Meeting the demand for potable water in Orange County in the 21st century: The role of membrane processes[1]

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Introduction

The population of Orange county, a semi arid region located on the pacific coast of southern California between Los Angeles and San Diego Counties, is projected to increase from 2.2 to 3.0 million in the next 20 years. In order to meet the increased demand for potable water, the local groundwater management agency and the county sanitation district have proposed an ambitious project that will produce a reliable supply of high quality, low salinity water that will be used to recharge the local groundwater basin. This Groundwater Replenishment (GWR) System, will be implemented in three phases by the year 2020 and will ultimately reclaim 100,000 acre feet of wastewater per year (afy) using a membrane based desalting process. The project is possible because of advances in membrane processes and is a logical extension of the existing wastewater reclamation process currently in operation at Water Factory 21 (WF21). The following paper provides a brief description of the treatment objectives and the benefits of the GWR System.

What is the Groundwater Replenishment System?

The GWR System is a wastewater recycling project. Potable quality water will be produced from municipal wastewater at an advanced water treatment (AWT) facility located on the current sites of OCWD and OCSD in Fountain Valley, California. Approximately 80% of the total water produced by the GWR System water will be piped 13 miles to the OCWD recharge facilities located near the City of Anaheim, while the balance will be used to expand the existing seawater intrusion barrier (Figure 1).

The GWR System is a logical extension of a 1970s reclamation project called Water Factory 21 (WF-21) which has injected potable quality reclaimed water into the coastal aquifers to prevent the ingress of seawater into the groundwater basin since 1976. GWR System source water will be clarified secondary effluent containing less than 15.0 milligrams per liter (mg/L) biochemical oxygen demand (BOD), 5.0 mg/L suspended solids (SS), 1,000 mg/L total dissolved solids (TDS) and 11 mg/L total organic carbon (TOC); the same source water supplied to WF-21. The GWR System product water, however, will contain 0.3 mg/L of TOC, negligible amounts of TSS and BOD and approximately 100 mg/L TDS. The quality of the GWR System water is better than the product currently produced at WF21 which contains approximately 2.0 mg/L TOC and 250 – 400 TDS. GWR System water also exceeds the most stringent of the current California

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Department of Health Services (DHS) criteria for aquifer recharge which currently allow TOC levels of 2.0 mg/L. DHS also requires a 2,000 feet horizontal separation and a one-year detention time between the point of injection and extraction so that the reclaimed water content at any production wells is less than 50%. GWR System water will receive additional natural treatment as it migrates through the aquifer. Routine testing at WF-21 indicates that the travel time to the nearest monitoring well, located within 1,000 feet of the point of injection, is approximately 2 years and that the extracted water contains approximately 1.0 mg/L of TOC, 50% less than the TOC concentration found in WF-21 water.

Development of the GWR System treatment process

The GWR System is possible because of the development of membrane systems over the last ten years. Most indirect potable reuse facilities consist of a pretreatment stage followed by an advanced treatment process for removal of organic carbon or salts. The advanced treatment processes are either granular activated carbon, reverse osmosis, ion-exchange, electrodialysis or a combination of these processes. Until the early 1990's the best pretreatment for indirect potable reuse projects was based on a conventional treatment process, consisting of flash mixing and flocculation at pH 11.4 using slaked lime, clarification, recarbonation for pH control and granular media filtration. Although this approach has worked successfully at plants in California, Colorado and Virginia, the GWR System is based on the use of low pressure, microporous membranes in place of the conventional treatment process. The use of a microporous membrane process, such as ultrafiltration (UF) and microfiltration (MF), as the a pretreatment for reverse osmosis (RO) has become the industry standard for the reclamation of municipal wastewater for industrial and indirect potable reuse applications. Clarified secondary effluent will be treated with a microporous membrane (MF or UF) to remove suspended solids, followed by 100% demineralization using thin film composite reverse osmosis (RO) membranes to reduce salinity, organic nitrogen and carbon. The RO product stream will be disinfected using a combination of ultraviolet radiation and chloramination prior to groundwater recharge.

Use of thin film composite reverse osmosis to remove organics and salts

The demineralization stage of the GWR System will use thin film composite RO membranes configured in spiral wound elements. These RO elements are produced by several manufactures in various sizes to fit all commercially available RO pressure vessels. The uniform design of the RO element and pressure vessel has promoted intense competition between RO manufactures and has inspired technical innovations that have reduced RO operating pressures, increased salt and organics rejection and decreased manufacturing costs.

Since 1997, OCWD has operated a 700 afy (0.7 mgd) membrane MF/RO/UV demonstration project for the GWR System at WF-21 to generate water quality data, develop detailed costs and refine design criteria for the GWR System. The demonstration project used thin film composite RO membranes in place of the cellulose acetate RO membranes currently used at WF-21. Water quality data from the demonstration plant indicates that GWR system water will meet all the requirements of the National Primary Drinking Water Regulations (Table 1). The thin film composite membranes were also very effective at removing the so called "wastewater indicator compounds". These compounds are derivatives of chemicals that are commonly used in foods and detergents. Common wastewater indicators include ethylenediamine tetraacetic acid (EDTA) and the structurally similar, but slightly more biodegradable nitrilotriacetic acid (NTA); both compounds are chelating agents and phosphate substitutes used as a stabilizers in detergents. EDTA and NTA are present in the raw wastewater and persist through the biological treatment process. Other wastewater indicators include the alkylphenol polyethoxcy carboxylates (APEC), formed by biodegradation and/or carboxylation of alkylphenol polyethoxylates (APEO), a class of non ionic surfactants, in the wastewater treatment process. These compounds are present in the feed water to the GWR system at concentrations up to 70 μg/L but are reduced below the detection limit 0.1 μg/L by the reverse osmosis membrane (Table 2). Consequently, the water produced by the GWR system exceeds the federal requirements for drinking water, does not contain the common compounds that are indicative of wastewater contamination, and contains less dissolved solids than all other sources currently available for groundwater recharge in Orange county, including local river water and waters imported from the Colorado river and northern California (Table 3).

