City of Boca Raton's NF Plant: A Plant History

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Abstract

The City of Boca Raton in Florida has operated a 40 mgd NanoFiltration (NF) Water Treatment Plant since August 2004. It was built for $55 million dollars and was designed to meet the more stringent Disinfection By-Products (DBPs) requirements of the Safe Drinking Water Act, improve the blended water goal of less than 6 color units (CU), and maintain sufficient hardness levels of 60-90 mg/l as CaCO3 for purposes of taste and corrosion control. Four years of pilot testing were required to create the optimal design which uses no pretreatment chemicals, to determine maximum recovery rates while controlling the rate of fouling so cleaning frequencies were optimized, to determine the need for multimedia pressure filters, and to determine the need for well field rehabilitation. The original design included two Brine Recovery NF trains which could be used to either increase plant recovery from 82-85% to 92% or function as a Primary NF train. The pilot also determined that the best membrane was a then state-of-the-art low fouling NF membrane, which started up at 80-83 psi feed pressure and 300 uS (micro-Siemens) permeate quality. This design eliminated the need for sulfuric acid and antiscalant for annual cost savings of over $1 million dollars per year while maintaining cleaning frequency to only 2-4 times per year.

The original membranes lasted ten years and were successfully replaced in early 2015 with the next generation of low fouling NF membranes. The new low fouling NF elements started up at only 63 psi for an initial 24% energy savings. These energy savings are attributed to lower pressure (higher flux) membranes and a 50% reduction in the feed-to-concentrate pressure drop.

1.0 Introduction

In May 1999, the City of Boca Raton began design of a 40 million gallon per day (mgd) capacity nanofiltration (NF) process addition to the City's existing 70 mgd conventional lime softening process at the Glades Road Water Treatment Plant.

The primary objective of the project was to maintain continued compliance with the disinfectant/disinfection by-product (D/DBP) rule (i.e., reduce total trihalomethanes (TTHMs) and haloacetic acids (HAAs), and improve the level of service to the Boca Raton customers by significantly improving the color in the blended finished water. A second goal established by the City for the project was to eliminate the need for acid pretreatment for the membrane process due to cost considerations as well as the logistical and safety concerns associated with handling the quantities of acid that would be needed for a plant of this size. Through extensive design-phase pilot testing, coupled with the development of new low-fouling membrane technology by the membrane element manufacturer (Hydranautics) the design team, led by CDM Engineers, was able to demonstrate stable operation of the membrane process without acid or antiscalant pretreatment.

The start-up phase for the NF process was initiated in August 2004. Due to the large size of this facility, and the fact that it was starting up without chemical pretreatment, the construction contract provided for a cautious, phased start-up program. Start-up of the process was planned to take place one unit at a time over a six-month period. The full 40-mgd capacity was scheduled to come on line with the start-up of the twelfth and last skid.

From the initial start-up in 2004, through 2015, the NF process exhibited stable operation with no chemical pretreatment, meeting all of the original water quality goals established by the City for the project. In 2013, the City began preparing for routine replacement (including upgrading) of the membrane elements for the NF plant. The City retained McCafferty Brinson Consulting, LLC, with consultant William B. Suratt, P.E., to assist with pilot testing, preparation of technical specifications, and other engineering and technical services associated with replacing the NF membrane elements. Similar to the original NF elements, the City procured the replacement NF elements directly from Hydranautics. Membrane replacement was completed in a staged fashion to enable the NF element manufacturer to adjust the membrane manufacturing and element selection based on feedback of full-scale testing data collected from the first units loaded and tested.

Membrane replacement for the full 40-mgd process has been completed, and the plant is achieving all water quality goals established for the project. The plant continues to operate with no acid or antiscalant pretreatment, and initial data reflect a substantial savings in operating power cost.

2.0 Background

The City's existing raw water supply is from three shallow (100 to 200 feet in depth) Biscayne aquifer wellfields. Table 1 presents a representative analysis of the raw water supply.

Table 1. Raw Water Analysis

Constituent/Parameter	Value
Total Hardness	250 mg/L as $CaCO_3$
Alkalinity	214 mg/L as $CaCO_3$
Total Dissolved Solids (TDS)	450 mg/L
Color	50 color units
Total Organic Carbon (TOC)	12 mg/L
Humic Acid	10 mg/L
pH	7.2

As noted above, the overall objective of the facility design was to maintain continued compliance with the D/DBP rule, and significantly improve the color in the blended finished water. Table 2 summarizes the key blended finished water quality goals, as the basis for the membrane process design.

Table 2. Blended Finished Water Quality Goals

Constituent/Parameter	Value
Total THMs	<0.064 mg/L
Five HAAs	<0.048 mg/L
Color	<6 CU
Total Hardness	60 to 90 mg/L as $CaCO_3$

Other major design objectives included:

- Provide separate third stage units to increase the process recovery rate above the "traditional" rate of 85% to approximately 92%. This objective was a result of a hydraulic capacity limitation during periods of peak wastewater flows on the City's existing wastewater effluent ocean outfall, which is used for concentrate disposal. The city has since installed piping so that the concentrate can be directly blended with the city's WWTP reuse storage and distribution system.
- Reduce or eliminate the use of acid for raw water pretreatment. This goal was established due to cost considerations as well as the logistical and safety concerns associated with handling the quantities of acid that would be needed for a plant of this size. In pilot testing during both the original design and the 2014 membrane element replacement, it was demonstrated that the selected membranes could be successfully operated for extended periods (in excess of 90 days) with no chemical pretreatment (acid or antiscalant), without significant fouling.
- Provide a permeate quality meeting a relatively narrow hardness "window" of 50 to 80 mg/L as $CaCO_3$. Hardness in this range is considered optimum, resulting in moderately soft water while maintaining sufficient hardness to avoid corrosion control concerns. This range of hardness also avoided concentrating the hardness and other foulants in the feed water as much as "tighter" conventional nanofilters.

This helped the plant operate without chemical pretreatment. Based on the results of full-scale, long-term operation from 2004 to 2013, the City decided to slightly modify this specification for the replacement membranes, revising the specified window to 60 to 90 mg/L as $CaCO_3$.

3.0 Process Description

The nanofiltration process operates in parallel with an existing 30 mgd lime softening plant, with the product water from the two facilities blended at a 2:1 permeate:lime softened water blending rate. Figure 1 presents a schematic of the lime softening and nanofiltration processes.

Figure 1. Glades Road Water Treatment Plant Process Schematic

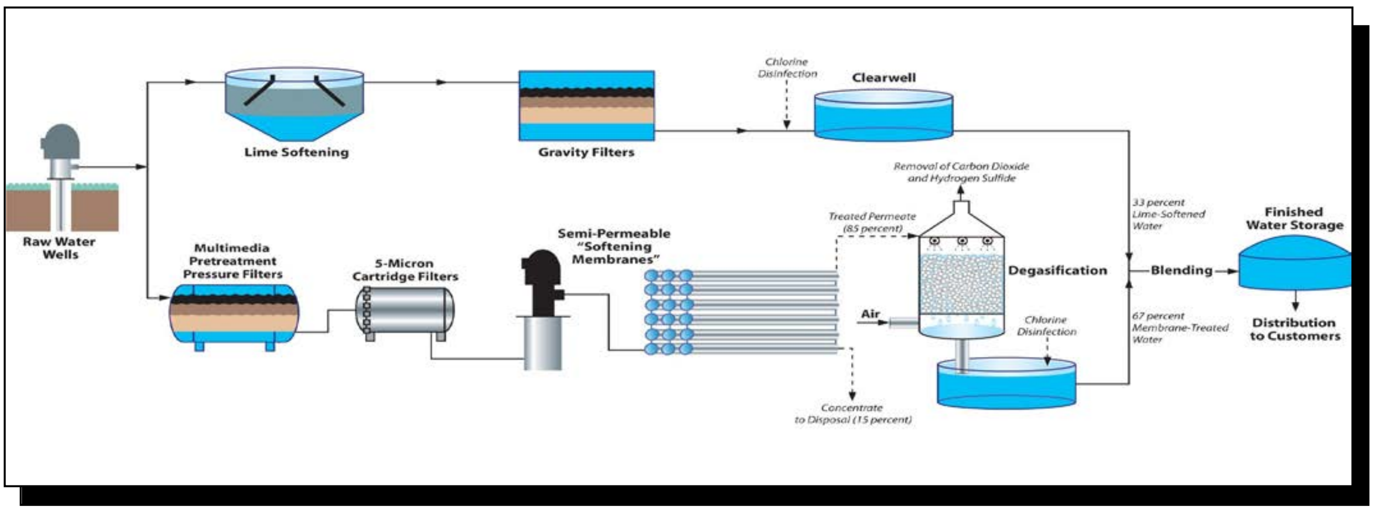


Figure 2: Glades Road Water Treatment Plant Physical Layout:

