Introduction

As the world's populations continue to increase, so does the need for water sources suitable to meet the needs of the population. Harnessing value from waste sources has always presented challenges but with advancements in technology and innovation in the implementation of technology, these challenges are becoming less insurmountable. Water sources such as moderate salinity (2,000 – 6,000 mg/L) brackish water represent potential value for meeting growing drinking water demands as well as other uses. In addition to BWD, other types of desalting technologies exist, each with its own set of pros and cons. Reverse osmosis (RO) (sea/brackish), electrodialysis, --both conventional (ED) and reversal (EDR), ion exchange (IE) (softeners and deionizers) and thermal systems -- mostly vapor compression (VC) have all found application within various industries [1]. Industrial applications are typically large scale and the waste streams from them are generally highly concentrated therefore the bulk of the focus regarding desalting targets this area.

As stated earlier, brackish water, generally lower in salinity than typical industrial waste streams represents a segment of the market that has received increased attention in recent years. This is due, in part, to the need for alternative potable water sources to meet growing demands in coastal regions as well as the economic attractiveness of low energy membrane processes. Although, implementation of BWD economically has its challenges, the emergence of innovative ideas has helped to develop low cost solutions to implementation.

Identification of possible solutions typically includes pilot testing of various potentially feasible processes on the subject source water. The following-on text shares the activities, findings and recommendation of our pilot study conducted for the Pinellas County WTE facility.

Purpose and Objectives

The purpose of our pilot study was to (1) pilot test RO pretreatment systems and select one process to provide feed water to an RO pilot system and (2) pilot test RO to confirm acceptability and finalize design criteria for the full-scale plant design to meet Schedule 20 requirements (water quality) as agreed to between the County and the WTE Contract Operator, Veolia. **Table 1** presents the contract requirements along with historical water quality ranges. Our objectives were to (1) simulate full-scale operating conditions, (2) identify optimal operating conditions, (3) project long-term system performance and (4) prepare a recommended conceptual system design.

TABLE 1: Water Treatment Goals and Historical Raw Water Quality Ranges

Parameter	Units	Schedule 20 Ops. Contract Reqmts.	Historical Raw Water Quality [1]		Veolia WTP Influent Water Quality [2]	
			Min	Max	Min	Max
pH	Std Units	<10.4	6.5	8.6	3.8	7.4
Chloride	mg/L	-	**225**	**940**	150	**1,620**
Sulfate	mg/L	-	28	**360**	**97**	**360**
Alkalinity	mg/L as $CaCO_3$	<70	29	**156**	0	46
Conductivity	uS/cm	<1,434	1,434	**3,627**	**2,360**	**5,100**
Calcium	mg/L as $CaCO_3$	<167	**450**	**525**	**317**	**660**
Total Hardness	mg/L as $CaCO_3$	-	**534**	**634**	**343**	**780**
Turbidity	NTU	<26	7	**100**	**57**	**271**

Table notes: [1] Historical raw data includes: May 1996 to Feb. 2006 discharge permit monitoring, February 2007 grab sampling by AECOM, and January23 to August 24, 2010 WTE Pilot Monitoring Data. Values in bold font indicate exceedance of the Schedule 20 requirement. [2] April 1 2008 to May 29, 2009 WTE WTP influent monitoring log data (post-chlorination).

Pilot Test

Pilot testing included multiple treatment processes. Raw Pond A water was coagulated, filtered, and desalted with RO. Coagulation was approached in two ways. One approach involved coagulant addition, high rate clarification and solids thickening followed by filtration. The other involved coagulant addition, flocculation, and filtration, which is referred to as direct coagulation.

Testing included three filtration processes: granular media, MF, and UF. Coagulated and settled water was tested with the granular media filtration and MF. The MF and UF systems were both tested with direct coagulation of the coagulated and flocculated raw water without sedimentation.

MF and UF systems comprised two different configurations. MF was configured as a pressurized system. UF was tested in submerged configuration with water pulled through the fibers under vacuum. The pilot systems represent the GE Zeeweed UF 500D system and Microza MF modules by Pall Corp.

The pretreatment trains are identified as:

- Pretreatment Train 1: Coagulation + Sedimentation → Granular Media Filtration
- Pretreatment Train 2: Coagulation + Sedimentation → Microfiltration
- Pretreatment Train 3A: Coagulation + Flocculation → Ultrafiltration
- Pretreatment Train 3B: Coagulation + Flocculation → Microfiltration

The pilot test was divided into two phases. **Table 2** provides an overview of the testing summary by phase. Phase 1 tests identified the pretreatment processes that best met the goals of achieving maximum RO recovery rate, run time between chemical cleaning, and overall membrane life expectancy against pretreatment capital cost, chemical consumption, production of residual waste streams (e.g., backwash water volume, sludge production), and ease of operation. Ferric chloride served as the coagulant for Phase 1. Selection was based on good removal capability for natural organics and suspended solids. Coagulation with aluminum sulfate was evaluated in Phase 2 to further optimize MF/UF and RO performance.