Use of microporous membranes as pretreatment for reverse osmosis

In contrast to the standard design of the reverse osmosis membrane elements and pressure vessels there are a variety of microporous membranes processes that can be used to treat municipal effluent upstream of the RO membrane. Several of these systems have been evaluated during the development studies for the Groundwater Replenishment System. The follow section briefly describes some of the general features of these pretreatment systems that have been evaluated in the last few years at the Orange County Water District.

UF and MF membranes used in municipal applications are generally manufactured as hollow fibers. Several manufactures cast hollow fiber membranes from organic polymers by various proprietary techniques based on the phase inversion casting process. In the phase inversion process a well solvated polymer is induced to precipitate, or "gel" as a solid film. For example, crystalline cellulose acetate will dissolve in a mixture of acetone and pyridine, then precipitate as a microporous film at the interface between the organic solvent and an aqueous solution. A similar change of phase is observed with polypropylene, which will exist in a solvated form in an organic solvent at over 150^{o}C and will revert to a crystalline form at a temperature of 150^{o}C. The structure of the resulting MF or UF membrane can be either symmetric or asymmetric (Figure 2). The structure of symmetric membranes is essentially uniform from the feed side (active surface) to the filtrate side; whereas, asymmetric membranes have a separate active surface layered on a porous support (Figure 2). The phase inversion process allows membranes to be produced with high, or low, surface porosity and with a narrow, or broad, distribution of pore sizes. The molecular weight cut off of the UF membranes used at WF21 have ranged from 13,000 to 500,000 Daltons, where as the nominal pore size of the MF membranes ranged from approximately 0.08 to 0.2 mm. The resistance of the polymers to strong oxidants range from high to negligible.

The microporous membrane elements used at WF21 have contained between 4,000 and 20,000 individual hollow fiber membranes (Table 4). The packing density, number of fibers per element, is a function of outside fiber diameter (O.D) which can range from 0.5 to 1.5 mm. The microporous membrane element is assembled by placing the base of the fibers in a mold. A resin, usually an epoxy, is injected into the mold an allowed to cure under either static or dynamic conditions (Figure 3). Under static curing conditions no external force, other than gravity, acts on the resin. In the absence of an external force the resin can be drawn up the outside of fiber by capillary forces in a phenomena referred to as “wicking” (Figure 3.B). It is possible that “wicking” of the resin can create a sharp edge at the base of fiber. This could create the potential for fiber damage should excessive lateral movement occur at the fiber base. The effect of the sharp edges can be mitigated by injecting a layer of elastomer at the junction between the base of the fiber and the top of the resin (Figure 3.B). The purpose of the elastomer is to adsorb shocks and limit lateral movement at the base of the fiber. Under dynamic conditions the membrane element is placed in centrifuge and the resin will cures in the presence of centrifugal force acting in a direction that is normal to the junction between the hollow fibers and top of the mold. The presence of the centrifugal force creates a concave surface at the top of the cured resin and minimizes the extent to which the resin can be drawn up around the outer surface of the fiber during the curing process (Figure 3.C).

Hollow fiber membrane elements can either be housed in a module (essentially a pressure vessel) or immersed in a tank or water treatment basin. For membrane elements housed in a module, the feed stream can contact either the outer surface of the fiber (shell side) or the lumen (inside) side of the fiber. The microporous system can be operated in either direct or cross flow filtration mode. The direct filtration mode of operation is similar to a multiple-batch filtration process. During operation, the feed water flow is normal to the membrane surface and suspended solids are retained on the membrane surface. The accumulation of solids at the surface continuously increases the resistance to flow across the membrane. The filtration process stops after either a preset time (typically 20 minutes on wastewater), or a preset increase in the transmembrane pressure (typically 1.0 to 1.5 psi), and the accumulated solids are removed from the surface by a backwash. In the crossflow process, the feed stream is pumped across the membrane surface which establishes a velocity gradient with a minimum at the membrane surface and a maximum in the bulk phase. A variety of mechanisms (inertial lift, shear enhanced diffusion) facilitates the transport of retained material away from the membrane and out of the module. Membrane elements immersed in a tank are operated in direct filtration mode. The lumens of the hollow fibers are directly connected, via a manifold, to the suction side of a pump. When the pump operates, a vacuum on the lumen side draws filtered water through the walls of fiber. Some forms of the immersed membrane design incorporate an aeration system which can be operated to continuously scour the outside of the microporous fiber to facilitate transport of retained material back into the bulk solution.

Effectiveness of microporous membranes as pretreatment for RO

The precursors to fouling of the RO membranes on secondary effluent include microorganisms, fine particles, colloids and macromolecules[1]. A general measurement of the effectiveness any RO pretreatment process to remove the particulate fouling precursors is the silt density index (SDI). The SDI test, as applied at WF21, uses a 0.45 μm membrane filter pad to measure the fouling potential associated with particles in the RO feed stream. There are limitations to the SDI test: It is difficult to gauge the potential for macromolecular fouling and it is not possible to differentiate between UF and MF pretreatment using this SDI test as the pore size of the SDI membrane is greater than the pore size of the pretreatment membrane. The SDI test can be improved to the point where it is possible to discriminated between UF and MF treated effluent data using a 0.2 μm pad [2] or using a modified fouling index test [3]. However, in this case, the SDI test was used only to highlight differences between the membrane pretreatment and the conventional high lime pretreatment. To this end the SDI test has been useful. The RO membranes used at WF21 operate on secondary effluent treated by chemical clarification using slaked lime followed by media filtration; the SDI of this feed water ranges from 4.5 to 6 and the RO membranes are cleaned at approximately 750 hour intervals [4]. In contrast, the SDI values for clarified secondary effluent filtered through a variety of UF and MF membranes typically range from 0.5 to 2.5 and the interval between chemical cleaning of the RO membranes downstream of the MF and UF systems is at least approximately 3000 hours.

