frac{100 \times \left[Q_p C_p + Q_c C_c \right]}{Q_f C_f} \qquad \text{Equation 1}$$

Table 3: System percent mass recovery

Parameter	Average Mass Recovery (%)	Std. Dev. (%)
Total Alkalinity	104.2	6.9
Calcium	102.2	6.8
Chlorides	95.5	9.5
Magnesium	104.9	8.7
Silica	99.1	6.8
Sodium	99.8	9.3
Sulfate	101.1	11.1
TDS	102.7	2.7

In order to address the Utilities concern that the sufficient quantity of surficial aquifer may not always be available due to seasonal or demand dynamics, different

percentages (10, 15, 20 and 25%) of surficial aquifer water was blended with the RO
permeate to evaluate the optimum blend percentage as well as to estimate the amount of
post-treatment chemicals that would be needed to have an acceptable water quality. This
was achieved in the field by changing the flow rate of the surficial aquifer blend to
correspond to the required blend percentage and then sampling for selected water quality
parameters (calcium, alkalinity, chlorides and sulfates etc.).

The goal was to have a water quality similar to the historic water quality. Water
quality parameters considered critical for this evaluation and their levels at different
percentages of blending are given in Table 4. The water quality of the blends was similar
to the predicted water quality from the desktop simulations as shown in Figure 1, Figure
2 and Figure 3. From an operational viewpoint, the optimum blend as defined by
producing a finished water by blending the surficial aquifer with the RO permeate stream
following treatment of the brackish aquifer would be 28% of surficial aquifer blended
with 72% of reverse osmosis permeate.

Table 4: Blended product water quality for different blend ratios

			(Blended Water Quality) % Well #2 Blended with RO Permeate			
Parameter	Units	Historic Plant #1	25%	20%	15%	10%
Calcium	mg/L	33	27	22	17	12
Magnesium	mg/L	9	1	1	1	1
Sodium	mg/L	33	13	14	13	13
Total Alkalinity (as CaCO3)	mg/L	80	68	56	42	31
Total Chlorides	mg/L	48	23	21	20	20
Sulfate	mg/L	17	6	7	8	8
Total Dissolved Solids	mg/L	230	125	110	94	70
pH (Field)	pH Units	8.24	6.8	6.5	6.5	6.4

Conclusions and Recommendations

➢ Reverse osmosis treatment is applicable to the desalination of the brackish water from deeper Floridian aquifer source. High removal of dissolved solids like calcium, alkalinity, magnesium, chloride, sulfate, sodium and other heavy metals was achieved.

➢ Blending with the surficial Floridian aquifer source provided a means of stabilizing the reverse osmosis permeate with respect to calcium carbonate and alkalinity.

➢ The selected membrane has high cleaning frequency (100 days) as evaluated from the flux decline. The normalized flux decline should be monitored closely during the first phase of operation to determine the cause of the increased cleaning frequency.

➢ The permeate and the blended waters meet the primary and secondary water quality standards. However, taste and odor tests are needed to determine the aesthetic water quality. The finished water needs to be treated for sulfide removal, dissolved oxygen content, pH elevation and chloramination.

➢ The full-scale facility should be operated at or below 80% recovery due to potential for fouling by silica.

➢ The optimum blend determined from simulations and pilot study are 25-28% surficial aquifer blended with 75-72% reverse osmosis permeate.

Recommendations for Full-Scale Plant

It is proposed to develop the ultimate 9 MGD production in three phases of 3 MGD each. Therefore, during the first phase of construction the design is only for a 3 MGD capacity. Additional capacity will be installed in multiples of 3 MGD. Table 5 gives the recommended flows, pressures and system configuration for the full-scale unit.

Table 5: Design flows, pressures and system configuration for full-scale plant

Parameter	Average	
	80% recovery (Deeper Floridian Aquifer Source)	75% recovery (Deeper Floridian Aquifer Source)
Flows (MGD)		
Deeper Floridian Aquifer Feed	2.82	3.01
Stage 1 Permeate	1.57	1.66
Stage 2 Permeate	0.67	0.60
System Permeate	2.24	2.26
Stage 1 Concentrate	1.25	1.35
System Concentrate	0.58	0.75
Surficial Aquifer Blend	0.76	0.74
Total Treated (Permeate + Blend)	3.00	3.00
Pressures (psi)		
Stage 1 Feed	128	138
Stage 1 Concentrate	111	122
Stage 2 Boost Feed	178	151
System Concentrate	166	137
System Permeate	30	30
System Design		
Number of Stages	2	2
Array Configuration	2:1	2:1
Element Selected	XLE-440	XLE-440
Surface Area of Element	440 ft^2	440 ft^2
Average Flux	15.4 gsfd	16.0 gsfd
Number of Pressure Vessels in 1st Stage	32	32
Number of Elements per Pressure Vessel	7	7
Number of Elements in 1st Stage	224	224
Number of Pressure Vessels in 2nd Stage	16	16
Number of Elements in 2nd Stage	112	112
Total Number of Membrane Elements	336	336