RECLAMATION
Managing Water in the West

Brine-Concentrate Treatment and Disposal Options Report

Southern California Regional Brine-Concentrate Management Study – Phase I
Lower Colorado Region

U.S. Department of the Interior
Bureau of Reclamation

October 2009

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Abbreviations and Acronyms

°C	degrees Celsius
µg/L	microgram per liter
µm	micrometer
AACE	Association for the Advancement of Cost Estimating
AFD	axial flow discharge
ARROW	Advanced Reject Recovery of Water
AS	antiscalant
BEMT	Brine Executive Management Team
BOD	biochemical oxygen demand
$CASO_4$	calcium sulfate
CCC	California Coastal Commission
CCR	California Code of Regulations
CDFG	California Department of Fish and Game
CDHS	California Department of Health Services
CDI	Capacitive Deionization
CEC	constituents of emerging concern
CEQA	California Environmental Quality Act
CFR	Code of Federal Regulations
CIMIS	California Irrigation Management Information System
CIP	clean in place
Cl-	chloride
cm/d	centimeters per day
CW	constructed wetlands
CZMA	Coastal Zone Management Act
dS/m	deciSiemens per meter
DWI	deep well injection

EC	Electrical Conductivity
ECE	salinity in soil
ED	electrodialysis
EDR	electrodialysis reversal
EMS	enhanced membrane system
EMWD	Eastern Municipal Water District
ET	evapotranspiration
FCC	forced circulation crystallizer
FO	forward osmosis
gfd	gallons per square foot per day
gpm	gallons per minute
HERO	High-Efficiency Reverse Osmosis
HMI	human-machine interface
IX	ion exchange
kWh	kilowatt-hour
LBWD	Long Beach Water Department
m	molality
m^2/g	square meters per gram
MD	membrane distillation
MF	microfiltration
mg/L	milligram per liter
mgd	million gallons per day
MIT	Massachusetts Institute of Technology
mL/L	milliliter per liter
MTE	mechanical and thermal evaporation
NA+	sodium
NF	nanofiltration
NOAA fisheries	National Marine Service Fisheries, a division of the Department of Commerce
NPDES	National Pollutant Discharge Elimination System

NTS	natural treatment systems
O&M	operations and maintenance
PFD	permeating flow discharge
PLC	programmable logic controller
PP	polypropylene
ppm	parts per million
PS	precipitative softening
psi	pounds per square inch
PTFE	polytetrafluoroethylene
pvf	polyvinylidene fluoride
Reclamation	United States Department of the Interior Bureau of Reclamation
RO	reverse osmosis
RWQCB	Regional Water Quality Control Board
SAL-PROC	Salt Solidification and Sequestration
SAV	submerged aquatic vegetation
SAWPA	Santa Ana Watershed Protection Authority
SF	surface flow
SLC	State Lands Commission
SPARRO	Slurry Precipitation and Reverse Osmosis
STLC	soluble threshold-limit concentration
SWQMP	State Water Quality Management Plan
SWQPA	State Water Quality Protection Areas
SWRCB	State Water Resources Control Board
SWRO	seawater reverse osmosis
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
TSS	total suspended solids
TTLC	total threshold-limit concentration
TUc	Chronic Toxicity Unit

U.S.	United States
UIC	underground injection control
USACE	United States Army Corps of Engineers
USDW	underground source of drinking water
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
V	volt
VSEP	Vibratory Shear-Enhanced Processing
WAIV	Wind-Aided Intensified Evaporation
WETCAT	Wetlands Capture and Treatment
WMWD	Western Municipal Water District
WWTP	wastewater treatment plant
ZLD	zero liquid discharge

1 Introduction and Study Objectives

This section of the report has the following subsections:

- Introduction
- Study Objectives
- Study Components
- Report Objectives

1.1 Introduction

The Southern California Regional Brine-Concentrate Management Study is a collaboration between the United States (U.S.) Department of the Interior Bureau of Reclamation (Reclamation) and 14 local and state agency partners. Table 1.1 provides a list of the agencies represented on the Brine Executive Management Team (BEMT). The project is funded on a 50/50 cost-sharing basis between Reclamation and the cost-sharing partners, who together form the BEMT. The purpose of the BEMT is to formulate, guide, and manage technical activities of the study. Figure 1.1 shows a map of the study area.