Although UF and MF remove the particulate fouling precursors it is possible for other forms of fouling, such as inorganic scaling, to occur on the RO membrane. The precipitation of inorganic salts at recoveries above 75% can be effectively prevented through the addition of 3.0 mg/L of threshold inhibitor to the UF of MF treated secondary provided that the pH is held below 7.4. However, an inorganic scale developed on membrane elements in the final pass of an RO system operating downstream of an immersed MF membrane. The shell side of the MF fibers were continuously scoured with air at 3.3×10^{-3} scfm/ft^2. The normalized flux for the polyamide thin film composite membrane decreased from 36 gfd to 22 gfd after 390 hours of operation at which point the RO membranes were rinsed with product water. The flux initially recovered to 28 gfd then declined to 17 gfd after another 500 hours of operation (Figure 4). This fouling was attributed to the precipitation of carbonate salts. The continuous aeration on the shell side of the MF fiber raised the pH of the clarified secondary effluent from 7.3 to 8.0; presumably by stripping dissolved gasses, such as carbon dioxide, which shifted the carbonate/bicarbonate equilibrium causing the precipitation of carbonate salts. It was possible to reverse the fouling by rinsing the membrane and lowering the pH of the MF filtrate to pH 7.0 through the addition of 93% sulfuric acid (Figure 4).

Effect of pretreatment membrane pore size on RO performance.

An un-compromised UF or MF membrane will reduce the concentration of the fouling precursors to various degrees depending on the membrane pore size. Consequently, it would be expected that an RO membrane would foul less if a 0.1 mm MF membrane was used as for pretreatment compared with a 0.2 mm MF membrane. It is difficult, however, to generalize about the mechanism of RO fouling. This is evident from the data for two sets of identical polyamide thin film composite RO membranes operating at an instantaneous flux of 10.4 gfd (Figure 5). The normalized flux for the RO membrane downstream of the 0.2 mm membrane decreased from 30 gfd to 20 gfd in the first 1000 hours of operation; in contrast the normalized flux of the RO membrane downstream of the 0.1 mm membrane of decreased from 30 gfd to 25 gfd. This trend continued for approximately 3700 h at which point the normalized flux for both sets of RO membranes reached 16 gfd (Figure 5). It is apparent from the normalized flux curves that the overall rate of fouling was greater for the RO membrane downstream of the 0.1 mm membrane. However, in the short term, the use of tighter pretreatment membranes reduced fouling on the RO membrane. In retrospect it would have been beneficial to clean the RO membrane downstream of the 0.1 mm membrane after 2500 hours to maintain a higher normalized flux.

Effect of a compromised pretreatment membrane on RO performance.

The normalized flux for a polyamide thin film composite RO membrane decreased from 27 gfd to 12.5 gfd in 750 hours as a result of a compromised membrane upstream of the RO membrane (Figure 6A). Loss of fiber integrity resulted in an increase in the SDI and the concentration of total coliforms in the RO feed water. The silt density index in the feed measured at approximately 100 hour intervals increased from 1.2 to 5; of the six samples collected, 4 were greater than 3. The presence of a 3 ppm combined chlorine residual in the pretreatment membrane filtrate masked the presence of total coliforms in most of the samples, however, by the end of the experiment the filtrate contained as much as 600 total coliform cfu/100 ml (Figure 6.B). After 750 hours the RO membrane was cleaned and all the pretreatment membrane elements were replaced. The SDI in the filtrate from the new pretreatment membrane ranged from 2.5 to 0.5 and the total coliform count was typically less than 10 cfu/100ml. After the pretreatment membranes were replaced, the RO operated with minimal fouling and the normalized flux decreased from 27 gfd to approximately 22 gfd over 1600 hours.

Advantages of microporous membrane pretreatment for reverse osmosis

Microporous membranes processes offer many advantages over the conventional pretreatment used at Water Factory 21. Microporous membranes processes occupy less space, do not require chemical pretreatment other than pre-chlorination, are easily automated, less maintenance intensive and improve the performance of the downstream processes. The thin film membranes used in the demonstration plant operated for more than 10,000 hours at a flux of 10.4 gallons per foot per day (gfd) with a TDS rejection of 98% at pressures of 130 to 190 psi. In contrast, the cellulose acetate attains pressures of 330 to 350 psi after 700 hours of operation at 10.4 gfd with a TDS rejection of 96% (Table 5). Microfiltration has simplified the reclamation process by eliminating the lime handling, addition and recovery systems as well as the flocculation, clarification, recarbonation and filtration processes, resulting in lower chemical requirements and elimination of the production and disposal of solid waste sludge, saving approximately $30/af. Moreover, by converting the pretreatment process to MF and replacing the cellulose acetate RO membranes with thin film composite membranes reduces the power costs by 60%, or $100 an acre foot. By using less energy, it is now possible to treat and recharge GWR System water using half the energy required to impact water from northern California and two-thirds of the energy required to import water from the Colorado River (Table 6).

In addition to the reduction in O&M costs, the use of MF would significantly increase the capacity of WF-21 through the more efficient use of available space. WF-21 is located in a neighborhood zoned for medium density housing with some retail and light manufacturing. Given the commercial and residential value of the land it would be prohibitively expensive to use any process other than membranes to produce the flows projected in the GWR System project for the year 2020. Membrane processes require only one-fifth of the space of conventional treatment processes. The flocculation, sedimentation and recarbonation basins plus the media filters at WF-21, occupy 29,000 ft^2 and treat 15 mgd, equivalent to a plant footprint of 520 gallons per square foot of plant per day ($g/ft^2/d$). In contrast, the plant footprint productivity of the full scale MF demonstration process is approximately 2500 $g/ft^2/d$.

Benefits of the GWR System

The GWR System has long term benefits for Orange County's water supply, offers more flexibility for the management of wastewater flows and supports regional efforts to develop local supplies and mitigate the effects of water transfers. The following is a brief description of some GWR System benefits.

