A PILOT STUDY USING SEAWATER REVERSE OSMOSIS MEMBRANES IN COMBINATION WITH VARIOUS PRETREATMENTS TO MEET THE CHALLENGES OF PACIFIC SEAWATER DESALINATION

Rich Franks, Hydranautics, Oceanside, CA
Dr. Mark Wilf, Hydranautics, Oceanside, CA
Nikolay Voutchkov, Poseidon Resources, San Diego, CA
Pravin Murkute, Hydranautics, Oceanside, CA
Jason Kizer, Zenon Environmental, San Diego, CA

Introduction

The desalination of seawater by reverse osmosis has long been considered an alternative and innovative water source for Southern California since the technology was first developed in the 1960s. The first large seawater RO commercial plants in California were built in 1985 and 1987 at Diablo Canyon nuclear Power Plant and Gaviota Refinery. One of the first major municipal seawater desalination plants in Southern California to produce water for potable use began operation in Santa Barbara, CA in the mid-1990s. This plant was eventually decommissioned due to the availability of lower cost fresh water supplies from the state aqueduct. The plant was later dismantled and transferred overseas.

The relatively higher cost associated with seawater desalination has traditionally limited its widespread use in the United States in general and in Southern California in particular. But during the past five years, thanks to membrane technology improvements, power reduction through more efficient pumping equipment, creative design options such as co-location with existing power plants, and subsidies offered by local water agencies such as the Metropolitan Water District (MWD), seawater desalination by reverse osmosis is now considered a viable alternative technology for production of potable water on a large scale[1]. As of January 2006, at least five major seawater desalination plants, each with a capacity greater than 10 MGD (38,000 m3/day), have been proposed and are in various stages of planning and development[2].

One of these proposed Southern California desalination plants will be located 25 miles north of the city of San Diego in the town of Carlsbad adjacent to the Encina power station. In support of the proposed desalination plant, a pilot study was initiated in early 2003 consisting of an RO system treating filtrate from one of three separate pretreatment units. The operation of this pilot plant has demonstrated the cost benefits of the recent developments in RO membrane technology and has confirmed the advantages of desalinating cooling water from a power plant. These advantages, which have been discussed in more detail elsewhere[1,3,4], include the use of existing intake and outfall structures and the reduced energy associated with treating water of elevated temperature as compared to that of the open ocean.

The Carlsbad pilot plant testing has allowed for the evaluation of some of the specific features of co-location with the power plant. Unlike typical open intake seawater desalination plants which draw their feed from pipes located hundreds of meters off shore and four to ten meters below the ocean surface, the source water for the desalination pilot is drawn from a shallow seawater lagoon through existing power plant intake channels that protrude above the waterline. The lagoon water is more susceptible than open-ocean water to fluctuations in quality during occasional events of heavy rains or high-intensity algal blooms. Two measurable changes in water quality occurred during the three-year pilot testing period and provide valuable data on the performance of the seawater desalination system under challenging conditions. This paper will compare the performance of the RO during those source water disruptions with performance during normal times of normal water quality to illustrate both the advantages and challenges of seawater desalination at this site in particular and Southern California in general.

Pilot Objectives

The objective of the pilot study is to demonstrate the feasibility of seawater desalination in support of the proposed 50 MGD (190,000 m3/d) seawater desalination plant to be located adjacent to the Encina Power Station. Specific objectives of the pilot study include:

- Evaluate the performance of the RO system under various conditions including dry and wet weather as well as periods of algal blooms.
- Compare the performance of sand filter pretreatment, MF membrane pretreatment, UF membrane pretreatment, and the performance of the RO when running on filtrate from the various pretreatment systems.
- Demonstrate the performance of high-productivity, high-rejection seawater RO membranes. Determine RO system feed pressure and salt rejection using energy saving membranes and assess boron rejection alternatives.

RO Process Description

Raw water source

Source water for the desalination pilot is taken from the 253 acre Agua Heionda Lagoon located adjacent to the Encina Power Plant. The lagoon was originally created in 1954 to provide a source of power station cooling water. The area of the lagoon near its connection to the open ocean is dredged every 16 to 18 months to maintain adequate volume of cooling water to the power plant and remove silt accumulated in the intake area as a result of tidal and wind action. Residential development lies to the north of the lagoon and limited agricultural activities occur along the southeastern shore. The lagoon water is primarily composed of Pacific Ocean seawater with occasional seasonal runoff from two creeks, 23 storm drains, and a 29 square mile watershed which drains into the lagoon[5]. Except during times of occasional heavy rainfall which does not occur every year, salinity remains consistent at 32,000 to 34,000 ppm. Biological activity and the concentration of potential foulants such as organics vary depending on seasonal influences such as rainfall and algal blooms.

Raw water from the lagoon is drawn from the power station's open intake and used for cooling before being processed by the desalination pilot. The increase in power plant effluent temperature relative to the lagoon water varies between 3 ^oC and 10 ^oC depending on cooling requirements of the power plant and the ambient ocean water temperature. The power plant draws between 200 MGD and 800 MGD (0.76 million m3/d to 3 million m3/d) of water through 2 inch bar screens followed by 3/8-inch fine self-cleaning traveling screens. The water is then delivered to the condensers of the plant's power generation units. Chlorine is injected at low levels such that concentration in the power plant effluent is kept below 0.02 ppm. Biological control of the cooling water lines is also done through periodic heat treatment by recirculating power plant cooling water and elevating the water temperature to 40 ^oC for a period of four to six hours. Heat treatment is completed every six to eight weeks.

After leaving the power plant condensers, the water is discharged back to the ocean by way of a canal which delivers the cooling water to a separate effluent lagoon from where it is discharged to the ocean. It is from this effluent lagoon that a submersible pump draws 180,000 gpd (680 m3/d) for the desalination pilot. The source water for the pilot plant is filtered through a 3/8-inch strainer, and then transferred to an equalization tank for processing by the pretreatment systems. Seawater pumped to the pilot varies daily and seasonally in temperature depending on weather and power plant demands. During summer months, the combination of warm seawater and high power demand can elevate daily average feed water temperature to 30^{o}C (and hourly average to 32 ^{o}C). During winter nights, hourly average feed water temperature can drop to 15 ^{o}C and daily average temperature can be as low as 18 ^{o}C. **Table 1** below gives a typical analysis of the seawater processed by the pilot unit.

Table 1. Seawater Pilot Intake (Power Station Effluent) Water Quality

	unit	value
Turbidity	NTU	2
pH		8.0
Ca	ppm	379
Mg	ppm	1798
Na	ppm	9695
K	ppm	541.5
Ba	ppm	0.01
Alk	ppm as CaCO3	122
SO4	ppm	2190.5
Cl	ppm	18719
F	ppm	1.2
B	ppm	4.2
Br	ppm	59.5
TOC	ppm	0.2

RO configuration

The RO is configured with two pressure vessels piped in series. Each pressure vessel contains four, eight-inch seawater elements to simulate a single, eight element vessel. Concentrate flow is manually controlled using a concentrate control valve while permeate flow is manually adjusted using the high pressure pump bypass valve. The RO pilot runs at 50% recovery to produce between18 gpm and 22 gpm of permeate. Depending on the surface area of the particular element installed and the permeate flow, average system flux is between 8 gfd and 10 gfd.