TABLE 1.1
LIST OF BEMT MEMBERS

List of BEMT Members	
City of San Bernardino	Orange County Sanitation District
California Department of Water Resources	Otay Water District
City of San Diego	Rancho California Water District
Inland Empire Utilities Agency	San Diego County Water Authority
Sanitation Districts of Los Angeles County	Santa Ana Watershed Project Authority
Los Angeles Department of Water and Power	U.S. Department of the Interior Bureau of Reclamation
Metropolitan Water District of Southern California	Western Municipal Water District
National Water Resources Institute/ Southern California Salinity Coalition	

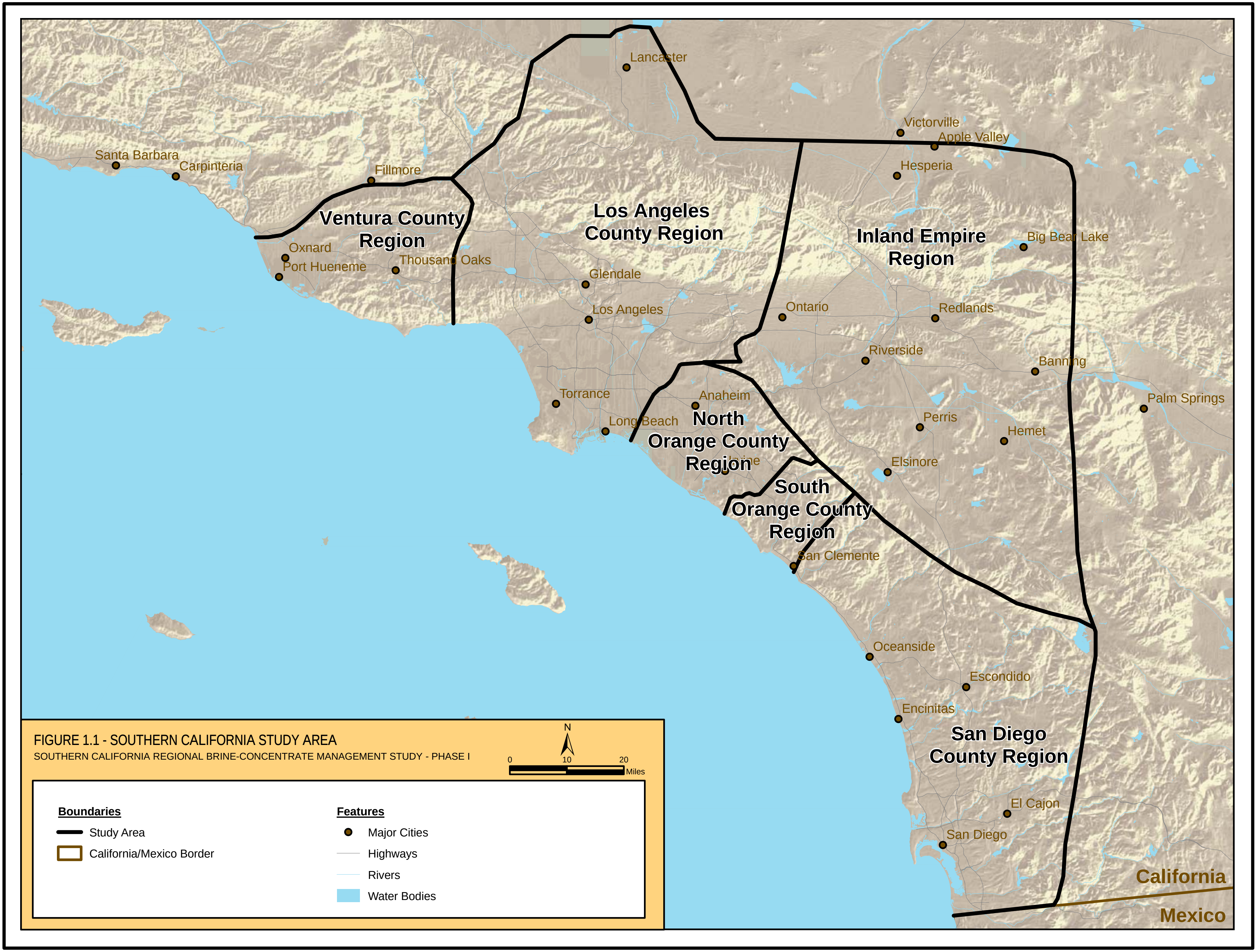

FIGURE 1.1 - SOUTHERN CALIFORNIA STUDY AREA

SOUTHERN CALIFORNIA REGIONAL BRINE-CONCENTRATE MANAGEMENT STUDY - PHASE I

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1.2 Study Objectives

The objectives of this study are twofold:

- To assess the brine-concentrate landscape in southern California including brine-concentrate management technologies, regulatory environment, existing infrastructure, and future needs
- To make recommendations for Phase 2 pilot/demonstration projects

To accomplish these objectives, the study will develop six reports that ultimately will be incorporated into a final study report.

1.3 Study Components

The Southern California Regional Brine-Concentrate Management Study has six major components. Each component is focused on providing a piece of the southern California brine-concentrate management landscape. Each component will be summarized in a draft report that will be incorporated into the Final Study Report. The six components of the study are:

- Survey Report – A regional survey to collect data from local agencies about the brine-concentrate landscape in southern California
- Regulatory Issue and Trends Report – A summary of regulatory issues and trends associated with implementing a brine-concentrate project in southern California
- CECs Report – A summary of constituents of emerging concern (CECs) and how regulation of CECs might affect brine-concentrate management in southern California
- Institutional Issues Report – A summary of organizational structures that can be used to foster collaborative relationships between agencies implementing brine-concentrate management projects
- Brine-Concentrate Management Treatment and Disposal Options Report – A summary of brine-concentrate technologies and identification of potential local and regional solutions