Improved Regional Water Supply

Southern California is facing an acute shortage of water. By 2020, it is estimated that the annual demand will exceed supply by 1.43 million acre-feet [5]. It is impossible to overemphasize the need for southern California to develop new local sources of potable water. Sixteen million southern Californians and a dynamic $450 billion regional economy depend on a reliable and affordable supply of water. Increasing water demands are likely to result in a shortage in supply, particularly with an extended drought. OCWD currently requires approximately 300,000 afy to recharge the groundwater basin. It is estimated that an additional 150,000 afy of water will be required by the year 2020 to satisfy future demands on the basin [6]. The availability of imported water supplies from the Colorado River and State Water Project is uncertain. The GWR System would be capable of supplying at least two-thirds of the projected increase in demand and provide approximately 22% of the water needed to recharge the Orange County groundwater basin in the year 2020.

Improved Regional Water Quality

The biggest water quality issue facing Southern California is the rising levels of total dissolved solids (TDS), or salinity, in the water supply. The damage to residential and industrial water fixtures and groundwater supplies in Southern California that can be traced to the high levels of salinity is estimated at $750 million per year [7]. The Orange County groundwater basin receives local water from the Santa Ana River (SAR) and imported water from the Colorado River Aqueduct (CRA) and the State Water Project (SWP) (Table 3). The high levels of salinity in the SAR are attributed to the discharge of tertiary effluent from wastewater treatment plants in Riverside and San Bernardino counties. Similarly, the TDS levels in CRA can be traced to agricultural, industrial and municipal activities in the upper reaches of the Colorado River basin. SWP water contains low levels of TDS, however, the reliability of additional SWP supplies is very uncertain in light of the efforts to repair the Sacramento - San Joaquin delta. Consequently, the quality of Orange County's groundwater is mostly dependent on the quality of the SAR and the CRA. The use of GWR System water which will provide 100,000 afy (approximately 22%) of low TDS water for groundwater recharge will mitigate the increase in TDS introduced into the basin from the SAR and the CRA. Given that the TDS of the current recharge blend averages approximately 600 mg/l and that GWR System contains <100 mg/L TDS the quality of the new water mix will be 490 mg/L; a reduction of 110 mg/L or 18% as a result of the GWR System.

Wastewater Management Benefits

The OCSD Charter allows for water reclamation, recognizing its importance in resource management. OCSD has actively supported water reclamation by supplying a combined total of

17,000 afy of secondary effluent for WF-21 and non-potable reuse conducted by OCWD. Participation by OCSD in the GWR System expands this commitment to reclamation. More importantly, participation in the GWR System supports the OCSD waiver, under Section 301(h) of the Clean Water Act, from the requirement for full secondary treatment for effluent discharge. This waiver was granted by US EPA because OCSD has a history of producing superior quality effluent that is a blend of primary and secondary treatment and because OCSD has a highly effective industrial waste (source control) compliance program that limits toxins in the wastewater. In 1989, OCSD estimated that the 301 (h) waiver saved over $50 million per year in capital, operation and maintenance charges. Protection of this waiver is of the highest priority to OCSD. Under average operating conditions, participation in the GWR System will increase diversions of secondary effluent from OCSD Plant No.1 to the AWT Plant and recycled water facilities. This will support the waiver by reducing the effluent discharge to the ocean.

Participation in the GWR System will also assist OCSD in its efforts to manage effluent discharge to the ocean under wet weather conditions. During peak wet weather events, the OCSD Strategic Plan predicts wet weather peaks of about 750 million gallons per day (mgd) while the ocean disposal system capacity is approximately 480 mgd. To make up for this shortfall, the OCSD Strategic Plan is considering a variety of options including use of existing standby disposal facilities, retarding flows (peak shaving), and inflow reduction techniques to delay the near-term cost of constructing a second ocean outfall. However, the most significant way to reduce the peak is the diversion of flow through the GWR System. The initial capacity of the GWR System is approximately 78 mgd, however, the membrane processes tested by OCWD have the capacity to operate for short periods, typically 24 to 48 hours, at 50% above design capacity. This gives the Sanitation District the flexibility to divert 100 million gallons per day (mgd) from the ocean outfall. By diverting peak wet weather secondary effluent flows to the GWR System, the total discharge to the ocean would be significantly reduced. OCSD estimates that this method of peak shaving would delay the need to construct a new ocean outfall, at a cost $150 million, by at least ten years. If half of that delay is due to the GWR System (5 years), the savings at 6% interest spread over 20 years gives a $4 million per year benefit.

The California State Constitution and the CALFED Process

The use of reclaimed water, as proposed by CALFED in the GWR System, is consistent with the section of the California State Constitution dealing with the beneficial and reasonable use of water. A unique feature of the State Constitution is the uniform prohibition on the wasteful use of water. Article X, Section 2 of the Constitution contains the express proclamation that “the water resources of the State be put to beneficial use to the fullest extent of which they are capable, and that the waste or unreasonable use or unreasonable method of use of water be prevented”[8]. Reclaimed water is a valuable resource. The Porter-Cologne Act, Division Seven of the California Water Code, defines reclaimed water as water which, as a result of treatment of waste, is suitable for a direct beneficial use or a controlled use that would otherwise not occur and is therefore a valuable resource [9]. The tenet of Article X, Section 2 is reiterated in California’s Reasonable Use Doctrine. Under California Law, it is possible that the use of potable water could be considered a waste, or unreasonable, if reclaimed water is available and the water quality is appropriate for a particular use [9]. For example, the expansion of the seawater intrusion barrier could be accomplished using imported water, however, as reclaimed water is available at WF-21 the reasonable use doctrine would consider the use of imported water to be unreasonable. Moreover, it has been found that it is less expensive to expand the seawater intrusion barrier under the terms of the GWR System than to introduce imported water into the barrier [10]. The importance of this doctrine will increase as the state's water resources become further strained.

Conformance with Objectives of CALFED Process

The purpose of the CALFED process is to repair the health of the San Francisco Bay/San Joaquin Delta Estuary and improve water quality by decreasing the potential to form disinfection by-products, while maintaining, or increasing, the water supply capabilities of the delta to users throughout California. Water transfers through the Sacramento-San Joaquin Delta reverse the natural movement of water in this area, resulting in the ingress of seawater into the low salinity reaches of the Delta. Seawater ingress, combined with the inflow of agricultural run off from the San Joaquin Valley, has damaged the delicate ecosystem in the estuaries that form the Delta. As a result, 22 wildlife and 2 fish species require special protection in the Sacramento San Joaquin Delta. Under one CALFED proposal, future water imports and drought relief will partially depend on the implementation of Best Management Practices (BMPs) which include water conservation and water reuse. OCWD and OCSD will demonstrate their commitment to these BMPs through the implementation of the GWR System. By providing a new water supply that will be reliable even during drought conditions, the project will benefit all of California.