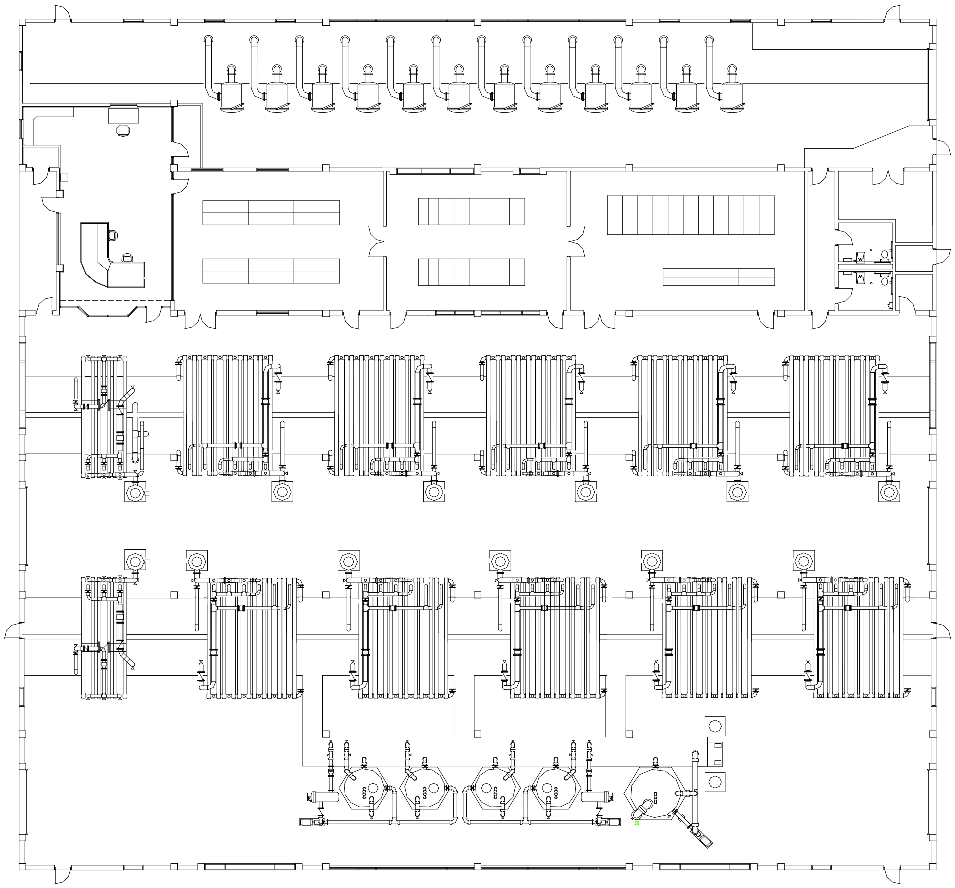


Table 3 presents the general design parameters for the membrane treatment process.

Table 3. General Design Parameters for Full-Scale Nanofiltration Process

Design Paramter	**Stage 1&2 Units (Units 1 through 10)**	**Convertible Units (Units 11 and 12) 3rd Stage/Two-Stage Mode**
Capacity	36.76 mgd	3.24 mgd
Recovery Rate	85 %	50 % / 85 %
Raw Water Feed	43.2 mgd	6.48 mgd / 3.81 mgd
No. of Skids	10 x 3.676 mgd	2 x 1.62 mgd
Array	72:36	54 / 36:18
No. Elements per Vessel	7	7
Flux Rate	12.2 gfd	10.7 gfd / 10.7 gfd
Transmembrane Pressure	80 psi	100 psi / 80 psi

The membrane process design consists of the following:

- Six constant speed, horizontal split case raw water booster pumps

- A pretreatment sand filter pressure filter system
- Twelve cartridge filters
- Ten 3.676 mgd capacity stage 1&2 membrane units
- Two 1.62 mgd capacity convertible membrane units. These units can be operated either as two-stage, 85% recovery units using raw feedwater from the wellfield, or as third-stage "concentrator" units, operating at 50% recovery using concentrate from the other ten membrane units as feedwater.
- Two independent membrane cleaning systems
- A permeate flush system to displace the concentrated feedwater in the membrane unit with permeate upon shut-down of the unit
- Caustic storage and feed system. Antiscalant and sulfuric acid have been removed.
- Six 6.67 mgd capacity degasifiers.
- Two packed tower odor control scrubbers

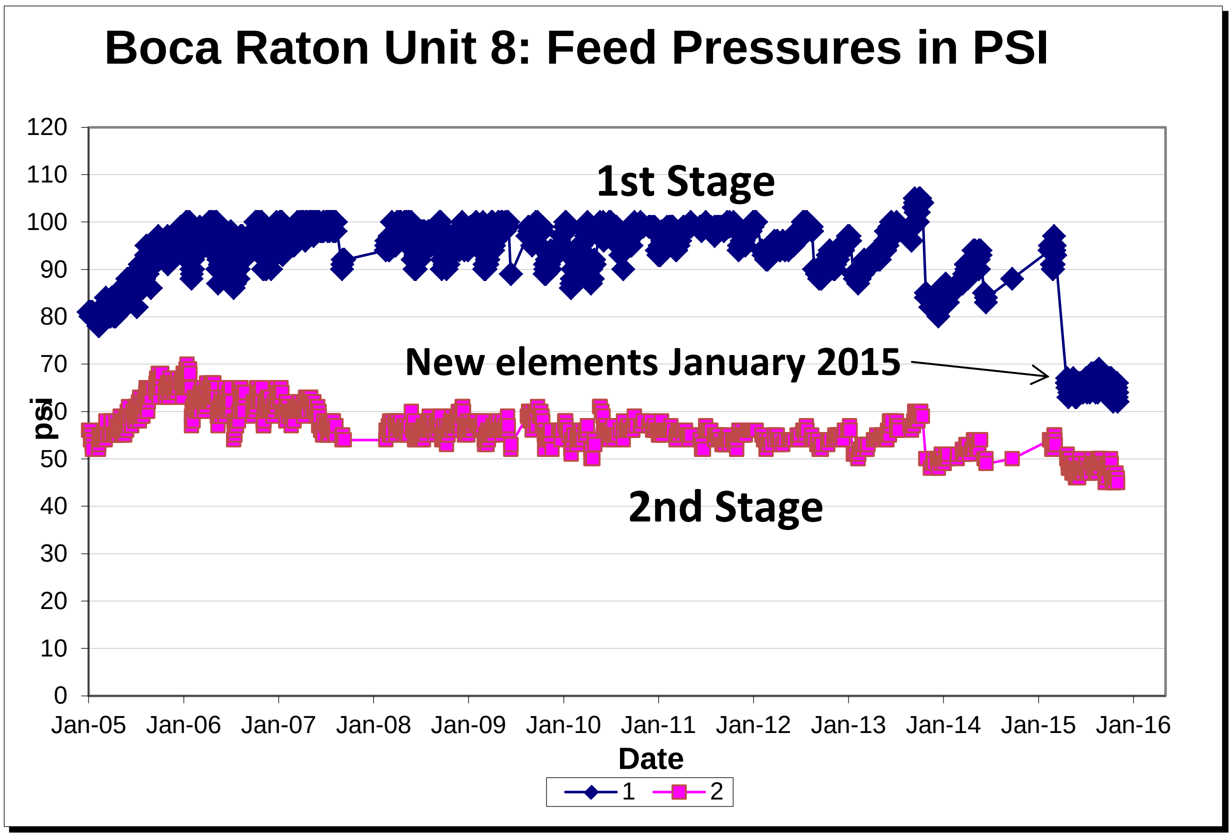
The degasified permeate drops from the degasifiers into a clearwell below. Sodium hypochlorite, corrosion inhibitor, and caustic soda are fed to this clearwell for disinfection, pH adjustment, and corrosion control. Three new transfer pumps are installed at the end of the clearwell to pump the membrane permeate to the on-site finished water storage tanks. Blending of the membrane permeate and lime softened water and addition of ammonia takes place in the common transfer line from the existing transfer pumps, to the on-site finished water storage.