Since the start of the pilot operation in 2003, several different types of seawater elements have been tested including high area, high flow membranes as well as membrane with high salt and high boron rejection. The performance at standard test conditions of the various seawater elements tested are shown in **Table 2** and reflect the evolution of seawater membrane technology over the past five years as increasing permeability is achieved while high salt and high boron rejection is maintained. These performance improvements have come about by focusing research and development on all aspects of the seawater element and its components, including membrane barrier structure, element design, and element manufacturing. The culmination of these improvements, the SWC5, was first demonstrated at this sight on May 4, 2005. Feed pressure at startup was 803 psi. Permeate TDS was 165 ppm and permeate boron was 0.74 ppm boron. A summary of operating conditions is given in **Table 3**.

Table 2. Performance at standard wet test condition (800 psi, 32,000 ppm NaCl, 25°C) of Hydranautics seawater RO membranes tested at the Carlsbad desalination pilot between 2003 and 2006.

Element	*Flow*	*Rejection*
SWC4	5500	99.8
SWC3	5900	99.7
SWC3+	7000	99.8
SWC4+	6500	99.83
SWC5	9000	99.8

Table 3. Performance of RO at starup on May 4, 2005 using eight new SWC5 membranes in series; operating at 50% recovery and 8 gfd.

	units	*Feed*	*Perm*
Temperature	°C	26	n/a
pH		7.6	n/a
Salinity	ppm	34,000	165
Boron	ppm	4.4	0.74
Flow	gpm	36	18
Pressure	psi	803	4

RO Pretreatment

The RO is run on filtrate from one of three different pretreatment systems. One of the pretreatments consists of sand filtration while the other two are capillary MF or UF membranes.

Sand Pretreatment

The granular-media pretreatment system includes two Parkson Dynasand© D-2©continuous backwash upflow filters in series, further referred to as a D2© system. The first filter has a coarse (0.9-mm) sand media bed which is 2.03 m (80-inch) deep. The second filter contains finer (0.5-mm) sand media and its media depth is 1.02 m (40 inches). **Figure 1** depicts the D-2 pretreatment system. As the seawater passes through the sand filter media the sand granules travel from the bottom of the filter to the top and back to the bottom in a continuous motion. Seawater solids trapped by the sand media travel downwards with the sand particles to the bottom of the filter. From there, the removed solids are lifted upwards to the sand washer located on the top of the filter via an air lift, and are removed from the filter cell as a waste filter backwash (reject). Both first and second-stage filters have instrumentation for continuous turbidity monitoring and data logging. The second-stage filter is equipped with a particle counter as well.

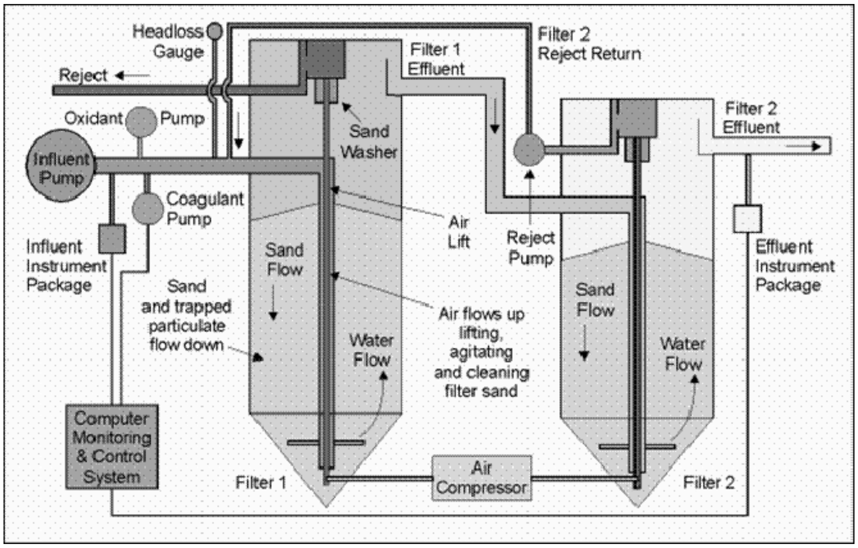

Figure 1. Parkson Dynasand© D-2©continuous backwash upflow filters in series used as one of three pretreatment systems for the SWRO pilot.

The source seawater is conditioned with ferric sulfate at a dosage of 2 to 15 mg/L and chlorine (0.3 to 1.5 mg/L) prior to entering the first filter stage. In addition, polymer is fed to the source water during heavy rain and red tide events to enhance the flocculation of the source water particles prior to filtration. Ferric sulfate and all other chemicals are fed upstream of a static mixer installed on the feed pipe at a distance of approximately 400 times the feed pipe diameter upstream of the entrance to the first-stage filter to simulate the full-scale location and performance of the static mixer. No chemicals are added to the second stage feed water of the D-2 system.

The actual ferric sulfate dosage varies depending on the amount of solids in the source seawater. The amount of chlorine added to the source water is selected to be sufficient only insofar as to be consumed within the filter beds. Second-stage filter effluent contains little to no chlorine residual. Chlorine concentration produce an oxidation-reduction potential (ORP) of the second-stage filter effluent below 200 mV. This ORP is acceptable for processing through the RO membranes and has no negative effect on membrane integrity, useful membrane life or performance. Nonetheless, when the RO was treating effluent from the sand filters, sodium meta bisulfite (SBS) was dosed in the RO feed before the RO cartridge filters as a precautionary measure.

MF Membrane Pretreatment

The Hydranautics HYDRAsub™ microfiltration pilot consists of a test vessel which contains two completely submerged membrane modules with 12 membrane fiber bundles per module (**Figure 2**). Each bundle contains over 16,800 capillary fibers. The fibers are made of polypropylene and have outside diameter of 0.31 mm and wall thickness of 0.035 mm. The fiber pore size is less than 0.2 μ and fiber porosity is 45 percent. The total active surface area of one module is 2,700 sq. ft. (250 m2). The production capacity of one module is 18.7 gpm at 10 gfd (102 m3/day at flux of 17 lmh).