Conclusion

The GWR System is an example of how a suite of environmental problems associated with water supply and wastewater disposal can be solved through the application of innovative membrane processes. The project will provide for the water needs of Orange County's increasing population. It will partially offset regional losses of supplies from the Colorado River Aqueduct and possible reductions in expected deliveries through the Bay Delta. The GWR System water will be available in all seasons and contain less dissolved solids than imported water from the Colorado River. Consequently the GWR System will provide significant relief to Orange County in times of drought and, by lowering TDS levels in the groundwater, will help mitigate the damages to water fixtures that result from increasing levels of salts in imported supplies. The project also supports the reclamation objectives contained in the Orange County Sanitation Districts Charter and provides additional options for the management of wastewater discharge under wet weather conditions. Finally, the project is consistent with the reasonable use doctrine of the California State constitution and the efforts to restore the Bay Delta as outlined in recycling objectives of the CALFED process.

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TABLE 1
Groundwater Replenishment System Finished Water Quality[1]

Inorganic Chemicals (μg/L)					
Constituent	GWRS	MCL	Constituent	GWRS	MCL
Antimony	< 6	6	Cyanide	< 5	200
Arsenic	< 5	50	Fluoride	100	4000
Asbestos	NA	7 MFL	Lead	< 1	0
Barium	< 1	2000	Mercury	< 0.5	2
Beryllium	< 1	4	Nitrate (as N)	200	10,000
Cadmium	< 1	5	Nitrite (as N)		1,000
Chromium	< 2	100	Selenium	< 16	50
Copper	< 3	1300	Thallium	< 1	2

Synthetic Organic Compounds (SOC's)

Volatile SOC's (μg/L)		
Constituent	GWRS	MCL
Benzene	<0.5	5
carbon tetrachloride	< 0.5	5
1,2 dichlorobenzene	< 0.5	600
1,4 dichlorobenzene	0.9	75
1,1 dichlorethane	< 0.5	5
1,2 dichlorethane	< 0.5	5
1,1 dichlorethylene	< 0.5	7
cis-1,2 dichlorethylene	< 0.5	70
trans-1,2dichlorethylene	< 0.5	100
dichlormethane	3.4	5
1,2 dichlorpropane	< 0.5	5
1,3 dichloropropane	< 0.5	
ethylbenzene	< 0.5	700
chlorobenzene	< 0.5	100
styrene	< 0.5	100
1,1,2,2 tetrachlorethane	< 0.5	
tetrachlorethylene	0.4	5
toluene	< 0.5	1,000
1,2,4-trichlorobenzene	< 0.5	70
1,1,1 trichloroethane	0.3	200
1,1,2 trichloroethane	< 0.5	5
trichloroethylene	< 0.5	5
trichlorofluoromethane	< 0.5	150
trichlorotrifluoroethane	< 0.5	1200
vinyl chloride	< 0.5	2
xylenes	< 0.5	10,000
Total trihalomethanes	4.0	100

Radionuclides		
Analyte	GWRS	MCL
Gross Alpha	1.2	15 pCi/L
Gross Beta	1.5	50 pCi/L
Uranium	0.2	20 pCi/L
Radium	0.1	5 pCi/L

Non-Volatile SOC's (μg/L)		
Constituent	GWRS	MCL
Alachlor	< 0.05	2.0
Atrazine	< 0.1	3
Bentezon		
Benzo(a)pyrene	< 0.1	0.2
carbofuran	< 0.1	40
chlordane	< 0.1	2.0
2,4 D	< 0.5	70
Dalapon	< 0.1	200
Dibromochloropropane	< 0.01	0.2
di(2-ethylhexyl)adipate	< 2	400
di(2-ethylexyl)phthlate	< 2	6
Dinoseb	< 0.5	7
Diquat	< 4	20
Endothal	< 45	100
Endrin	< 0.03	2
Ethylene dibromide	< 0.01	0.05
Glyphosate	< 25	700
Heptachlor	< 0.01	0.4
Heptachlor Epoxide	< 0.01	0.2
Hexachlorobenzene	< 0.5	1
Hexachlorocyclopentadiene	< 0.5	50
Lindane	< 0.1	0.2
Methoxychlor	< 1.0	40
Molinate	< 0.5	20
Oxamyl	< 2.0	200
Pentachlorophenol	< 1.0	1
Picloram	< 0.5	500
Polychlorinated biphenyls	< 0.5	0.5
Simazine	< 0.1	4
Thiobencarb	< 0.5	70
Toxaphene	< 1.0	3
2,3,7,8-TCDD (Dioxin)[3]	NA	0.00003
2,4,5-TP (Silvex)	< 0.5	50

1. Constituents and maximum contaminant levels taken from the National Primary Drinking Water Standards
2. WF-21 has a waiver for asbestos fibers and dioxin

TABLE 2
Removal of Wastewater Indicator Compounds by Thin Film Composite Reverse Osmosis[1]

	Microfiltered Wastewater	GWR System Water1
Ethylenediaminetetraacetic acid	65 +/- 27 μg/L	ND
Nitrilotriacetic acid	1.6 +/- 27 μg/L	ND
alkylphenol polyethoxcy carboxylates	59 +/- 30 μg/L	ND

1. M.Reinhardt, Stanford University; Unpublished data from Santa Ana River Water Quality & Health Study

TABLE 3
Groundwater and Recharge Water Quality (Milligrams Per Liter)

		Possible Recharge Water Sources			
	Anaheim Groundwater	GWR System	Santa Ana River	Colorado River	State Project Water
Total Dissolved Solids	587	<100	505	670	250
Total Nitrogen	4.7	2.4	6.1	1.0	1.0
Total Organic Carbon	0.88	0.1	5.5	2.5	2.0