Based on the outcome of Phase 1, two pretreatment trains were tested in Phase 2, Trains 3A and 3B. A single RO membrane was tested. This allowed the full RO test period, approximately 1,600 hours, to be used for optimization and determination of the projected run time between chemical cleaning. BW30XFR membranes were procured from DOW FilmTec. Selection was based on enhanced fouling resistance and cleanability.

Following coagulation and filtration, the pretreated RO feed water was dosed with anti-scalant to inhibit scaling within the RO membranes. The water quality gathered in Phase 1 supported operating the RO process in the range of 80 to 87-percent [2, 3].

Pilot operations were monitored each day to verify proper system operation, collect operational data, and maintain target operating conditions. Field data collection included recording of process flows, chemical feed rates, raw and treated water quality (pH, turbidity, temperature, conductivity), and silt density index (SDI).

Multiple factors were taken into account in selecting, configuring, and developing the various treatment systems. The pretreatment processes were intended to achieve suitable RO feed water quality. Success in achieving these goals was dependent on RO pretreated water quality. Guidelines were established for key parameters to minimize RO fouling.

TABLE 2: Pilot Testing Summary by Process and Test Phase

Process / Parameter	Phase 1 RO Pretreatment Screening	Phase 2 RO Desalting
Clarifier & Thickener *(DensaDeg)*		
Feed Water Supply	*Raw Pond A*	*Not tested in Phase 2*
Flow rate	*65 gal/min*	
Surf. Loading Rate	*6 gal/ft^2-min*	
Product	*Coagulated and Settled Water*	
Granular Media Filt. *(Siemens)*		
Feed Water Supply	*Coagulated and Settled Water*	*Not tested in Phase 2*
Flow rate	*20 gal/min*	
Surf. Loading Rate	*1.5 - 3 gal/ft^2-min*	
Product	*Filtered Water*	
Microfiltration *(Pall)*		
Feed Water Supply	*Coagulated and Settled Water*	*Raw Pond A Water Flocculated with Alum*
Flow rate	*14.9 – 22.4 gal/min*	*20 – 30 gal/min*
Water Flux Rate	*40 - 60 gal/ft^2-day*	*40 - 53 gal/ft^2-day*
Product	*Filtered Water*	*Filtered Water*
Ultrafiltration *(GE – Zeeweed)*		
Feed Water Supply	*Raw Pond A Water Flocculated with $FeCl_3$*	*Raw Pond A Water Flocculated with $FeCl_3$ & Alum*
Flow rate	*16.6 – 27.8 gal/min*	*16.6 – 27.8 gal/min*
Water Flux Rate	*27.2 – 33 gal/ft^2-day*	*27.2 – 30 gal/ft^2-day*
Product	*Filtered Water*	*Filtered Water*
RO Desalination *(Harn RO)*		
Feed water supply	*Not tested in Phase 1*	*Trains 3A & 3B (See Figure 2)*
Feed flow rate		*15.2 -16.3 gal/min*
Cartridge filtration		*5 micron*
Chemical Pre-treatment		*Anti-scalant – AWC 102 Plus* *Biocide – Avista DB20*
Membrane		*DOW FilmTec BW30XFR 4"x40" & 2.5"x40" elements*
Product recovery rate		*80% - 2 Stage RO* *87% - 3 Stage RO*
Water flux rate		*12.5 gal/ft^2-day*

Table 3 lists key water quality parameters and their desired ranges in addition to the associated foulant impact and source.

TABLE 3: Conceptual RO Feed Water Quality Guidelines

Parameter	Units	RO Feed Quality	Foulant Impact / Source
SDI	---	<3	Particles / Raw water
Turbidity	NTU	<0.1	Particles / Raw water
Total Org. Carbon	mg/L C	<10	Organics / Raw water Biological Growth / Raw water
pH	Std. Units	6 – 7	Metal oxides / Coagulation pH control Scaling / Coagulation pH control
Aluminum	mg/L	<0.1	Metal oxides / Coagulation
Iron	mg/L	<0.1	Metal oxides / Coagulation
Barium	mg/L	<0.1	Scaling / Raw water
Sulfate	mg/L	<300	Scaling / Raw water & Coagulant addition
Alkalinity	mg/L as $CaCO_3$	<50	Scaling / Raw water & Coag. pH control
Calcium	mg/L as $CaCO_3$	<700	Scaling / Raw water & Coag. pH control

Results

The Pond A water supply is brackish with high concentrations of natural organics, suspended solids, biologicals, and hardness. Macroalgae (chlorophyll a) levels were representative of the eutrophic nutrient conditions and symptomatic of stormwater and landfill leachate input to the pond. In addition, the Pond A influent typically had a cloudy green coloration with moderate turbidity, and often emitted an unpleasant odor.