4.0 NF Plant History with 1st Set of NF Membranes

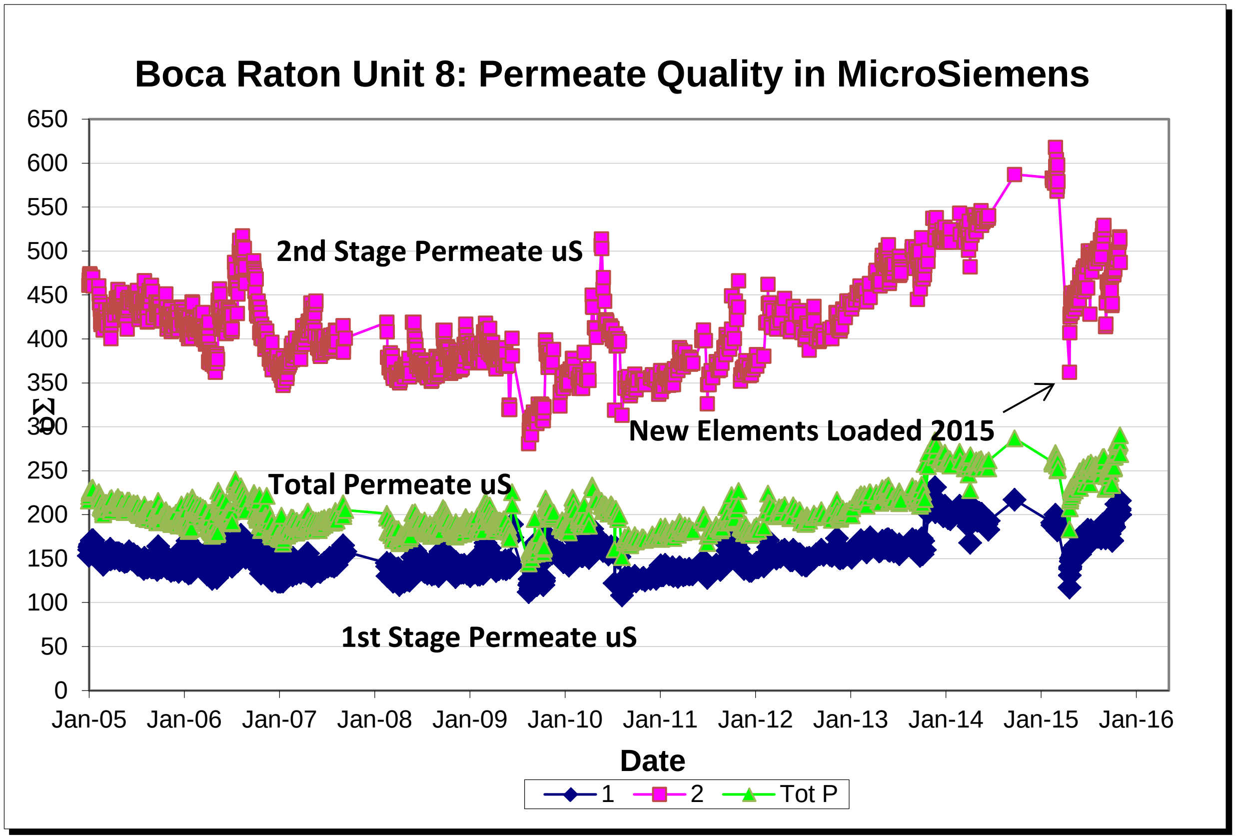
This plant in 2004 used a 3rd generation NF membrane model ESNA1-LF2 which offered the lowest feed pressure available at that time. The 1st generation model of NF was a model PVD1 membrane casted with a polyvinyl alcohol derivative and was introduced in 1988. The 2nd generation model of NF was a model ESNA1-LF membrane casted with a composite polyamide polymer in 1996 which offered lower feed pressure and better permeate quality for hardness, alkalinity, iron, TDS, TOC all other ions. This 3rd generation of ESNA1-LF2 NF membrane was started up in August 2004 and operations over the years has been typically smooth with a low level fouling rate which allowed for predictable cleanings a couple of times per year. During initial commissioning in 2004, a sand exposure occurred one time. All of the exposed elements, which were limited to the 1st stage lead elements, were removed and consolidated in Unit No. 1 to prevent the potential migration of sand downstream which could scratch the membrane surface and adversely impact downstream elements. During their tenure they were exposed to colloidal material during wellfield upsets, to ongoing organic materials concentration, and to multiple annual cleanings.

After 10 years of use the feed pressures had climbed from 80 psi to over 100 psi as noted in Graph 1 below and the permeate quality had increased from about 200 to 275 uS as noted in Graph 2.

Graph 1: Boca Raton Unit 8 Feed Pressures from 2005 to 2015



Graph 2: Boca Raton Unit 8 Permeate Quality in MicroSiemens



The City chose to replace the first set of ESNA1-LF2's with the 4th generation of ESNA1-LF2-LD's after 10 years of successful operation The primary reason was to start the benefit of the operating cost saving associated with reduced feed pressure and the associated electrical cost savings. The permeate quality of the existing membranes was not a consideration for the change out. Hydranautics had made improvements in its NF membrane technology with lower pressures due to improvements in the chemistry and manufacturing of the membrane and in a 50% reduction in pressure drop (delta P) from the feed-to-concentrate flow path using a 34-mil feed spacer and still maintaining 400 square feet of membrane area per element.

5.0 NF Membrane Replacement Contract and Startup

The membrane replacement contract provided for the direct purchase of the selected membranes from Hydranautics by the City. This contract required a separate 7-day full-scale performance test of each of the ten Stage 1 and 2 membrane units (the City did not replace the membranes in the two smaller membrane units). The key permeate quality and quantity parameters required in the membrane procurement documents are summarized in Table 4. In general, the requirements for each performance test included continuous operation for 7 days, producing permeate meeting the specified permeate quantity and quality, without exceeding the specified maximum transmembrane pressure of 80 psi. For each performance test, operating data were collected either continuously or on a daily basis and water quality analytical data were collected weekly over the 7-day test period for each unit. At the conclusion of each performance test, a report was submitted to the engineer.

Table 4. Specified Permeate Quality

Constituent/Parameter	Unit	Projected Raw Water Quality	Stage 1&2 Permeate Quality
Bicarbonate	mg/L	265	<175
Color	CU	50	<2.0
Total Hardness	mg/L as $CaCO_3$	250	60 to 90
Total Organic Carbon	mg/L as C	12.0	<1.0
TTHM Formation Potential	mg/L	0.60	<0.042
HAA Formation Potential	mg/L	0.40	<0.030

The loading and start-up of the individual membrane units was staged to allow Hydranautics to make adjustments to the membrane manufacturing and membrane element selection to correct for any specification variances observed during initial full-scale testing. Loading and testing was staged as follows:

- Membrane elements for Units 1 and 2 (only) were delivered following satisfactory completion of pilot-scale testing of the initial 21 membrane elements.
- Loading and start-up of Unit 2 was allowed only after Unit 1 successfully completed its 7-day performance test.
- Membrane elements for Units 3 through 10 were delivered in individual shipments containing the elements for two membrane units at a time.
- The Contractor was allowed to have two membrane units out of service at a time.

From January to May 2015, the mechanical contractor RJ Sullivan and Hydranautics worked on site with the consulting engineers from McCafferty Brinson who oversaw the project of taking each of the 10 NF units apart, unload the old membranes, clean the vessels, custom stage, load, then start each up for a 7 day performance acceptance testing (PAT) to make permeate quality that was agreed upon per the contract.

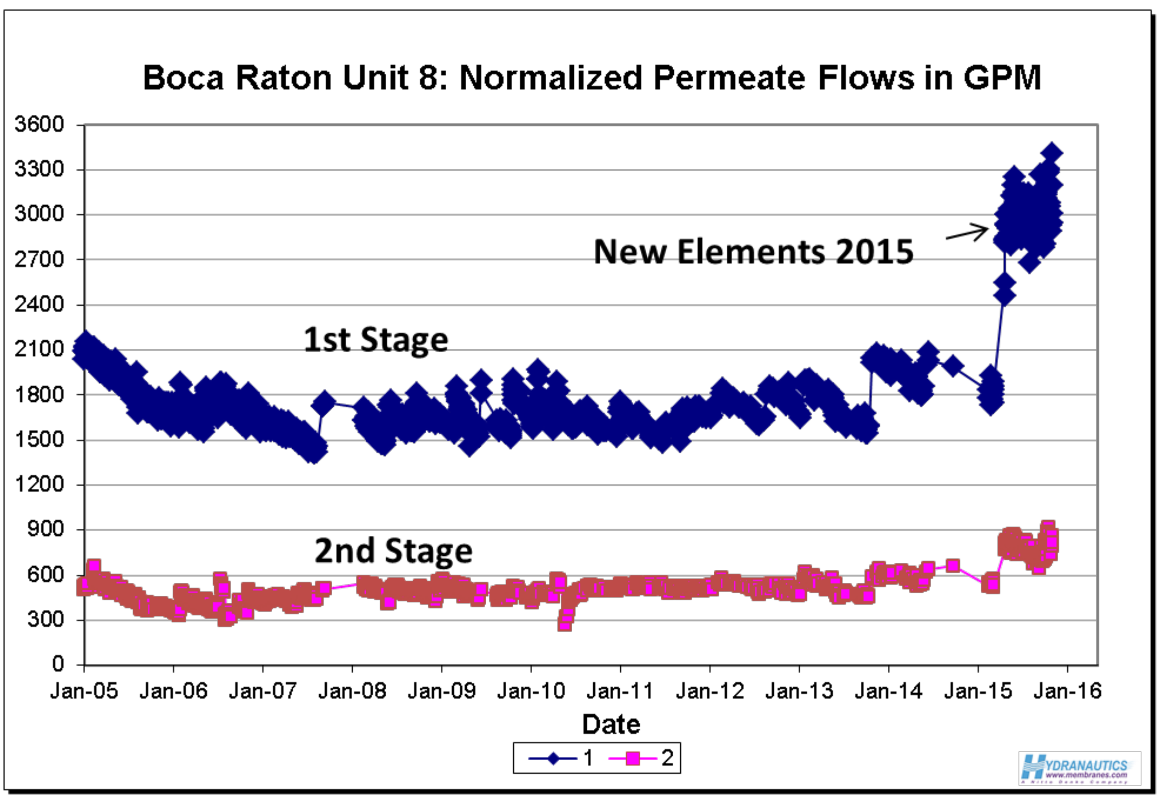
The actual start-up results were relatively close to the membrane manufacturers projections as noted in Table 5. It should be noted that this feed water with these site specific organics in the Boca Raton wells will in the first few days be absorbed to the membrane surface and result in a small increase feed pressure (about 5 psi) and an increase in permeate conductivity and hardness after which it will stabilize.