TABLE 5
Comparative Performance of Conventional and Membrane Processes

Process & Performance	**Water Factory 21 Process**	**GWR System Process**
Pretreatment	High pH lime	Microfiltration
Organics removal	50% GAC : 50% RO	100% RO
Product TOC	2.0 mg/L	0.1 mg/L
Space requirements	500 gal/ ft^2/day	2,500 gal/ ft^2/day
RO cleaning interval	4-6 weeks	8-12 months
Operation & Maintenance Costs	$320 per acre-foot	$190 per acre-foot

TABLE 6
Energy Requirements of Water Transfers to Southern California and the GWR System

	kilo watt hours per acre foot (kWh/af)		
	Colorado River Aqueduct	State Water Project	GWR System
Delivery	2,000	3,260	20
Waste treatment[1]	110	110	140
Ocean discharge	130	130	-
GWR System[2]	-	-	900
Reuse conveyance[3]	-	-	430
Total	2,240	3,240	1,470

Notes:

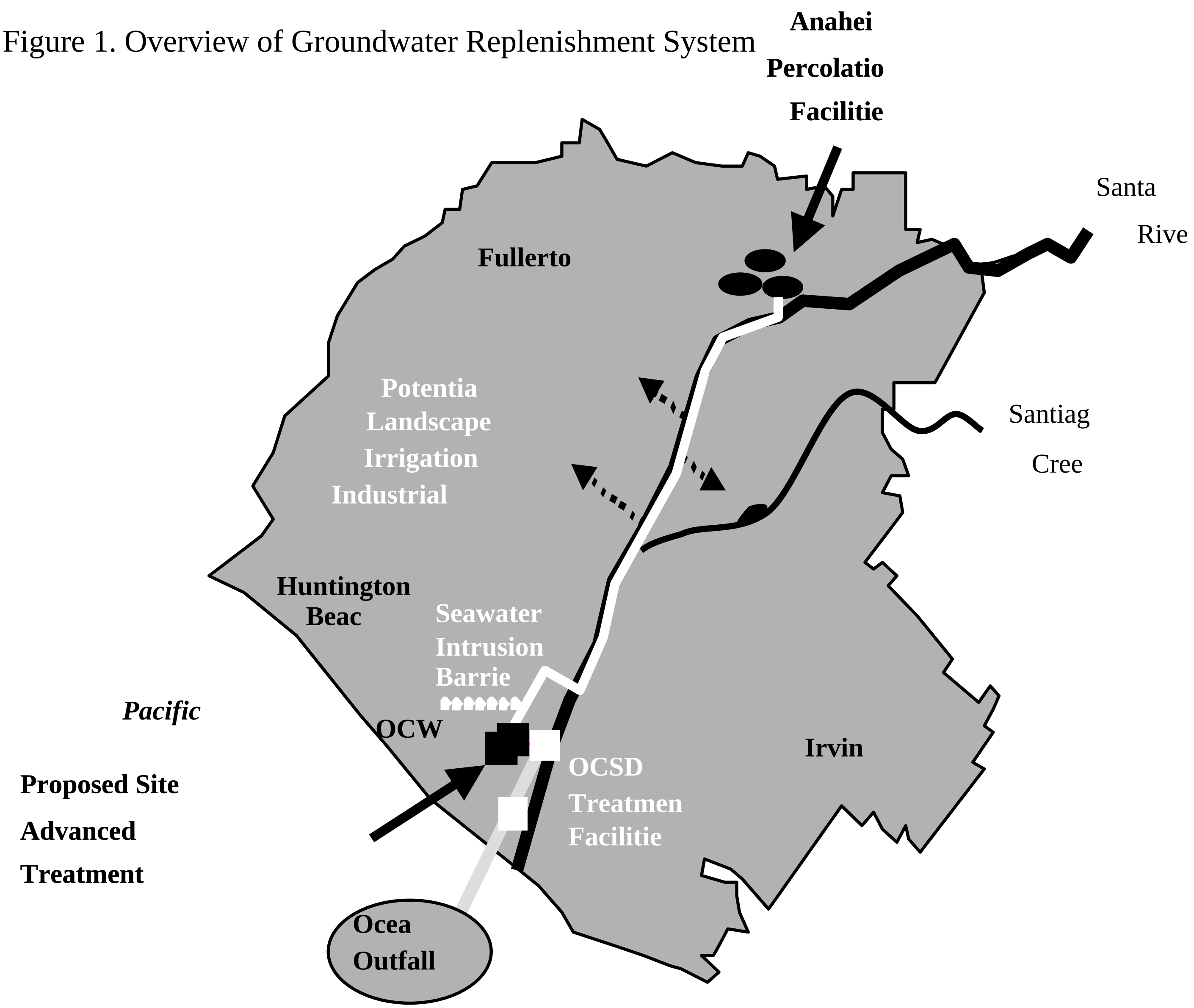
1. Energy requirements for wastewater discharged to the ocean based on 50:50 blend of primary and secondary. Water used for GWR System receives full secondary treatment.
2. GWR System process based on full treatment with MF, 100% demineralization with RO and 30% treatment using UV disinfection
3. Reuse conveyance energy requirements based on a blend of direct injection plus conveyance to recharge facilities.