Overall, raw water quality was relatively stable throughout testing. Dissolved solids were predominantly sodium, chloride, calcium, bicarbonate and potassium. Conductivity (specific conductance) averaged 3,192 uS/cm and varied between 2,880 and 3,627 uS/cm. Chloride represents the dominant ion for this supply with average concentrations of 740 and 940 mg/L. However, the added organics, nutrients, algae, and suspended solids make this application dramatically different from traditional RO facilities treating brackish groundwater in Florida. Based on similar experience, Pond A requires high removal of suspended solids and biologicals, and substantial reductions in natural organics before serving as a suitable RO feed water.

Pretreatment Performance

Regarding pretreatment performance, the high rate clarifier produced good settled water quality at a relatively high surface loading rate. However, coagulant dosages were also relatively high requiring polymer for good sludge blanket formation and floc settleability. The granular media filter was unable to sufficiently treat settled water from the clarifier and indications that successful treatment could be achieved were only slight therefore it was decided to abandon the media filter in favor of the membrane filtration processes. Overall, the Pall MF system performed well even at the highest water flux rate of 53 gsfd. Its water recovery rate ranged from 94 to 95 percent. However, the direct coagulation treatment mode showed limited ability to handle coagulant dosages necessary to achieve enhanced natural organics removal. After testing increased alum dosages, the maximum dose in direct coagulation mode was determined to be in the 80 - 100 mg/L range. TOC remaining after alum coagulation at 80 and 100 mg/L was nearly identical at 13 to 13.5 mg/L C. Furthermore, it was concluded that the MF could not handle the worst case historical turbidity in direct coagulation mode. The GE UF process consistently provided a high quality filtered product. However, its ability to operate for extended periods of time between CIP events was sensitive to coagulant dose and flocculation pH. It demonstrated superior TOC removal and solids loading capacity, however, drawbacks included lower recovery rate (92-percent) and higher rate of fouling and associated membrane cleaning.

RO Performance

Analysis was conducted on the data derived from operations on each of the pretreatment systems included in Phase 2 of the pilot study. A determination of the desalting process performance of the RO system included parameters such as cartridge filter performance, feed pH, temperature, silt density index (SDI), water recovery rate, flux, permeability, and feed-channel pressure drop.

The total RO operating time spanned 1,640 hours although the testing was segmented into test intervals for ease of identification of test and operating conditions. During early operations of the 3-stage RO unit, water recovery was maintained at 80-percent but was later increased to 87-percent. Water flux was well controlled at 12 gsfd. It should be noted that this was the actual flux rate without temperature correction. Permeability varied but did stabilize during certain segments of the testing. Comparison of productivity between different test segments showed a decrease indicating foulant accumulation on the membrane surface. Further comparison of the same test segments showed corresponding increases in feed channel pressure drop which in is indicative of fouling of the feed channel spacer. In either case, the fouling was reversible with normal chemical cleaning.

In addition to analysis of operating performance data, forensic testing was also conducted on specific membranes. Conditions were profiled across the membrane train by autopsying elements from the Stage 1 lead, Stage 2 lag, and Stage 3 lag positions. Fouled and non-fouled membranes were analyzed by sampling membranes pre- and post-CIP. Stage 1 and 2 membranes represent pre-CIP conditions. The Stage 3 element represents post-CIP conditions. Overall, the autopsies showed effective foulant removal which is a key component of successful long-term operations. Based on the broad range of foulants identified, RO cleaning with high and low pH solutions is expected.

Economic Impacts Evaluation

Conceptual opinions of probable cost were developed for the County's consideration relative to their decision making and planning activities. These opinions included capital and operation and maintenance costs which took into account the pilot performance data, vendor-based cost estimates, and experience with analogous systems. **Table 4** presents a summary of this evaluation.