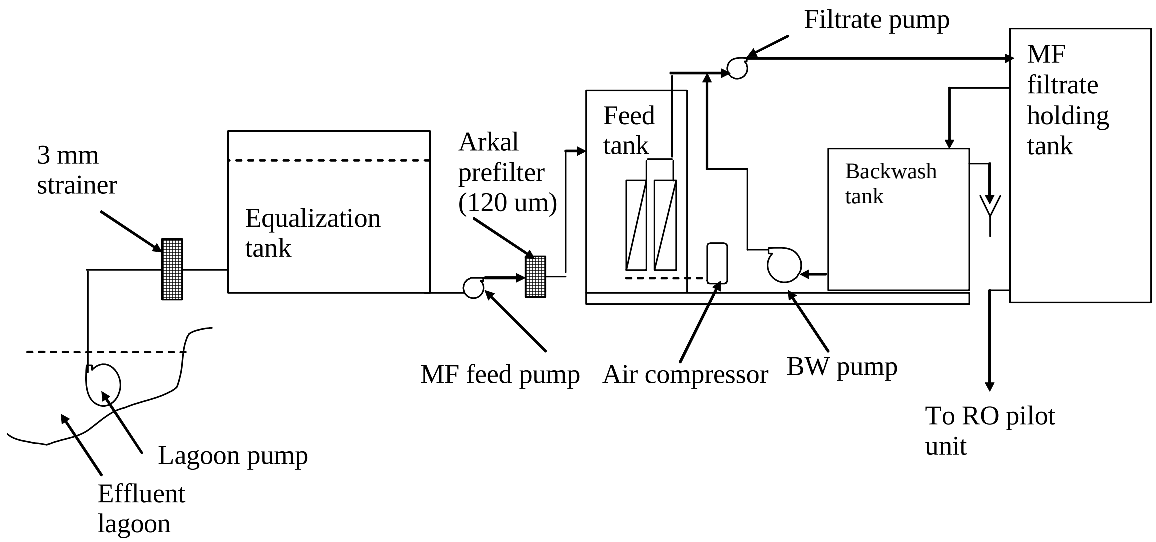

Figure 2. Microfiltration Pretreatment System

The permeate side of the modules is connected to the suction of a centrifugal pump, which moves the seawater across the MF membranes in direct-flow (with bleed) operation. As the membrane fibers foul during the filtration process, higher vacuum is required for production of the same amount of filtered water (permeate). The pump suction pressure is regulated by a variable frequency drive controlling the pump motor speed. This system is also equipped with instrumentation for feed water and filtrate turbidity monitoring, and for automated data reporting and acquisition.

The MF filtration process sequence consists of 15-minute filtration cycle followed by 15-second backwash cycle. The membrane surface is kept clean by air scouring. During the backwash cycles membrane filtration effluent is forced in a reverse direction, i.e. from the inside of the membrane lumen through the fiber walls out into the test tank. The reversal of flow direction results in improved removal of foulants deposited on the membrane fiber surface. The MF modules are periodically cleaned using chemically enhanced backwash (CEB) with a combination of chlorine and mineral acid. Under normal operating conditions the CEB frequency is once a day. The cleaning-in-place (CIP) frequency of the MF system is typically 60 to 90 days. To date the MF system has been operated without chemical conditioning of the source seawater.

The MF system feed seawater is prescreened by a self-cleaning disk filter with a nominal screening size of 100 µ. The self-cleaning disk filter was selected after a conventional micro-screen of the same size was tested for eight months and replaced because of the more reliable and consistent performance of the disk filter. Initially a 120-µ mesh micro-screen was used for MF membrane feed seawater prescreening. Although this size micro-screen was adequate to protect the integrity of the MF fibers, it did not provide an effective removal of the larvae of the barnacle particles in the source seawater. As a result barnacle growth was observed on the MF vessel's inner walls after approximately six months of operation. Barnacle incrustations are very difficult to remove and their uncontrolled growth may interfere with the normal operations of the pretreatment system. While adult barnacles are quite large, their larvae are relatively small and can pass through 120-µ screen openings. Subsequent investigation by an expert marine biologist identified that the size of the barnacle larvae in question is approximately 100 µ. To address this issue, the 120-µ screen was replaced with 100-µ screening filters. After the installation of the finer screen filter, no barnacle growth in the MF reactors was observed. Subsequent investigations of the MF influent indicate that barnacle larvae were effectively retained by the prescreening equipment.

UF Membrane Pretreatment

The same prescreening filters successfully used on the MF filtration unit where used before the ZeeWeed® UF filtration unit. The UF water treatment is a low energy immersed membrane process that consists of outside-in, hollow-fiber modules immersed directly in the feed-water. The small pore size of the membranes ensures that no particulate matter, including *Cryptosporidium* oocysts, *Giardia* cysts, suspended solids or other contaminants of concern, will pass into the treated water stream.

The pilot system uses six modules each with an area of 500 ft^2 for a total of 3000 ft^2 of membrane surface area. At a maximum flux rate of 40 gallons per square foot per day (gfd), the pilot unit is capable of producing 120,000 gallons of UF pre-treated feed to the RO pilot skids. Each module is comprised of 40,000 individual fibers with a nominal pore size of 0.02 µm. The membrane material is comprised of a PVDF based polymer.

The filtration process consists of a 40-minute filtration cycle followed by a backwash cycle. The backwash cycle is made up of a number of different sequences. The backwash cycle starts by aerating the membranes for 15-seconds followed by a 30-second reversal of flow where a portion of the permeate is sent back through the fibers to the membrane process tank. During this backpulse, aeration is maintained to assist in the removal of foulants from the membrane surface. The membrane tank is then drained. Since the membrane system operates in deposition mode, the tank drain is the only point where solids are rejected by the system. During the tank drain, aeration is maintained at a constant air flow rate regardless of backpressure on the aeration diffuser. This effectively applies the aeration energy in a constant manner throughout the membrane column. The procedure results an overall system recovery of 95% at an operating flux of 27.5 gfd.

The UF membranes are periodically cleaned using a maintenance cleaning procedure or chemically enhanced backwash (MC or CEB). The membranes can be cleaned using either an oxidizer or an acidic solution. The most common chemicals used are chlorine or mineral acid. The CEB procedure is performed once per 24 hour period. Chemical concentrations used during the CEB procedure are 50-250mg/L of an oxidizer and 500-1000mg/L of an acidic solution. The total duration of the CEB procedure is generally less than one hour per day.

A more extensive cleaning procedure known as a recovery clean is performed when the TMP level of the membranes rises to 12 psig. This is similar to a CEB procedure except the concentrations of chemicals used are higher and the soak times are longer. To date, no pretreatment chemicals have been utilized at this site.

RO Performance

To illustrate both the challenges and advantages of RO operation at this sight, three different cases, using three different pretreatments to treat the raw seawater under three very different seawater conditions are compared. Each case begins with newly cleaned RO membranes and presents data on RO feed quality, membrane permeability, and differential pressure to compare the typically stable performance of the RO with performance when the source water has been adversely effected by heavy rainfall or heavy marine activity.

Case 1. Dry Weather Performance

Case 1 refers to operation in the winter of 2006 using SWC5 membrane, and demonstrates the performance of the RO during typical seawater conditions in the absence of severe algal blooms or storm water runoff. During this time, raw seawater turbidity ranged between 0.5 and 5 NTU (**Figure 3**). Temperature fluctuated between 16 ^{o}C and 22 ^{o}C with some short spikes to 26 ^{o}C. RO feed water from the UF pretreatment was stable with turbidity below 0.03 NTU and SDIs usually below 2 (**Figure 4**). Soon after the startup of the RO system using SWC5 membranes, a phytoplankton bloom occurred. SDIs reached 2.9 on the UF filtrate and 4.9 coming from the sand filter (**Figure 5**). Microbial activity in the RO feed during this bloom was 10^3 counts/mL-slightly higher than the typical 10^2 counts/mL. TOC concentration based on grab sampling remained below 5.0 ppm during and after the bloom.