TABLE 4
Membrane and Module Properties of Microporous Membranes Evaluated at Water Factory 21

Manufacturer	Koch UF	Zenon	Zenon	Zenon	Pall	Pall MF1	Pall MF2	Memcor	Memcor
Manufacturer’s Serial #	PM -100	ZW150-ADC	ZW500-CFA	ZW500-OCP	LGV-3010	XLSV-5200	XUSV-5203	M10	M10C
Material	PS	*	*	*	PAN	PE	PVDF	PP	PP
Symmetry	A	A	A	A	A	S	S	S	S
Pore Size (µm)	100,000 MWCO	0.08	0.08	0.035	13,000 MWCO	0.1	0.1	0.2	0.2
Porosity	*	25%	50%	50%	*	50-60%	50-60%	30-40%	30-40%
Fiber O.D. (mm)	1.32	1.9	1.9	1.9	1.4	1.2	1.25	0.65	0.55
Fiber I.D. (mm)	0.76	0.9	0.9	0.9	0.8	0.68	0.7	0.31	0.25
Exposed length (m)	1.02	1.5	1.65	1.65	2	2	2	0.97	0.97
Fibers per module	3228	1530	4670	4670	4800	4800	4800	11000	20000
Active Surface	lumen	shell	shell	shell	shell	shell	shell	shell	shell
Active Area per Fiber (m^2)	0.002	0.009	0.010	0.010	0.007	0.008	0.008	0.002	0.0017
Active Area per Module (m^2)	10.3	13.8	46.0	46.0	33.2	36.2	37.7	21.8	34.6
Active Area per Module (ft^2)	112	150	500	500	356	389	405	242	372
Potting Type	Static (1)	Static (2)	Static (1)	Static (1)	Static (2)	Static (2)	Static (2)	Dynamic	Dynamic

Static (1): Membranes potted under static conditions
Static (2): Membranes potted under static conditions + elastomer overlay
Dynamic: Membranes potted under dynamic conditions

Figure 1. Overview of Groundwater Replenishment System



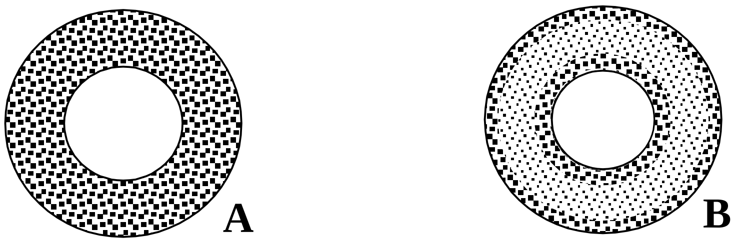


Figure2 Schematic of symmetric (A) and asymmetric (B) hollow fiber

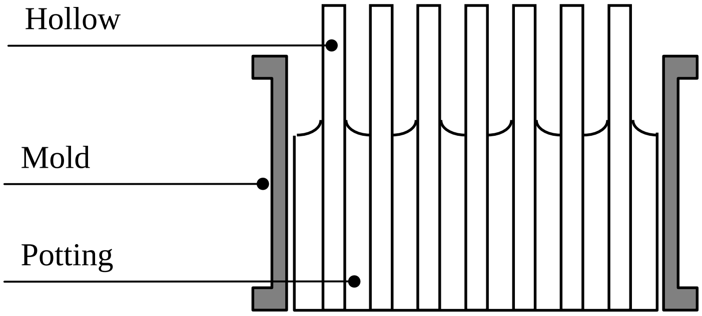


Figure3. Fiber bundle potted under static

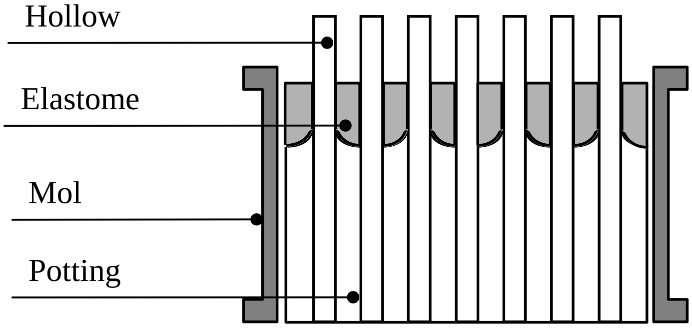


Figure3. Fiber bundle potted under static with elastomer

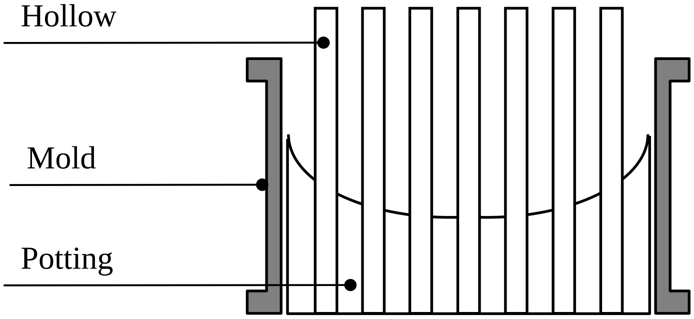


Figure 3.C Fiber bundle potted under dynamic

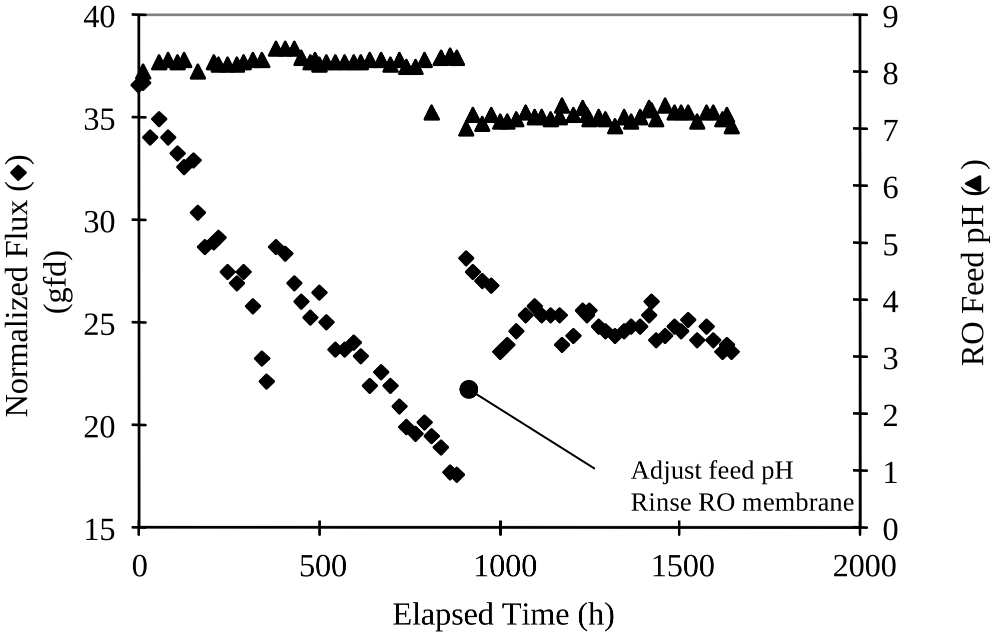


Figure 4. Normalized flux as a function of time for polyamide thin film composite RO membranes downstream of continuously aerated immersed MF membrane. The RO membranes were rinsed at 350 h & 750 h. Flux decline was arrested by controlling pH.