TABLE 4: Economics Evaluation

Description	Alternative 1	Alternative 2	Alternative 3
Capital Cost	$14,145,000	$13,418,000	$14,839,000
Total Combined Unit Cost, $/gal	$5.06	$4.77	$5.37
O&M Cost	$2,984,000	$3,312,000	$2,839,000
Total Combined Unit Cost, $/gal	$4.42	$4.95	$4.16
Present Worth	$51,733,000	$55,129,000	$50,592,000

Summary and Recommendation

The pilot study demonstrated that desalting of Pond A water with reverse osmosis is feasible. However, RO process efficiency was highly dependent upon pretreated water quality. The variable nature combined with a high degree of potential RO foulants makes this a particularly challenging treatment application. As a result, effective treatment requires multiple barriers to address particulates, organics, biologicals and inorganics prior to treatment by the RO process.

Three treatment alternatives were identified. These included conventional coagulation, clarification (sedimentation), with filtration, and two membrane filtration processes operated in direct coagulation mode and are identified as:

- Alternative 1 – Coagulation + Clarification + Microfiltration + RO
- Alternative 2 – Direct Coagulation + Microfiltration + RO
- Alternative 3 – Direct Coagulation + Ultrafiltration + RO

Each of the processes was capable of meeting the finished water quality goals. The RO process removes salinity and hardness to the extent that 20 to 30-percent of the RO feed water can bypass around the RO process for blending with RO permeate. Significant differences were identified in terms of reliability, ease of operation, chemical and power consumption, and residuals disposal. After weighing these differences, it was concluded that Alternatives 1 and 3 offered significant advantages over Alternative 2. Alternatives 1 and 3 were demonstrated as technically viable treatment processes. However, Alternative 1 is more robust with the highest number of treatment barriers to multiple contaminants.

Based on the pilot test results, cost and non-cost factors, AECOM recommended the County implement Alternative 1 as summarized below:

- *RO Pretreatment*:

  Alum coagulation, flocculation and sedimentation using conventional upflow solids contact clarification. Alum dosage of 150 mg/L with caustic pH control. Filtration of coagulated and settled water using Pall Microfiltration. Design operating conditions of 60 gsfd flux rate, 95-percent recovery, and 15 minute backwash frequency. Anti-scalant addition plus continuous biocide feed followed by 5-micron cartridge filtration. Pretreatment dosages of 3 mg/L anti-scalant and 3 mg/L biocide.

- *RO Desalting*:

  Single pass 3-Stage RO trains, 6 elements per pressure vessel, employing DOW FilmTec BW30XFR high rejection brackish water RO membranes. Operating recovery of 87-percent and 12.5 gsfd water flux.

- *By-pass Blending*:

  Finished water comprising a 20 to 30-percent bypass blend of RO pretreated feed water with RO permeate.

- *Residuals*:

  Clarifier sludge blowdown discharge to sludge thickening tank. Clarified overflow from sludge tank is discharged back to head-end of clarifier. Thickened sludge pumped to sewer for disposal. MF backwash water returned directly to clarifier influent. RO concentrate discharged to sewer.

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Enzymatic Treatment of Alginate to Reduce UF/MF Membrane Fouling for Municipal Wastewater Reuse

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ABSTRACT

Wastewater reuse has proven to be effective and successful to solve water shortage problems and to support the sustainable development of the economy. Nonpotable reuse is a widely accepted practice that will continue to grow in many parts of the world. In order to meet the safety and quality requirements for wastewater reuse, advanced treatment technologies like membrane filtration are necessary. However, polysaccharides, the polymeric carbohydrates secreted by microorganisms from the effluent of wastewater treatment plants may cause significant membrane fouling. Alginate is one the typical polysaccharides found in wastewater effluent. This study explored using the enzyme of alginate lyase to catalytically degrade alginate in order to decrease their affinity and fouling potential to γ-Al_2O_3 membranes of 0.2 and 0.02 µm pore size, respectively. Size exclusion chromatography indicates a significant decrease in molecular weight of alginate after enzymatic reactions for 2 hours. Enzymatically treated alginate caused less fouling on both membranes than original alginate at pH 6.7±0.3 and ionic strength of 0.075 M. Alginate lyase reduced the foulant resistance by 82% and 85% for 0.2 and 0.02 µm membranes, respectively. Compare to 0.2 µm membrane, enzyme had more significant enhancement of backwashing of 0.02 µm membrane with a 100% recovery rate obtained. The foulant structure composed of treated alginate was more readily removed by backwashing, suggesting reversible fouling. The advantages of using enzymatic technique to control membrane fouling include high efficiency and no damage to the membrane materials.

Keywords: membrane fouling, alginate, alginate lyase, enzyme, depolymerize, ultrafiltration, microfiltration