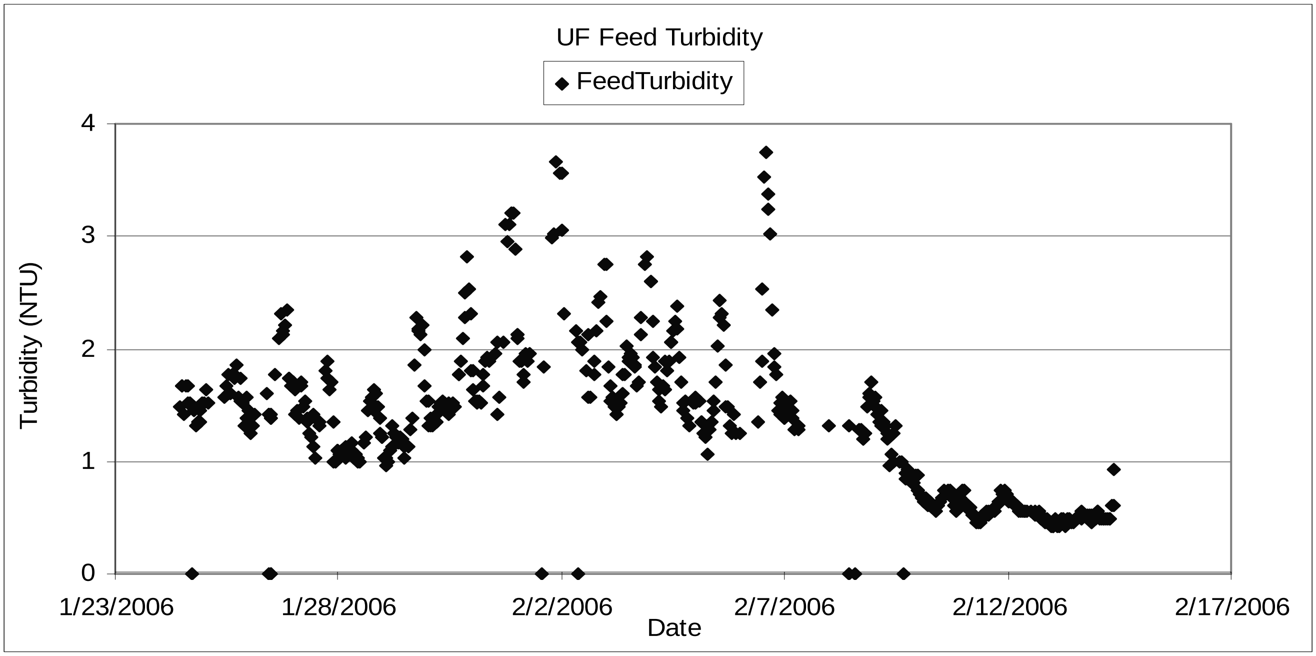

Figure 3. Feed turbidity to the UF pretreatment during dry weather conditions.

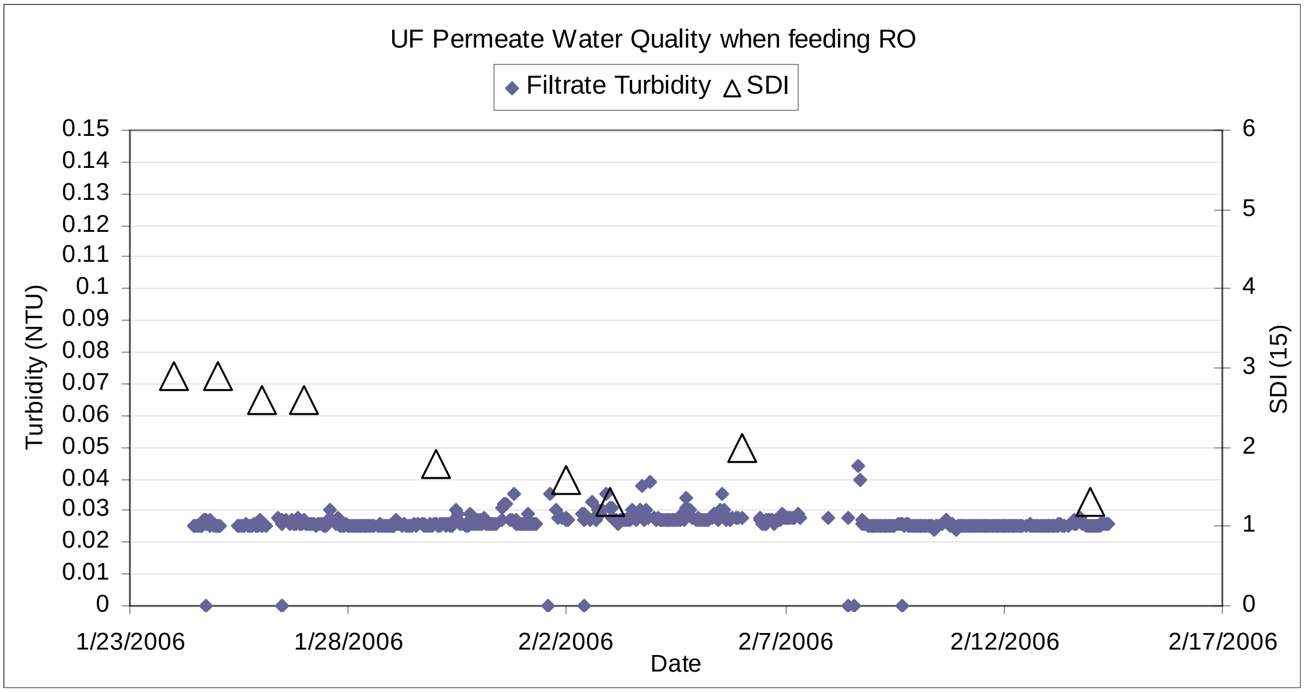

Figure 4. UF filtrate water quality (turbidity and SDI) when feeding RO during dry weather conditions.