Table 5: Actual Versus Projected Results at Day 1 Start Up for Unit 2

Constituent/Parameter	Unit	Projected	Specified	Actual
Feed Pressure	**PSI**	60	< 100	60
Permeate:				
Bicarbonate	**mg/L**	85	<175	85
Total Hardness as CaCO3	**mg/L**	68	60 to 90	
TDS	**Mg/l**	161		176
Conductivity	**uS**	239		240
Color	**CU**		<2.0	< 2.0
Total Organic Carbon	**mg/L as C**		<1.0	< 0.25
TTHM Formation Potential	**mg/L**		<0.042	< 0.042
HAA Formation Potential	**mg/L**		<0.030	< 0.030

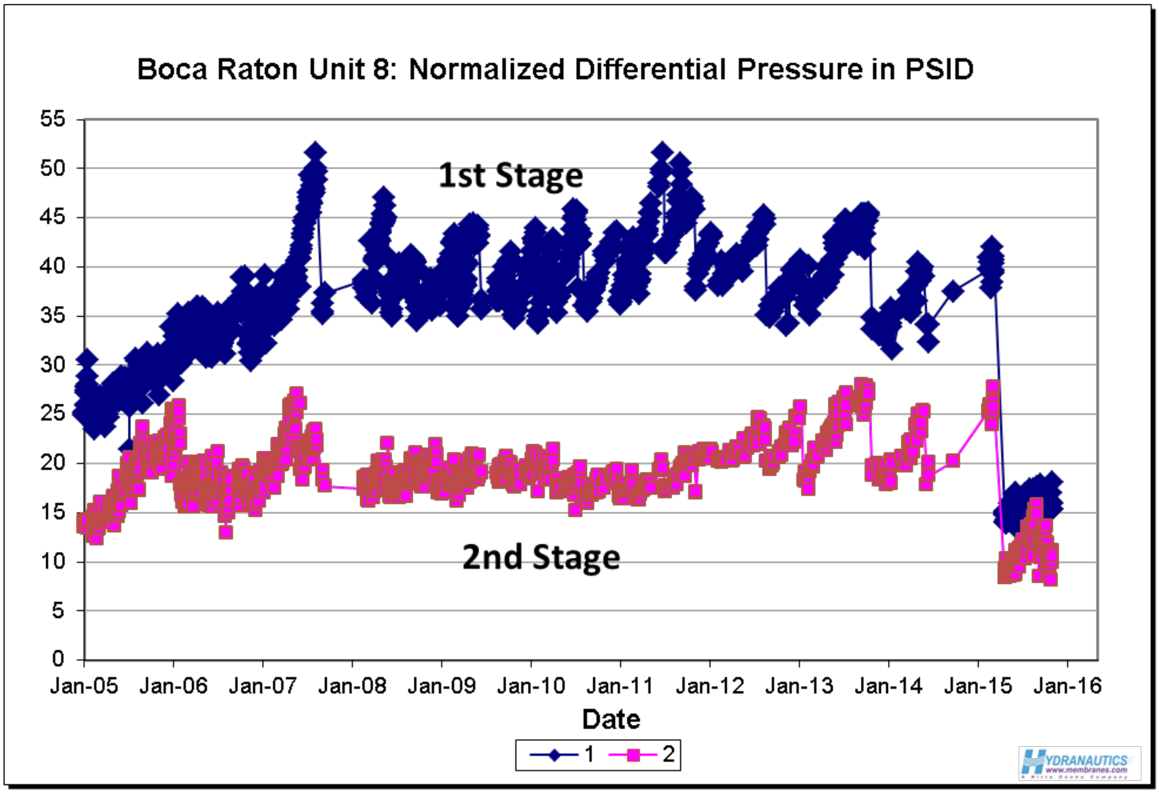
The normalized data for Boca Raton Unit 8 from January 2005 to November 2015 are in Graphs 3-4.Graph 3 is the Normalized Permeate Flow in GPM and it indicates an increase in normalized permeate flow of 50-80%, indicating a significant improvement in the specific flux and flow of water through the membrane which correlates to lower feed pressures and energy savings.

Graph 3: Normalized Permeate Flow in GPM



Graph 4 shows the dramatic improvement in normalized differential pressure as measured as the difference between the feed and concentrate pressures. This reduced delta P is a significant part of the energy savings and it also results in a better flux balanced system which reduces the rate of fouling.

Graph 4: Normalized Differential Pressure in PSID



6. Conclusion

All 10 NF membrane treatment units were originally designed for 3.67 MGD and 85% recovery without the addition of any pretreatment chemicals. The primary objective of the project was to maintain continued compliance with the disinfectant/disinfection by-product (D/DBP) rule (i.e., reduce total trihalomethanes (TTHMs) and haloacetic acids (HAAs), and improve the level of service to the Boca Raton customers by significantly improving the color in the blended finished water. Another key objective in permeate quality is to maintain 60-90 ppm total hardness as CaCO3 to minimize corrosion in downstream piping. Power savings of 24-30% are expected with the use of newest NF elements. A cleaning frequency of 6-8 months is expected based on historical operations and the addition of new NF elements which use 34 mil feed spacers which clean better and have a better flux distribution during service.. The frequency of cleaning will optimized by continued use of no pretreatment chemicals, the recovery has been reduced from 85 to 82% to improve crossflow velocity and reduce the deposition of foulants, and cleaning the membranes on a timely basis.

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Optimizing Replacement Membranes for a 40 mgd Nanofiltration Plant

Introduction

- Background
- Facility Design
- Membrane Replacement
- Comparison of Performance:

  New vs. Old

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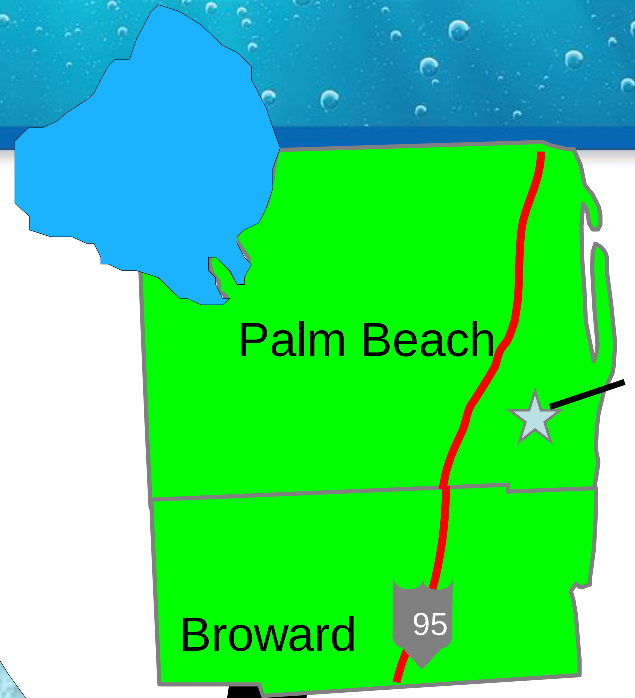
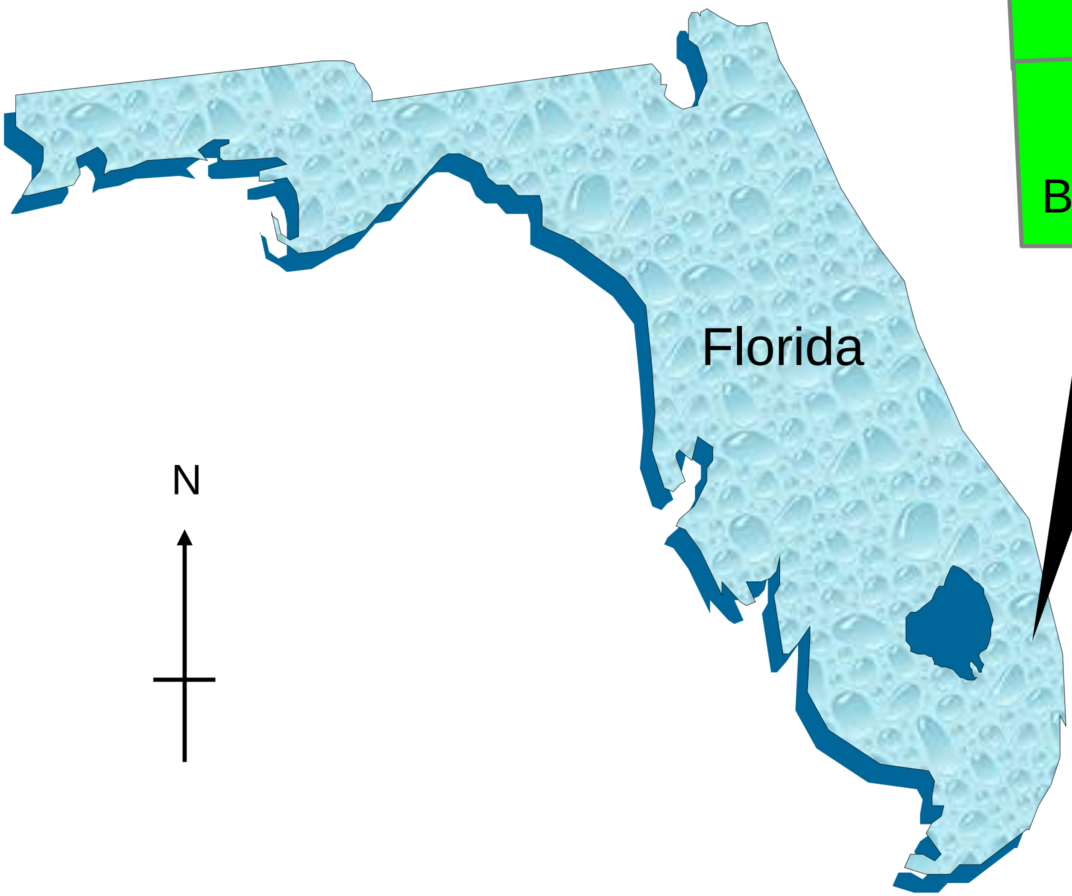
Boca Raton, Florida