- Pilot/Demonstration Project Recommendations Report – A list of recommended pilot/demonstration projects that could be implemented in the inland and coastal areas southern California

These six reports will be incorporated as appendices in the Final Study Report. The Final Report will provide highlights and conclusions of the six component reports in an executive summary format.

1.4 Report Objectives

There are a number of technologies that can be used for brine-concentrate management. The objective of this report is to describe and evaluate these technologies. The evaluation categorizes concentrate disposal technologies into three broad groups—volume reducing, zero liquid discharge, and final disposal technologies. The evaluation of each technology consists of:

- Description of the technology
- Advantages and disadvantages associated with the technology
- Capital and operations and maintenance (O&M) costs for the technology

The performance and limitations associated with each of the technologies are based on pilot, bench- and full-scale data and information obtained from vendors. Cost information about the technologies was obtained from equipment manufacturers and experience with project implementation.

The cost estimates provided in this section will be conceptual cost estimates or Class 5 estimates in accordance with the Association for the Advancement of Cost Estimating (AACE). An AACE defines order-of-magnitude costs as Class 5 cost estimates without detailed engineering data. Examples of order-of-magnitude cost estimates include:

- An estimate from cost capacity curves
- An estimate using scale-up or scale-down factors
- An approximate ratio estimate

The estimates shown, and any resulting conclusions on the financial or economic feasibility or funding requirements of a concentrate management option, have been prepared to guide evaluation and implementation of the project based on information available at the time of the cost estimate. The expected accuracy ranges for a Class 5 cost estimate are –15 to –30 percent on the low side and +20 to +50 percent on the high side. The final costs of the project and resulting feasibility will depend on actual labor and material costs, competitive market conditions, actual site conditions, scope of the final project, implementation schedule, continuity of personnel and engineering, and other variable factors. As a result, the final cost estimates will vary from the estimates presented in this report.