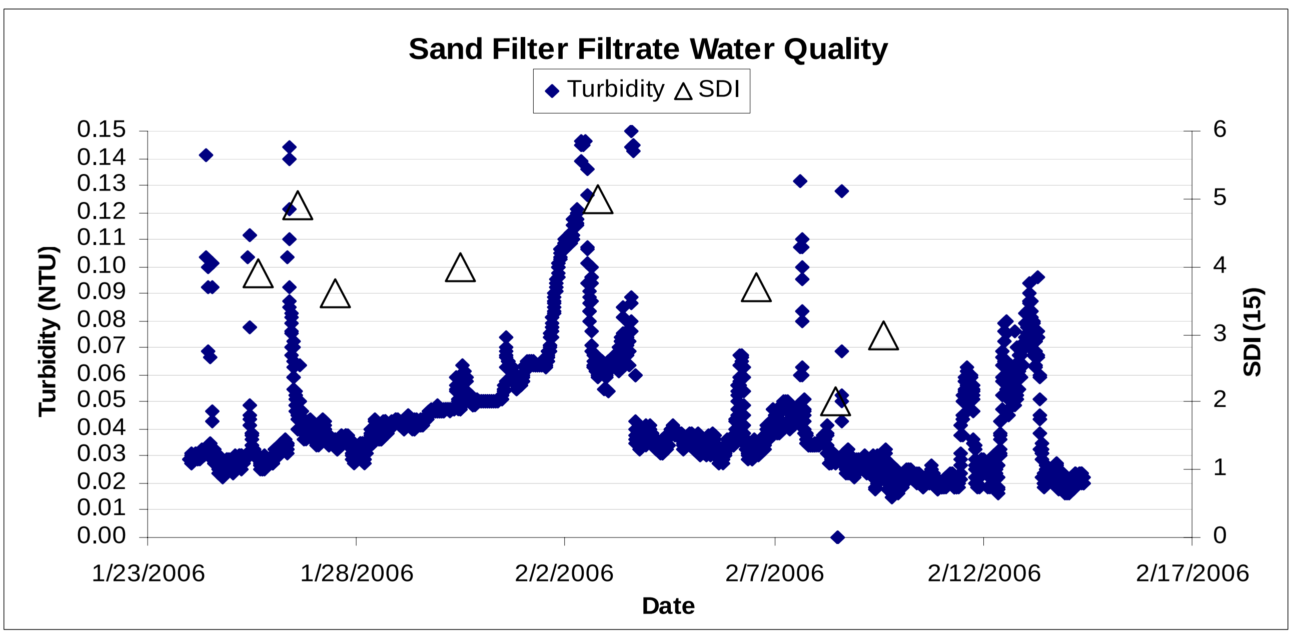

Figure 5. Sand filter filtrate water quality (turbidity and SDI) during dry weather conditions.

RO performance during this time was stable (**Figure 6**). Differential pressure, when corrected for temperature, was consistent at 19 to 20 psi. Microbial growth on the lead element was moderate to light. Membrane permeability was stable at 0.035 gfd/psi during and after the phytoplankton bloom and showed very little change during the three weeks of operation of RO permeate flux rate at 8 gfd and continued to remain stable after flux was increased to 10 gfd (17 lmh) on February 16. Overall salt rejection was 99.7%.

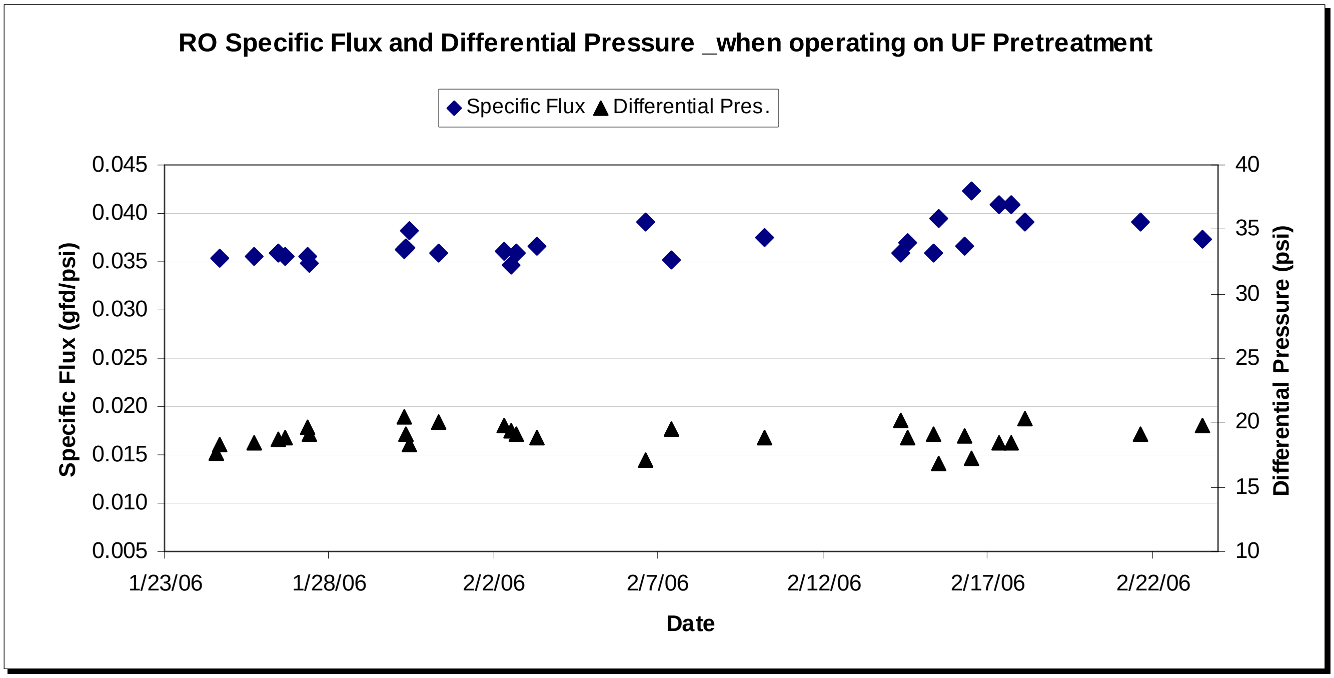

Figure 6. RO specific flux and differential pressure when treating UF filtrate during dry weather condition.

Case 1 is typical of the RO performance during dry weather and normal marine conditions when lagoon water is of fair to good quality and TOC remains below 5 ppm. Based on historical trends, such conditions are typical during a high percentage of the year. But the source water quality is susceptible to upsets during times of heavy rain or intense algal blooms. Two such events occurred during pilot operation; providing valuable data on the operation of the RO and the effectiveness of the pretreatments during periods of degraded source water quality.

Case 2. Wet weather performance

San Diego is an arid region with an average annual rainfall of 11 inches. Long periods of dry weather and droughts are periodically interrupted with precipitation during the late fall and early winter months. These precipitation cycles allow for the build up of foulants, such as automobile pollutants deposited on roadways and pesticides, nutrients and chemicals in agricultural and industrial areas; foulants which are flushed into the ocean during periods of heavy rainfall. An extreme dry-wet cycle occurred during RO testing when a two year drought in 2003-2004 was followed by record precipitation of 23 inches during the fall and winter of 2004 to 2005[6]. The effect of surface runoff from heavy rains on water quality and RO performance can be seen when, beginning on January 28, 2005, new SWC4 elements began treating filtrate from the sand filters. Within the first few hours of startup, 0.41 inches of rain fell on the region. The RO immediately began to loose permeability at the rate of 1% per day over the next 15 days (**Figure 7**). The differential pressure remained stable for the first six days, followed a sharp increase from 20 psi to 25 psi during the remaining nine days (**Figure 7**). The unstable RO performance beginning at startup corresponds to the disruption in the feed water quality caused by the rainfall. Both Turbidity and SDI spiked at 0.135 NTU and 4.8 respectively on January 29 (**Figure 8**)- indicating a higher than normal level of foulants reached the RO. The foulants included organics which deposited on the membrane surface causing the loss of permeability. These organics also provided a food source for subsequent microbial growth which inhibited flow through the RO feed channels and subsequently increased differential pressure. TOC analysis of the feed water on February 11 (14 days after the storm event) indicates that TOC levels in the source water were higher than the typical level of 0.2 ppm or less.