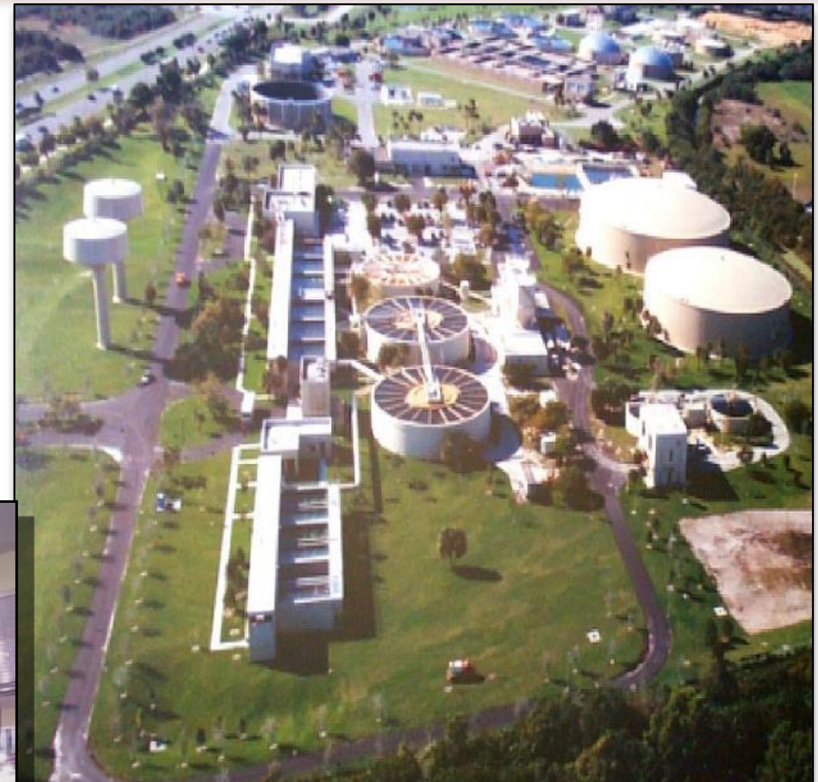
<u>Water Demands</u>

45 mgd Average Day

60 mgd Maximum Day

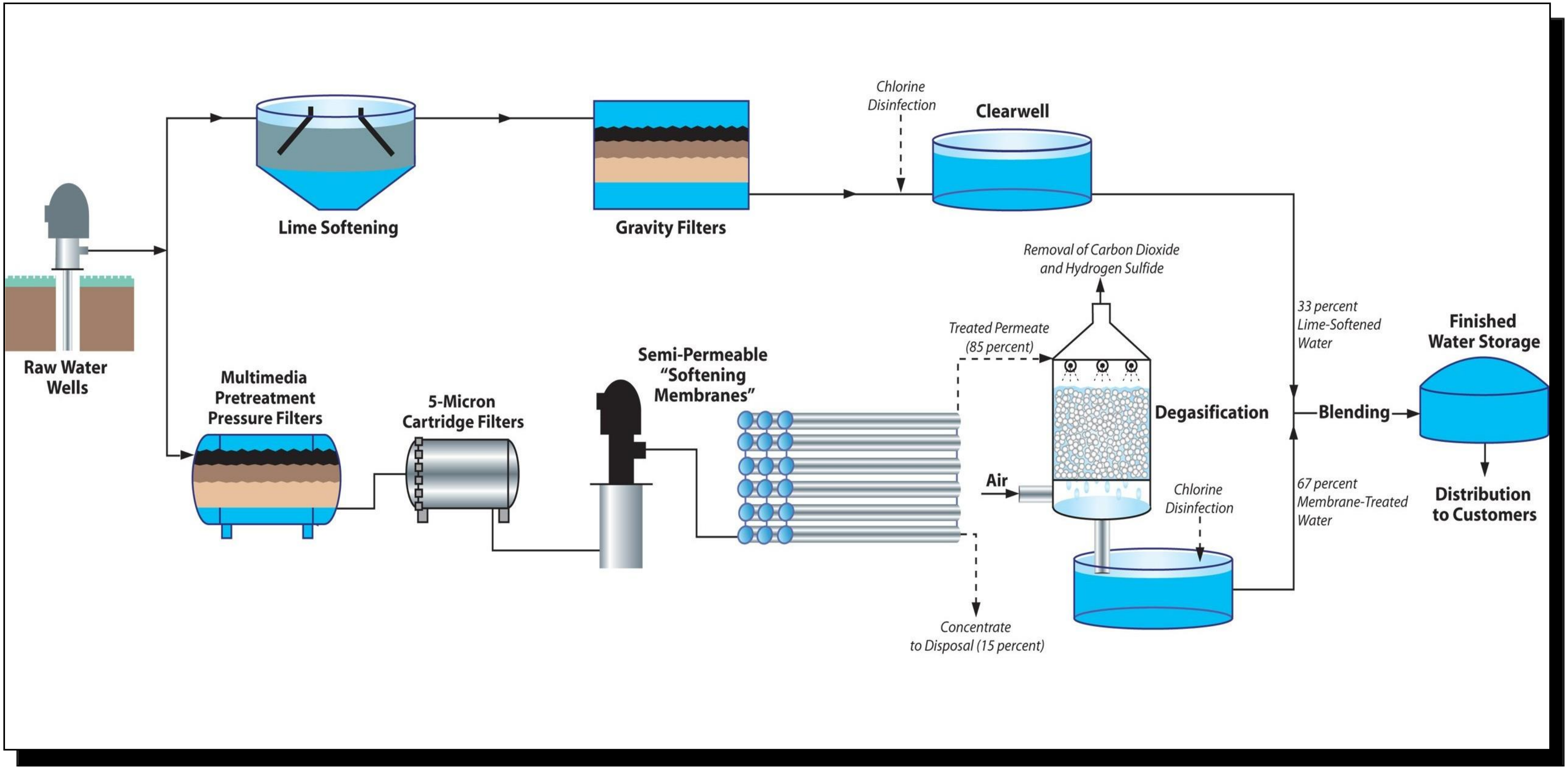
Glades Road Water Treatment Plant

- Biscayne Aquifer Raw Water Supply
- 70 mgd Treatment Capacity
- 30 mgd Conventional Lime Softening
- 40 mgd Nanofiltration
- 2:1 Blend NF:LS



- NF Plant Constructed 2002-4
- Membranes Replaced 2015

Glades Road WTP Process Schematic



Raw Water Quality

Constituent/Parameter	Value
Total Hardness	250 mg/L as $CaCO_3$
Alkalinity	214 mg/L as $CaCO_3$
Total Dissolved Solids	450 mg/L
Color	50 Color Units
Total Organic Carbon (TOC)	12 mg/L
Humic Acid	10 mg/L
pH	7.2
Iron	0.3 mg/L

Blended Finished Water Quality Goals

Constituent/Parameter	Value
Total Hardness	70 - 90 mg/L as $CaCO_3$
Color	< 6 Color Units
Total Trihalomethanes (TTHM)	< 0.064 mg/L
Five Haloacetic Acids (HAA5)	< 0.048 mg/L

Specified Permeate Quality

Constituent/Parameter	Original Membranes (2004)	Replacement Membranes (2015)
Bicarbonate	<175 mg/L	<175 mg/L
Color	< 2 Color Units	< 2 Color Units
Total Dissolved Solids	< 300 mg/L	< 300 mg/L
Total Hardness	50–80 mg/L as $CaCO_3$	60–90 mg/L as $CaCO_3$
Total Organic Carbon	< 1.0 mg/L as C	< 1.0 mg/L as C
TTHM Formation Potential	< 0.042 mg/L	< 0.042 mg/L
HAA5 Formation Potential	< 0.030 mg/L	< 0.030 mg/L