This report will provide data on energy generation and recovery including co-location of facilities, energy generation from concentrate, and energy recovery mechanisms.

2 Volume Reduction Technologies

Volume reduction technologies are designed to reduce size and cost of the ultimate concentrate facilities. Because the technologies produce a liquid residual stream, they are often named liquid-residual-producing processes. Depending upon the water quality and technology used, volume reduction technologies can reduce concentrate volumes by up to 90 percent. After the volume of concentrate is reduced using one of these technologies, an additional process is required to completely dispose of the concentrate either by solidifying the concentrate product or discharging the liquid concentrate. The volume reduction technologies that are available include:

- Electrodialysis/Electrodialysis Reversal
- Vibratory Shear-Enhanced Processing
- Precipitative Softening and Reverse Osmosis
- Enhanced Membrane System
- Brine Concentrator
- Natural Treatment Systems

Other technologies that are not available in US market and under development include:

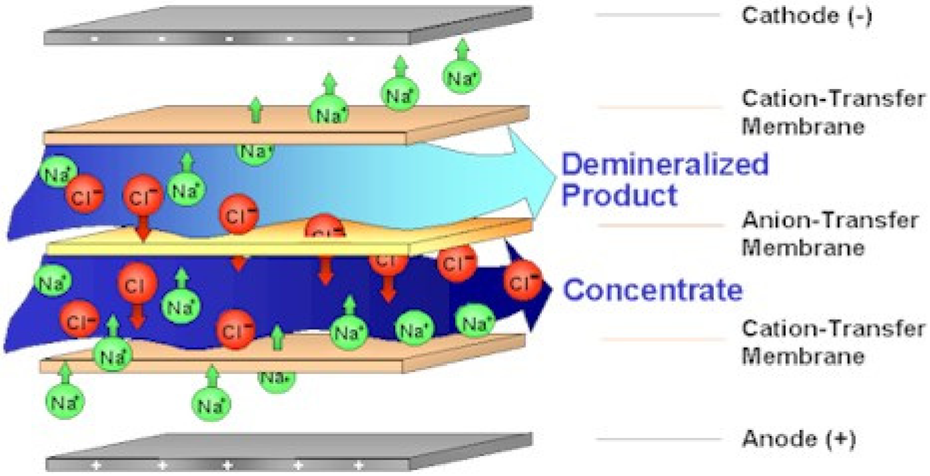
- Two Pass Nanofiltration
- Forward Osmosis
- Membrane Distillation
- Slurry Precipitation and Reverse Osmosis
- Advanced Reject Recovery of Water
- Capacitive Deionization

The following subsections provide a summary of the volume reduction technologies.

2.1 Electrodialysis/Electrodialysis Reversal

Electrodialysis (ED) is a process that uses an electrical current to remove salt ions from a solution. The ED technology is based on the property that salts in solution are dissociated into positively and negatively charged ions. The key to the ED process is a semipermeable barrier that allows passage of either positively charged ions (cations) or negatively charged ions (anions) but excludes passage of ions of the opposite charge. These semipermeable barriers commonly are known as ion-exchange (IX), ion-selective, or electrodialysis membranes. Figure 2.1 is a simplified representation of the ED/Electrodialysis Reversal (EDR) process, illustrating how the positively charged ions (for example, sodium [Na+]) in the influent are pulled across the cation-transfer membrane toward the cathode, and the negatively charged ions (for example, chloride [Cl-]) are pulled across the cation-transfer membrane toward the anode. Figure 2.2 is a photograph of an EDR unit. The selective removal of cations and anions produces a concentrate stream and a demineralized product stream. Because the product water does not pass through a membrane barrier, the California Department of Health Services (CDHS) does not recognize ED/EDR as a barrier process for turbidity and pathogen removal.