Cleaning of the membranes with a high pH solution removed a dark brown foulant indicative of organic fouling. After cleaning, RO performance was only partially recovered. After restarting the system, the permeability remained stable, but differential pressure began to increase again. To further investigate the nature of the fouling, a lead and tail element were removed and analyzed. The elements and the inside wall of the pressure vessel were covered with a light slimy film. The surfaces of the front end seal carrier of the lead and tail elements were tested for microbial growth. The lead element seal carrier showed very heavy growth. The tail element showed moderate growth. Autopsy of the elements revealed a brown coating, indicative of organic fouling, on the lead membrane and a lighter brown coating on the tail membrane. An EDAX of the membrane surface showed the foulant also contained a small amount of inorganics, including 1.6% aluminum and 1.4% iron.

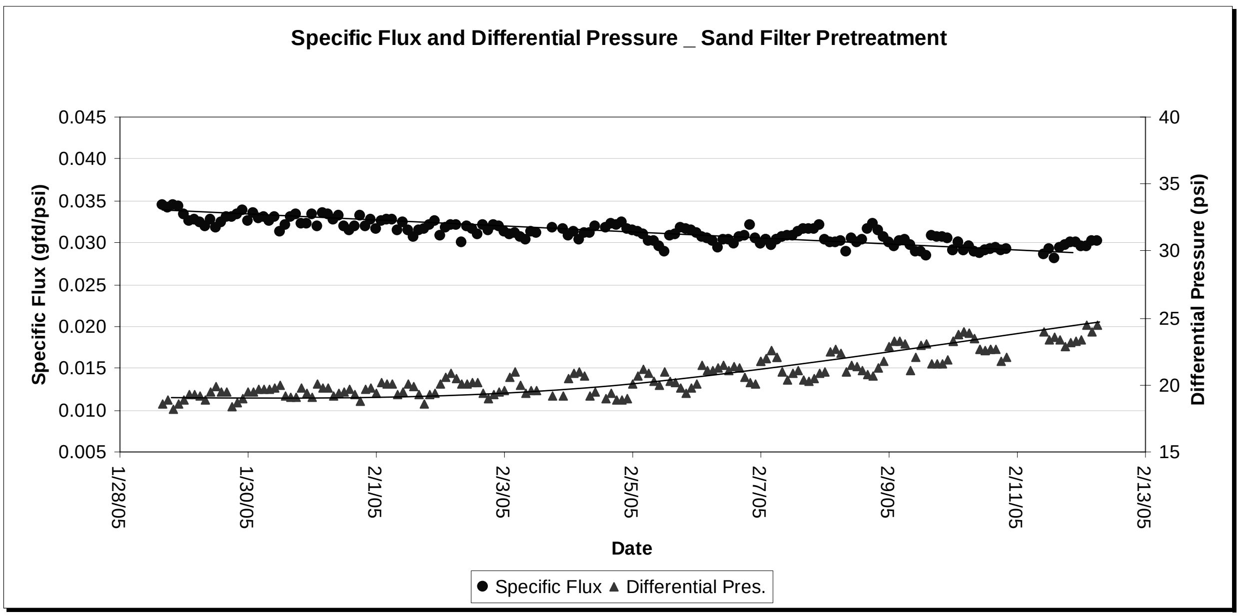

Figure 7. RO specific flux and differential pressure when treating filtrate from sand filters during wet weather condition.

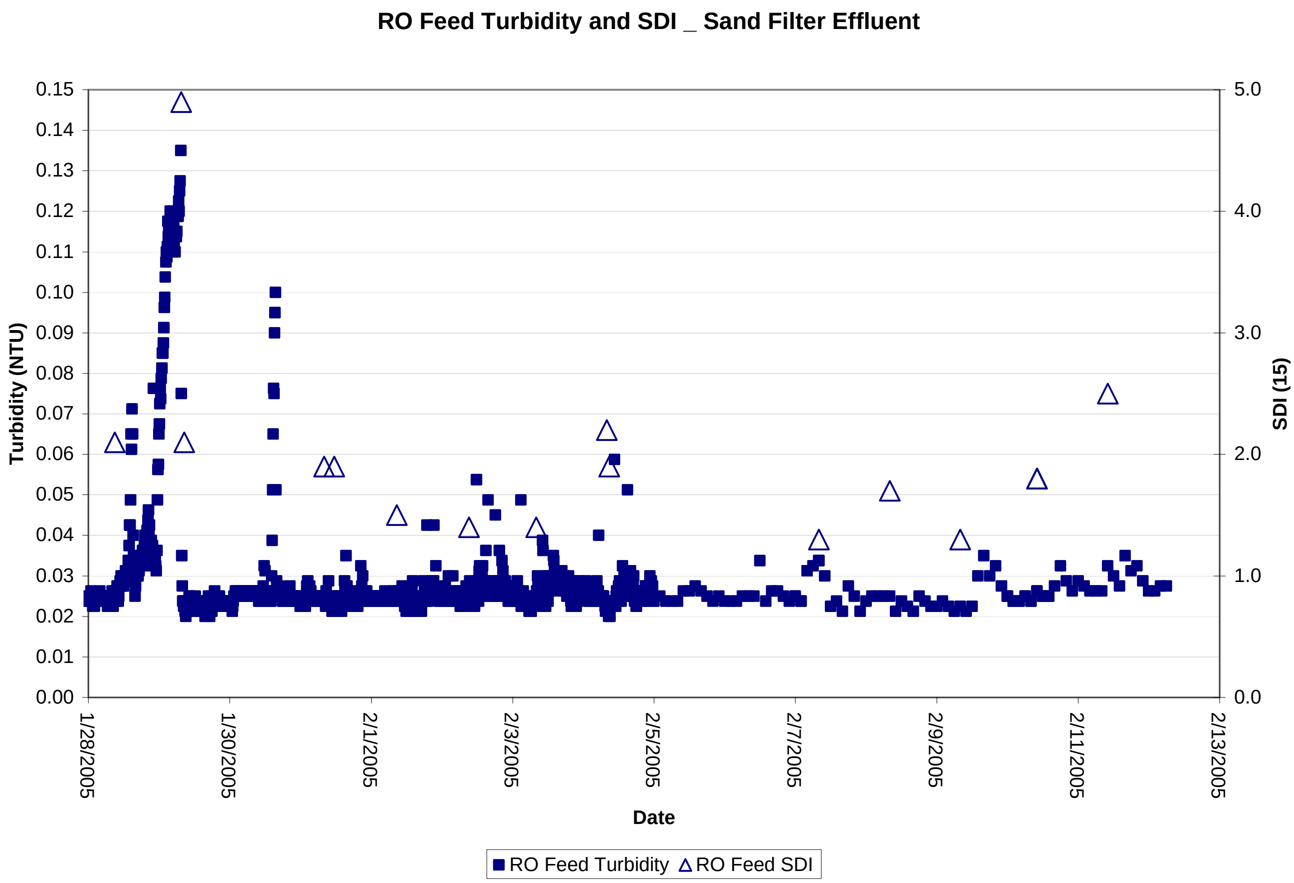

Figure 8. Sand filter filtrate water quality (turbidity and SDI) during wet weather conditions.