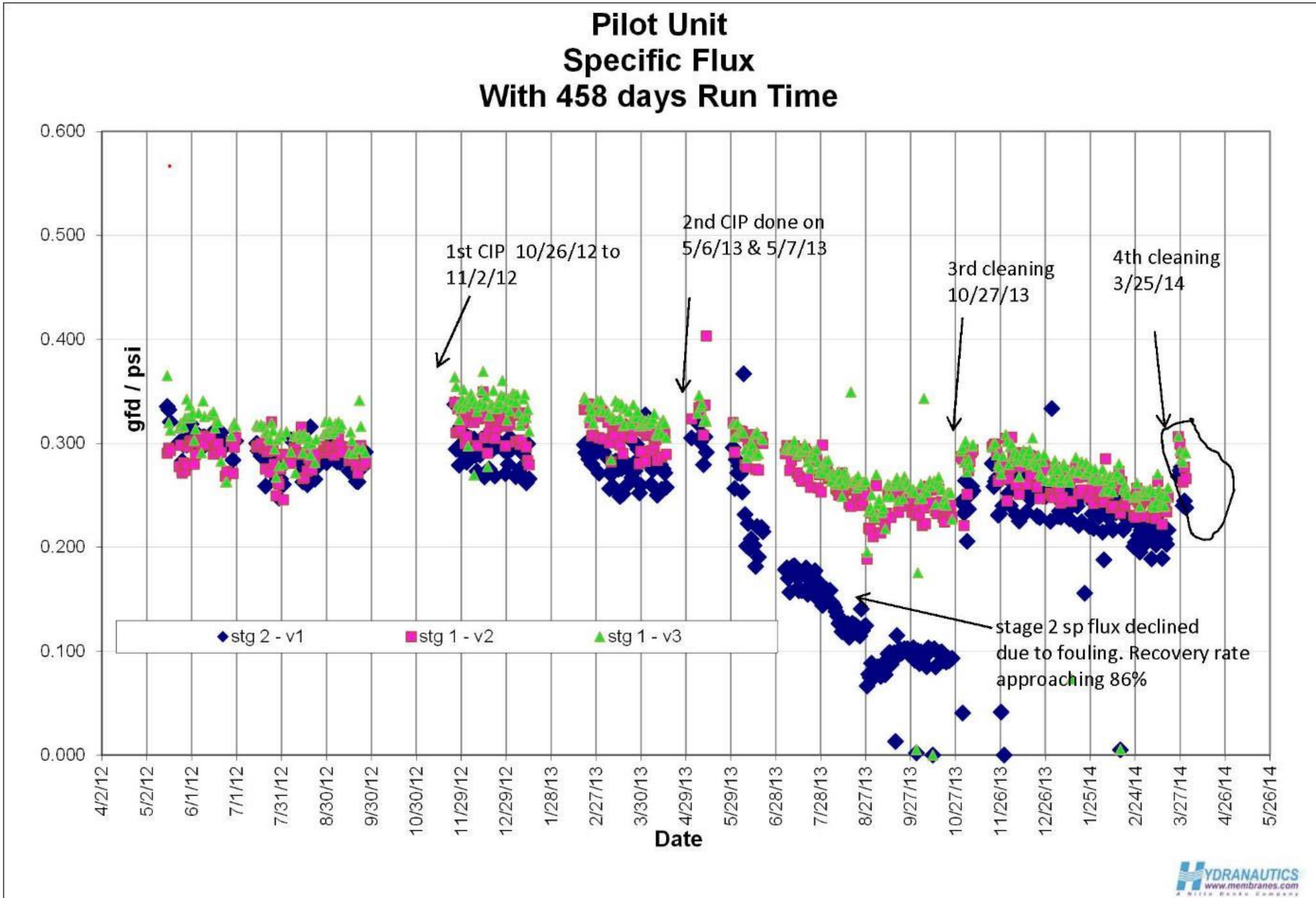
Design Parameters for NF Process

Design Parameter	Units 1 - 10 (Stg 1 and 2)	Units 11 - 12 (3rd Stg/2-Stg)
Capacity	36.76 mgd	3.24 mgd
Recovery Rate	85%	50% / 85%
Raw Water Feed	43.2 mgd	6.48 mgd/3.81 mgd
Number of Units	10 x 3.676 mgd	2 x 1.62 mgd
Array	72:36	54 / 36:18
Flux Rate	12.2 gfd	10.7 gfd / 10.7 gfd
Transmembrane Pressure	80 psi	100 psi / 80 psi

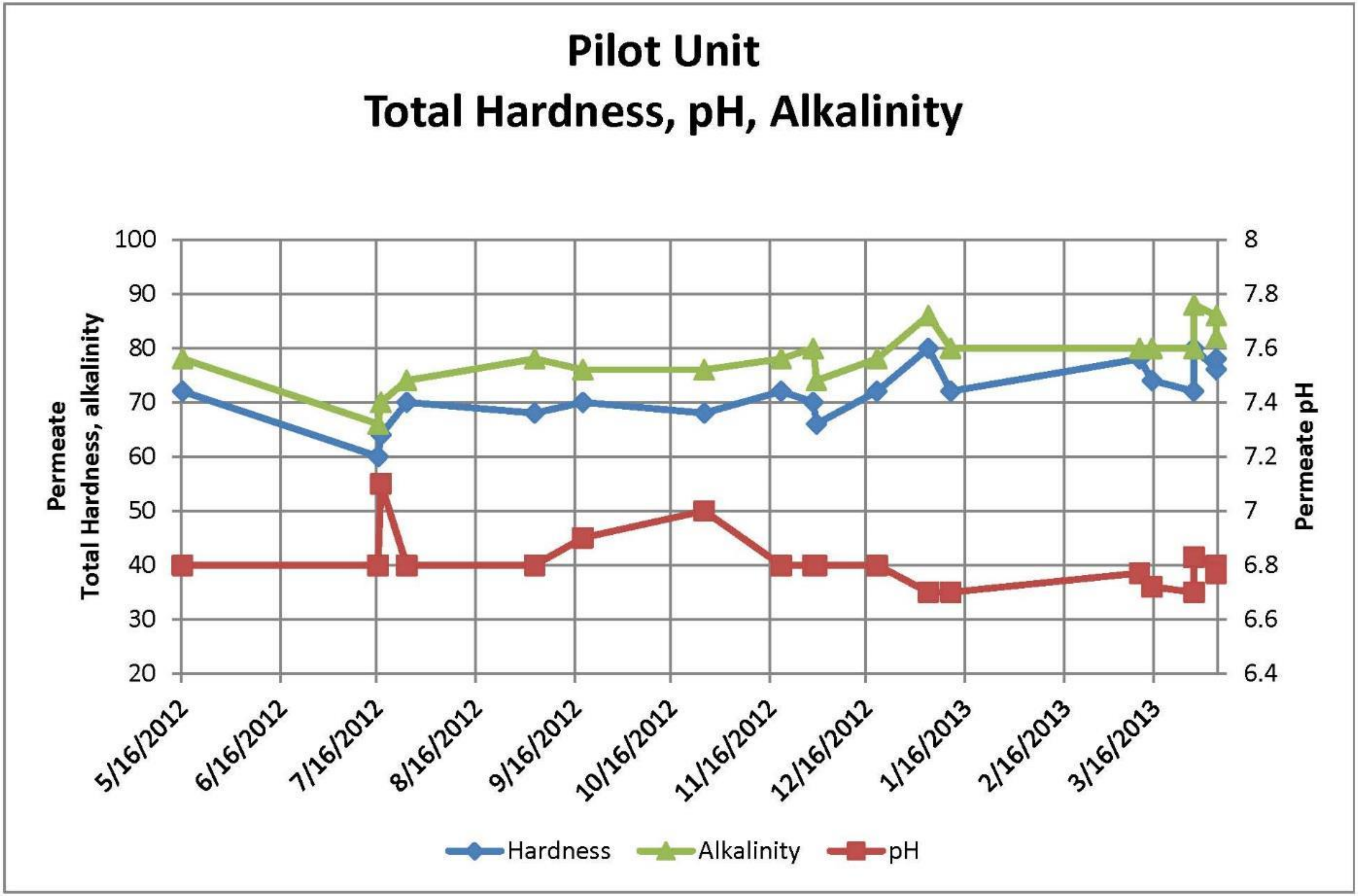
2012-2013 Pilot Test Unit

- Three full-size pressure vessels mounted on full-scale membrane unit
- Same feedwater as full-scale process
- 2:1 Array (21 membrane elements)