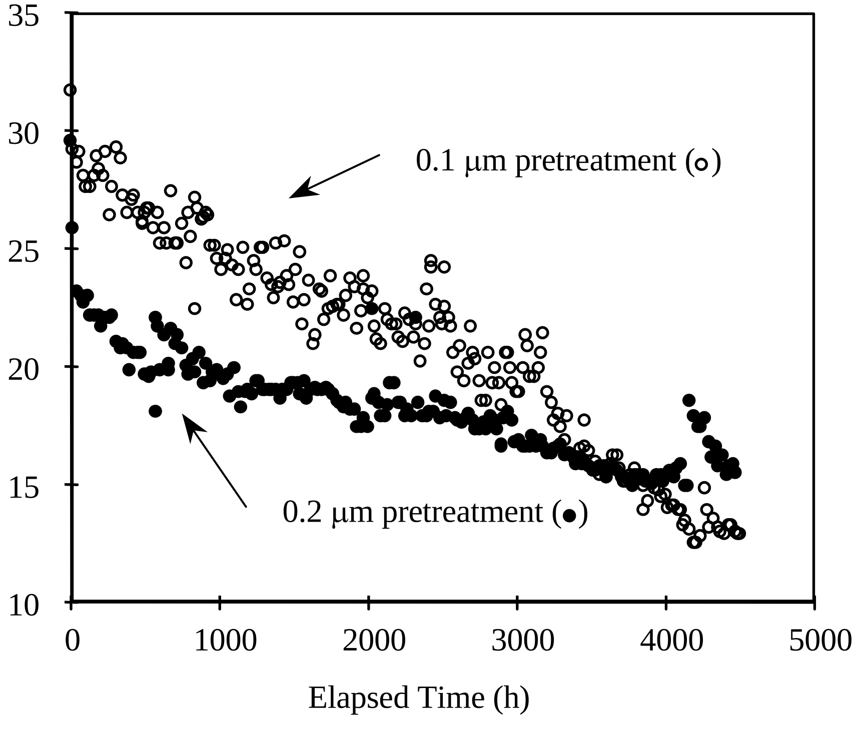


Figure 5. Normalized flux as a function of time for two sets of identical polyamide thin film composite RO membranes downstream of a 0.1 µm and 0.2 µm MF system.

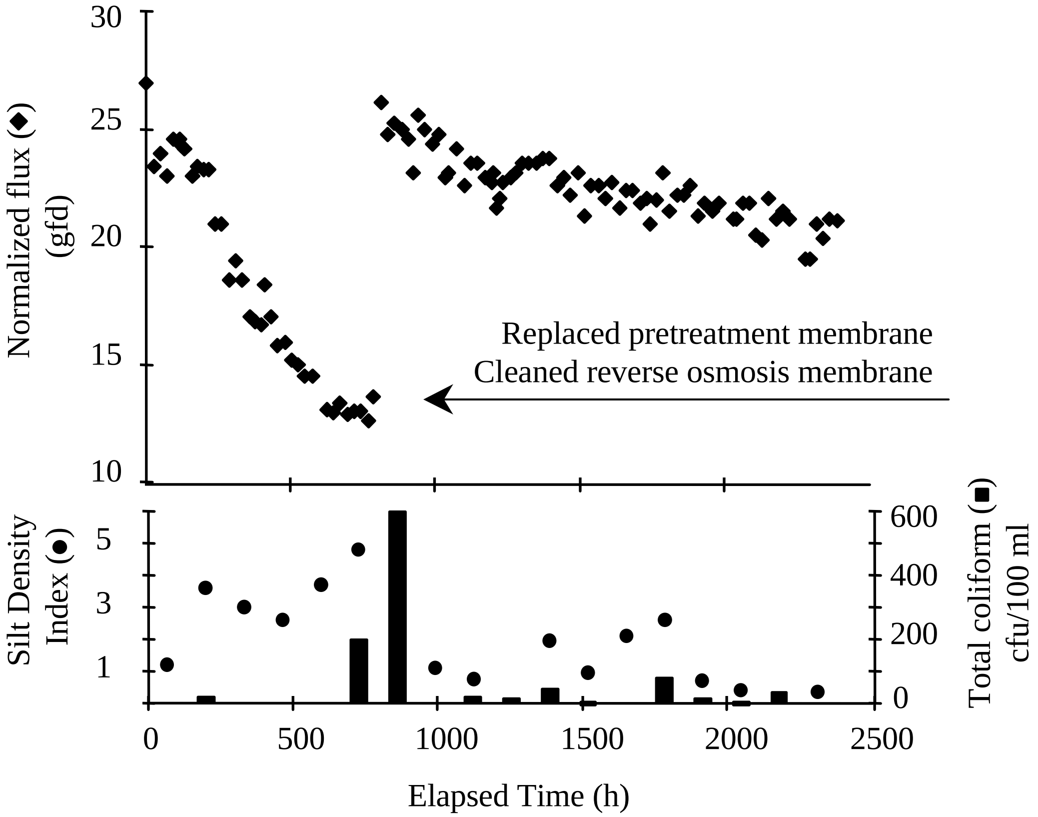


Figure 6. A. Normalized flux as a function of time for a polyamide thin film composite RO membranes downstream of a compromised pretreatment system. The pretreatment membranes were replaced at 750 h. Figure 6.B. pretreatment membrane filtrate water quality as a function of time.