Case 3. Performance during red tide

Another natural occurrence that has an impact on RO performance similar to the runoff from heavy rains, is algal blooms - specifically, a phenomenon known as "red tide". The red tide gets its name from the reddish brown color caused by an over abundance of a particular pigmented single celled organism called dinoflagellates. Under certain conditions, these organisms can reproduce very rapidly. Though the specific causes of the blooms are not known, they are likely related to a combination of high nutrient concentrations and warmer temperatures. There is a growing concern in the scientific community that occurrence of red tide is increasing in some areas due to human activities which introduce high levels of nutrients such as nitrogen and phosphorous into coastal waters. The moderate Southern California climate makes ocean water susceptible to occasional red tide events. Although red tides do not occur every year, their magnitude may be significant enough to effect RO system performance. Two red tide events have occurred during the three years of pilot operation. The first occurred during the fall of 2003 and a second, more intense red tide, occurred during the spring and summer of 2005.

High flow SWC5 elements began treating MF filtrate on May 4, 2005-one week after a red tide algal bloom appeared along the Southern California coast. This algal bloom progressed to one of the worst and longest red tide events in recent California history[6]. Relative to operation following the winter storm event discussed in Case 2, feedwater to the RO was warmer, fluctuating between 20 ^{o}C and 27 ^{o}C. Unlike the storm event, no one single spike in the RO feedwater quality occurred. SDI of the MF filtrate fluctuated between 1.5 and 3.3, but remained well below the 4.0 limit for acceptable RO feed

(**Figure 9**). Likewise, RO feed turbidity remained between 0.02 and 0.055 NTU; never exceeding the 0.5 NTU limit. Despite the relatively good filtrate quality as measured by SDI and turbidity, a rapid decline in RO performance occurred similar to the performance decline following the heavy rains. A combination of organic fouling followed by biological growth led to a drop in permeability of 13% during the first nine days of operation and a rapid increase in differential pressure from 18 psi to 23 psi (**Figure 10**).

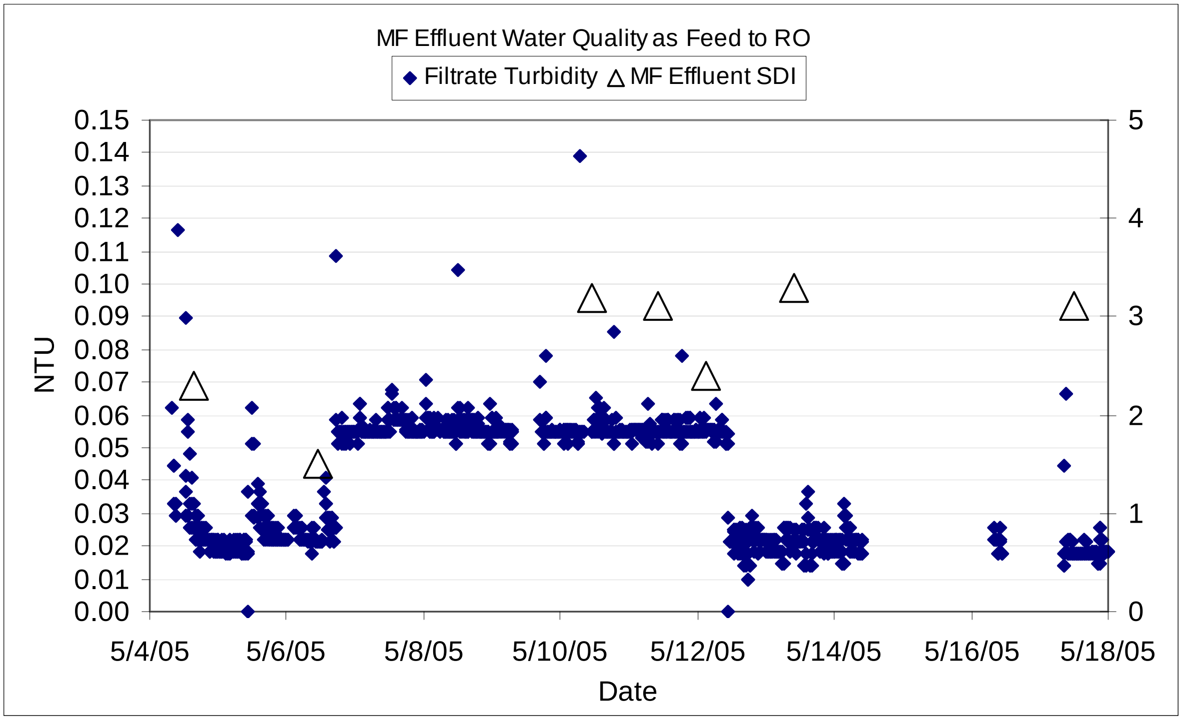

Figure 9. MF filtrate water quality (turbidity and SDI) during red tide conditions.

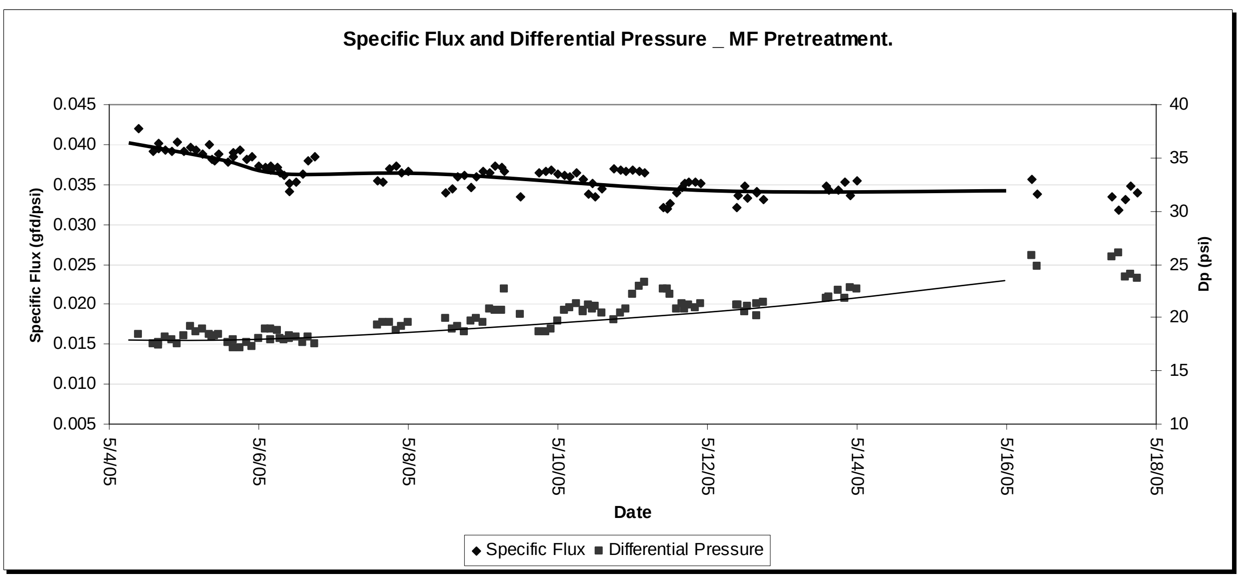

Figure 10. RO specific flux and differential pressure when treating filtrate from MF during red tide condition.