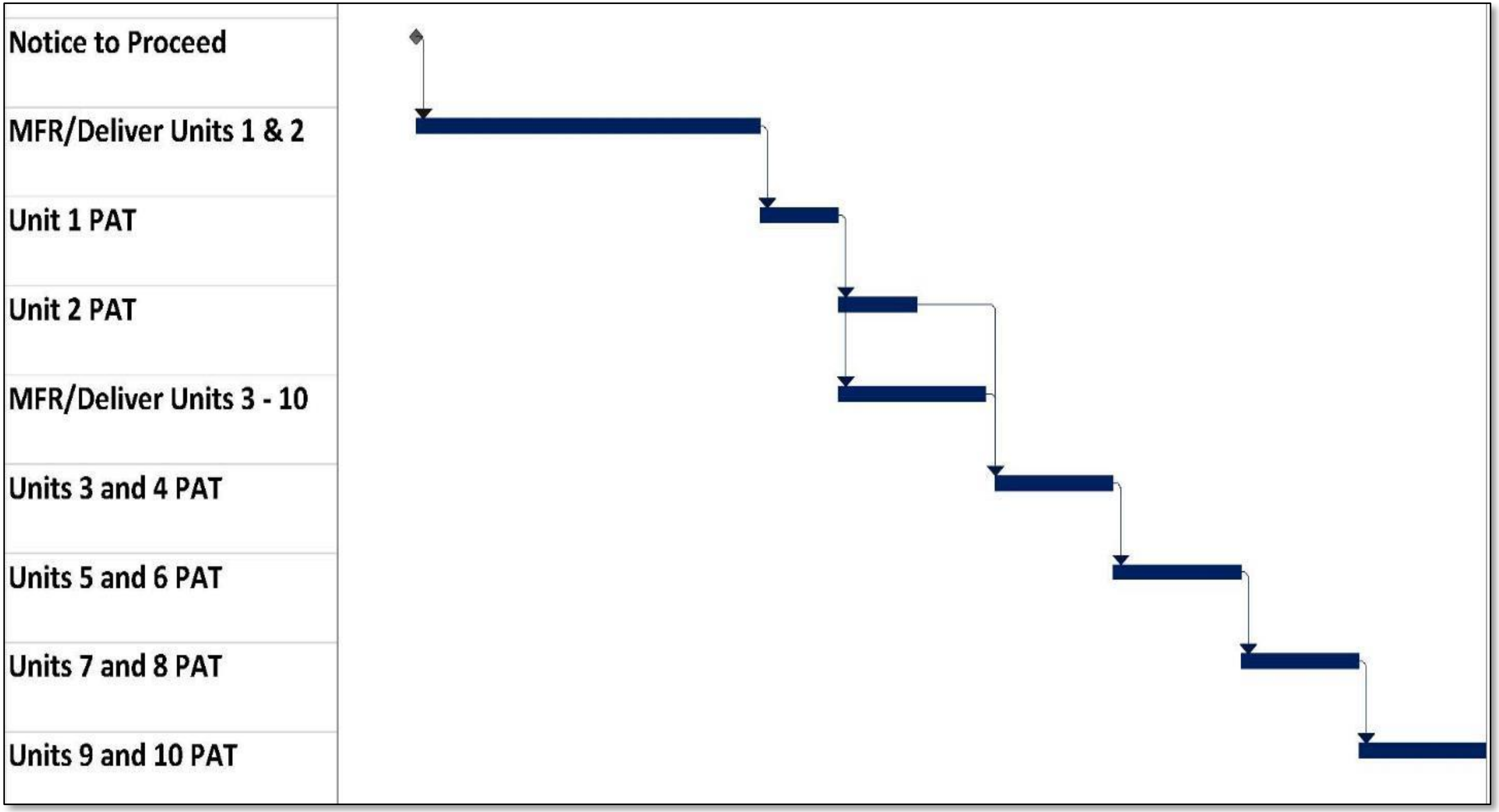
Pilot Unit Specific Flux



Pilot Unit Permeate Quality



NF Membrane Delivery, Loading, and Testing Schedule



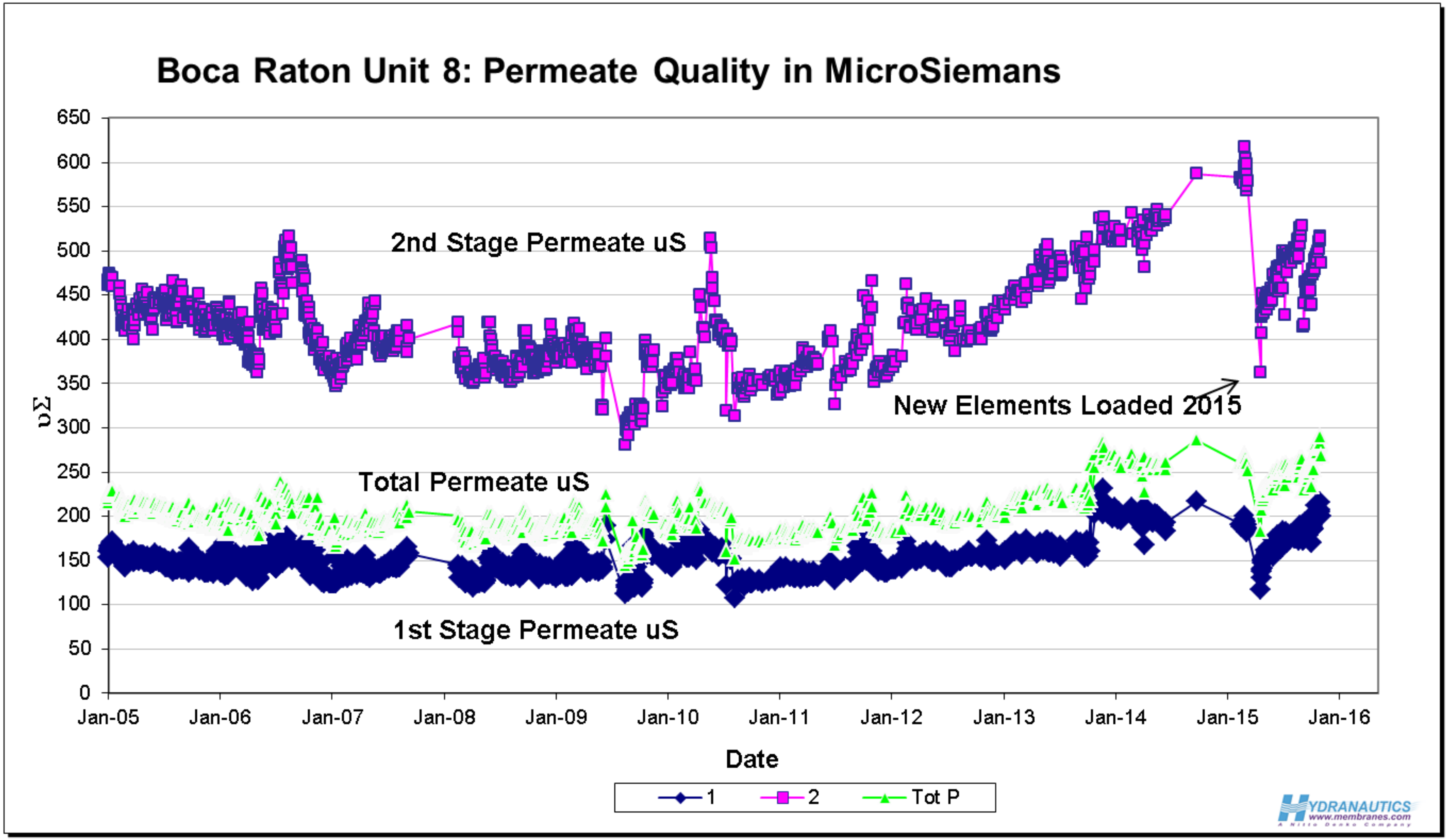
Unit 1 Reload: Results and Corrective Action

- Initial (January 2015) PAT Results were high: Hardness = 85 – 92 mg/L as $CaCO_3$
- Hydranautic's Corrective Action: Replaced 100 selected elements with higher-rejection NF
- Resulted in modifications to membrane selections for Units 4 through 10
- Results after corrective action: Unit 1 Hardness = 78 mg/L as $CaCO_3$

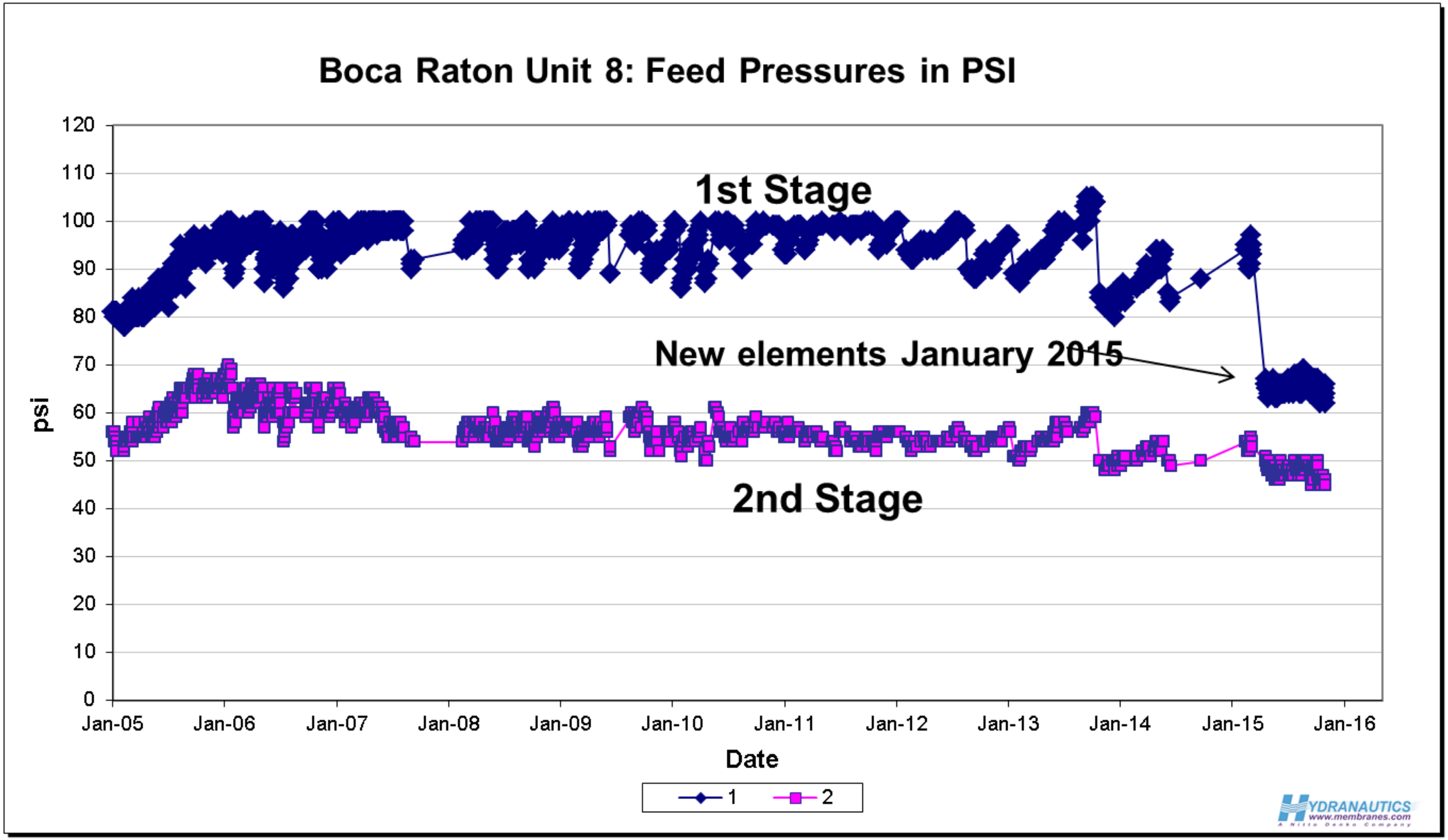
Summary of Performance Testing

Membrane Unit	TMP (psi)	Color (CU)	TDS (mg/L)	Hardness (mg/L as $CaCO_3$)	TOC (mg/L)	TTHM (µg/L)	HAA5 (µg/L)
Unit 1	45	1	140	78	0.54	10.7	2.71
Unit 2	45	1	107	76			
Unit 3	46	1	117	74			
Unit 4	53	1	111	68	0.64	8.2	
Unit 5	53	1	119	68			
Unit 6	51	1	106	64	0.45		
Unit 7	52	3	106	76	0.70	12.4	
Unit 8	52	1	110	62			
Unit 9	48	1	133	75			
Unit 10	47	1	122	80			
Average:	**49.2**	**1.2**	**117**	**72**	**0.6**	**10.4**	**2.7**
Specification:	**< 80**	**< 2**	**< 300**	**60 - 90**	**< 1.0**	**< 42**	**< 30**
Avg Original Membranes:	**68.6**	**1.1**		**75**	**0.8**	**16.2**	**14.6**
New vs. Old Membranes:	**19.4**	**-0.1**		**3.3**	**0.2**	**5.8**	**11.9**