Periodic grab samples taken of RO feed water during this period showed a wide swing in TOC levels. This fluctuation in TOC is characteristic of the cyclical phases of the algae bloom. If the algae bloom is in the active growth phase, the organisms consume organics from the water which in turn lowers TOC concentration, if the organisms are in a die out phase their decomposition adds to the TOC levels.

Based on a single test, microbial activity in the RO feed was 10^3 counts/mL- similar to the mild algae bloom during stable RO performance in case 1. Unlike case1, microbial growth on the face of the lead element was heavy after five days of operation.

Cleaning of the RO produced results similar to those in Case 2. A dark brown foulant was removed and permeability was partially restored, but differential pressure increased again soon after restart. Cartridge filters removed after two weeks contained a build up of a similar dark brown foulant.

Discussion

Based on the performance of the RO during normal seawater conditions, in the absence of heavy rainfall and intense algal blooms, membrane filtration or sand filtration provides sufficient pretreatment for stable operation of the RO system at this site. However, extreme cases when source water quality is influenced by excessive storm water runoff or intense algal blooms, present a challenge to both sand and membrane pretreatment systems. The elevated organic levels associated with these events may result in accelerated RO membrane biofouling.

Sand filters are more susceptible to turbidity spikes associated with heavy rain fall. Sand filters and membrane pretreatment systems both provide limited reduction of TOC concentrations associated with periods of challenging water quality. The high level of organic material which reaches the RO during these events fosters biogrowth on the RO membranes and on the RO feed/brine spacers.

The continuous chlorination practiced during the operation of the sand filters has both advantages and disadvantages. This low-dosage chlorine addition (0.2 to 0.5 mg/L) aids source water coagulation and typically lowers filter effluent SDI by 1 to 1.5. However, the continuous chlorination followed by dechlorination, which controls biogrowth in the sand filters, may contribute to biofouling of the RO system. The chlorination-dechlorination effect is more pronounced during red tide conditions and is practically negligible during normal operating conditions. The most likely mechanism of the effect of chlorination-dechlorination on the RO filtration process is that chlorine present in the sand filters serves to break down organic material into assmilable organic carbon (AOC), a form which acts as a food source for the re-growth of bacteria in the RO. Typically, the source seawater does not contain large amount of organics (TOC < 0.2 mg/L) and chlorination-dechlorination has more positive than negative effect on the filtered water quality. However, during red tide events or intense storms the source water contains elevated levels of TOC (TOC > 2.5 mg/L) and the negative effect of chlorination-dechlorination is more pronounced.

Though the MF membrane pretreatment produced a more consistent filtrate quality than the sand filter during challenging source water conditions when turbidity was greater than 5 NTU and TOC was greater than 2.5 mg/L, actual operation of the MF during the upsets proved more challenging due to fouling of the MF fibers. Similar to the sand media filters, the MF filtrate contained elevated organic levels which resulted in accelerated RO membrane biofouling.

Other studies conducted at seawater sites with similar runoff and algae bloom challenges, have demonstrated that UF/MF membrane pretreatment system produces acceptable filtrate quality (based on low turbidity and SDI<3) during challenging source water conditions [7,8]. But these studies lack data on the ability of the UF/MF membrane pretreatment to reduce the rate of fouling in the RO. As **Figure 9** in Case 3 (operation during red tide) demonstrates, low SDI and turbidity measurements of the MF membrane effluent do not necessarily correspond to stable RO performance during periods of challenging water quality.

Future plans of test unit operation

The Carlsbad pilot plant operation is projected to continue during the period of the full-scale plant design. The objectives will be to optimize operation of the pretreatment system during the periods of challenging raw water quality. In parallel operation of RO membranes will be optimized by experimenting with recovery and permeate flux rate to achieve stable and cost effective operation under all conditions of seawater quality expected at the Carlsbad site.

Conclusions

Results of pilot operation at the Carlsbad site demonstrated the following:

1. High permeability seawater RO membranes provide stable performance and good permeate quality, including good boron reduction, during typical periods of good source water quality. The RO performed well at 8 gfd (14 lmh) and at the higher flux of 10 gfd (17 lmh).
2. During occasional periods of high biological activity in the raw water, indications of membrane biofouling, such as pressure drop increase, were observed, regardless of pretreatment used.
3. Both the media filtration and membrane filtration pretreatment were able to produce RO feed water of satisfactory quality during the "dry" periods and in absence of algae blooms.
4. During the periods of heavy rain and/or algae blooms the elevated content of organic matter in the pretreatment filtrate from both the sand media and the membrane pretreatment systems, resulted in accelerated RO membrane biofouling. Additional pilot testing will be completed during the design phase of the project in order to optimize desalination plant design for cost-effective operation during these conditions.

Reference

1. Alspach, B.(2005), "Factors Driving the Increasingly Favorable Economics of Seawater Desalination in America", *WaterReuse Symposium*, Denver, CO.
2. Water Desalination Report (16 January 2006), Volume 42, Number 2.
3. Voutchkov, Nikolay and Jonathan Dietrich (2005), "Pilot Testing Alternative Pretreatment Systems for Seawater Desalination in Carlsbad, California", *International Desalination Association World Congress*, Singapore.
4. MacLaggan, Peter M. (2003), "Carlsbad Seawater Desalination Project Fresh Water Supply & Regional Perspective", International Desalination Association, Bahrain.
5. MEC Analytical Systems Inc. (1995. 1994 and 1995) "Field survey report of the ecological resources of Agua Hedionda Lagoon". 47 pp.
6. Fitzsimons, Elizabeth "Rainy Season Appears to be Anything But" San Diego Union Tribune, January 30, 2006.
7. Pearce, Graeme, Santi Talo, Kamran Chida, Amir Basha, Aziz Gulamhusein, (2004), "Pretreatment options for large scale SWRO plants: case studies of UF trials at Kindasa, Saudi Arabia, and conventional pretreatment in Spain" *Desalination* 167, pp. 175-189.
8. Bonnelye, Veronique, Miguel A. Sanz, Jean-Pierre Durand, Lodovic Plasse, Frederic Gueguen, Pierre Mazounie, (2004), "Reverse osmosis on open intake seawater: pre-treatment strategy", *Desalination* 167, pp. 191-200.