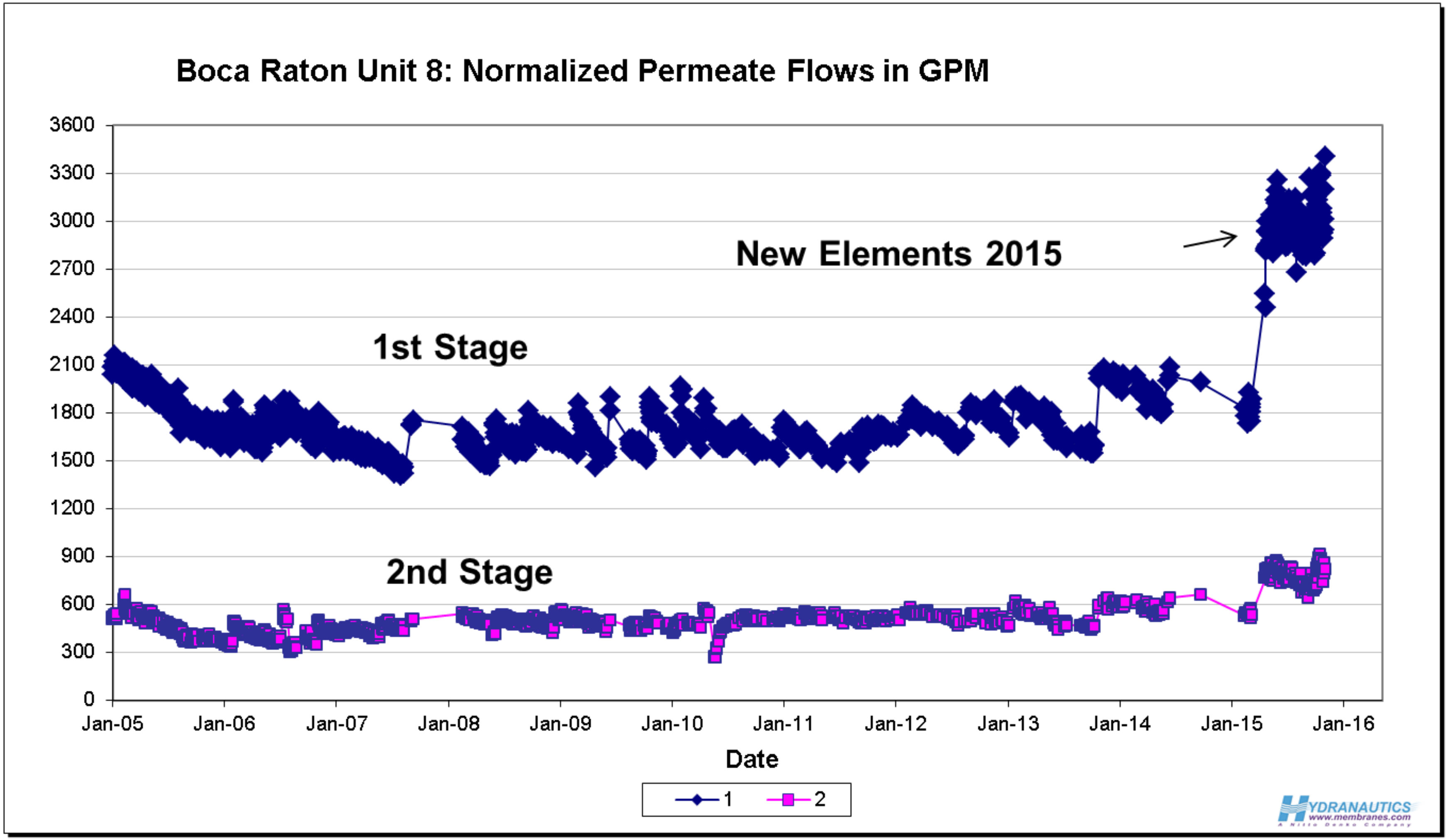
Actual Permeate Quality Since 2005



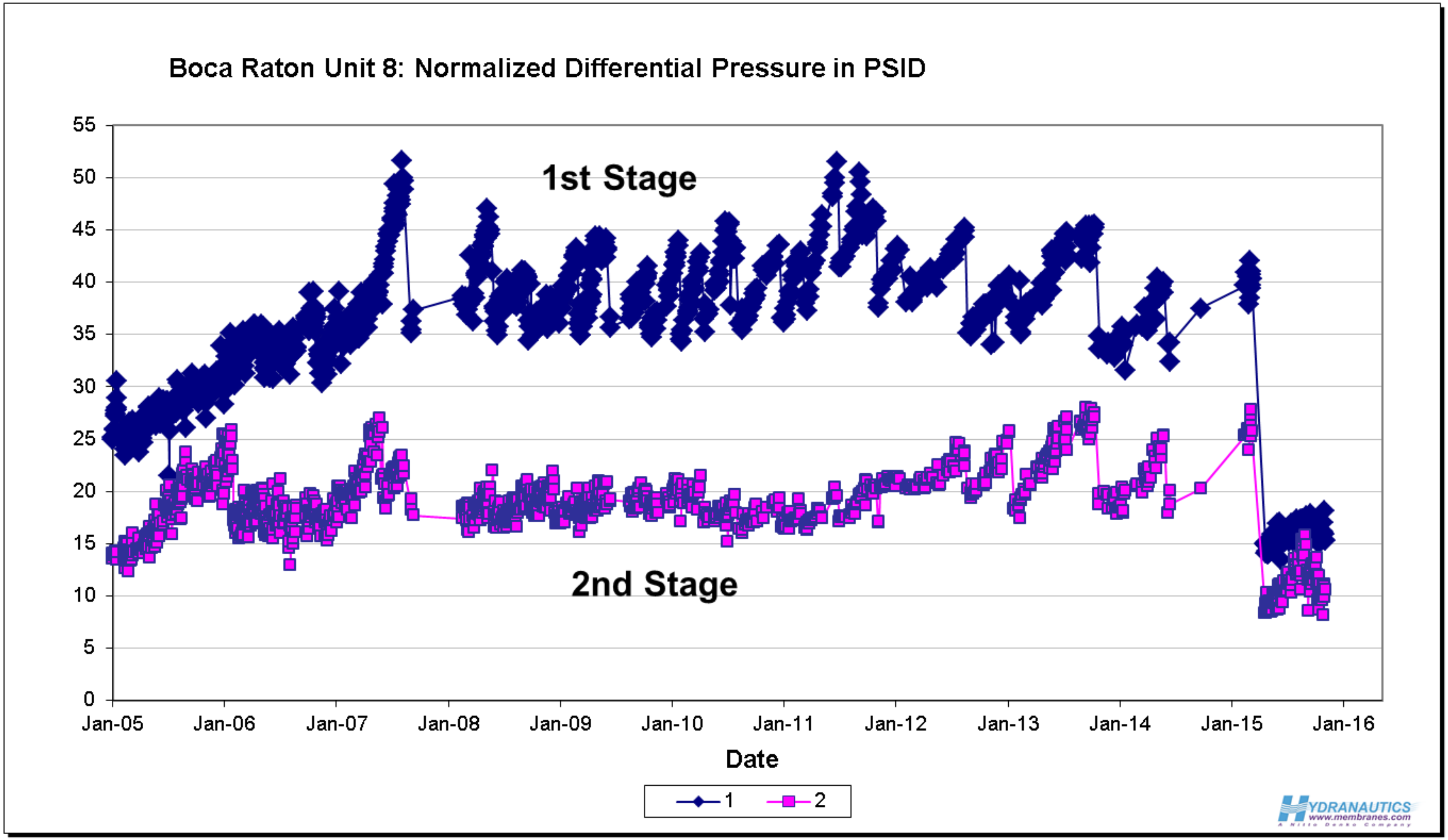
Actual Feed Pressure Since 2005



Normalized Permeate Flow Improved



Normalized Delta P Improved



Significant Energy Savings

Estimated Annual Power Cost Savings

(45 mgd Total ADD, 30 mgd Permeate ADD, 35.3 mgd Feed Flow)

- **85 psi – 65 psi Feed Pressure = Δ 20 psi reduction**
- **Unit power cost = $0.065/kW-hr**
- **Total Annual Cost Savings = + $267,000/year**

McCafferty Brinson consulting

Estimated Annual Chemical Cost Savings

(Based on 45 mgd Total ADD, 30 mgd Permeate ADD, 35.3 mgd Feed Flow)

- **Acid (110 mg/L at $0.045 per pound): $572,000**
- **Caustic (6 mg/L at $0.15 per pound): $97,000**
- **Antiscalant (3 mg/L at $0.80 per pound): $258,000**

- **Total Annual Cost Savings: $927,000/yr**

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Conclusions

- **Process has operated for ten years without chemical pretreatment resulting in annual cost savings of nearly $1 million.**

- **All water quality and capacity goals have been met since the 2004 startup and with the new low pressure NF elements.**

- **New NF membranes provide similar water quality and performance at a 24 percent reduction in pumping power cost and a $267,000 per year in energy savings.**

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