FIGURE 2.1 ED/EDR PROCESS



Source: GE Water and Process Technologies

FIGURE 2.2 PHOTOGRAPH OF EDR UNIT

Source: GE Water and Process Technologies

EDR is effective for feedwaters with total dissolved solids (TDS) measuring up to 8,000 parts per million (ppm). This technology has been used for potable water and for wastewater applications but does not have a proven history in dealing with brine concentrate from recycled water applications. Advantages associated with EDR include the following:

- Potential for higher recovery than other membrane processes.
- Lower fouling potential because nonionic contaminants (particulates) are not driven to the membrane surface by the flow of water through the membranes (as in reverse osmosis [RO]). Also, the use of polarity reversal is used to electrically displace foulants from the membrane and electrode surfaces on a frequent basis.

Potential disadvantages of EDR include the following:

- Inability to remove all constituents (such as, boron, silica, and uncharged micropollutants).
- Effectiveness is achieved only when TDS concentration in the feedwater is less than 8,000 ppm.
- CDHS does not recognize EDR as a water treatment technology because EDR does not provide a barrier against pathogens.
- Multiple stages are required for treatment of high-TDS feedwater, such as concentrate, which increases capital and O&M costs.

Capital costs for an EDR unit capable of handling 1 million gallons per day (mgd) of flow range from approximately $5,200,000 for a unit capable of handling brine concentrate flows with TDS measuring 5,000 ppm, as seen in Table 2.1. Cost estimates are based on information provided by Ionics[1] for a 1.0-mgd system.

The cost estimates provided for EDR and other technologies presented in this section (Section 2) and Section 3 are conceptual cost estimates or Class 5 estimates in accordance with the Association for the Advancement of Cost Estimating (AACE). An AACE defines order-of-magnitude costs as Class 5 cost estimates without detailed engineering data. Examples of order-of-magnitude cost estimates include:

- An estimate from cost capacity curves
- An estimate using scale-up or scale-down factors
- An approximate ratio estimate

The estimates shown, and any resulting conclusions on the financial or economic feasibility or funding requirements of a concentrate management option, have been prepared to guide project evaluation and implementation from the information available at the time of the cost estimate. The expected accuracy ranges for a Class 5 cost estimate are –15 to –30 percent on the low side and +20 to +50 percent on the high side. The final costs of the project and resulting feasibility will depend on actual labor and material costs, competitive market conditions, actual site conditions, scope of the final project, implementation schedule, continuity of personnel and

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[1] Currently, only one vendor of EDR is in the United States.

engineering, and other variable factors. As a result, the final cost estimates will vary from the estimates presented in this report.

There are a number of assumptions that are common to each concentrate management option cost estimate, these include:

- Neither engineering nor legal and land/easement acquisition were included in the analysis
- Electricity unit cost is $0.12 per kilowatt (kW)
- Total capital cost includes 25 percent contingency. This contingency was applied to account for any changes and uncertainties in market conditions.
- A new full-time operation staff would be a Class II certified operator, paid approximately $90,000 per year.

Assumptions that were used to develop the cost estimates for EDR include:

- Recovery of 85 percent assuming a concentrate feed with a TDS concentration of 5,000 ppm
- A three-stage system to meet TDS of less than 500 mg/L in product water.

TABLE 2.1
EDR CAPITAL COST MATRIX

	0.2 mgd	1.0 mgd	5.0 mgd
Total Capital Cost Including Equipment Installation and Building to House the Equipment, $	**$1,550,000**	**$5,196,000**	**$15,032,000**

Note:

Capital costs for 1.0-mgd system is according to the City of Santa Maria, 2009. Cost for other flow rates were estimated using the following formula:

Cost 2 = (Flow 2/Flow 1)^0.66*Cost 1. (Flow 1 is 1.0 mgd).

A breakdown of projected annual O&M costs for a 1-mgd facility is shown in Table 2.2. The O&M costs include power, labor, antiscalant and acid addition to feed water, membrane replacement every 5 years, annual electrode replacement, chemical cleaning, and routine maintenance and replacement of parts.

TABLE 2.2
EDR OPERATION AND MAINTENANCE COSTS

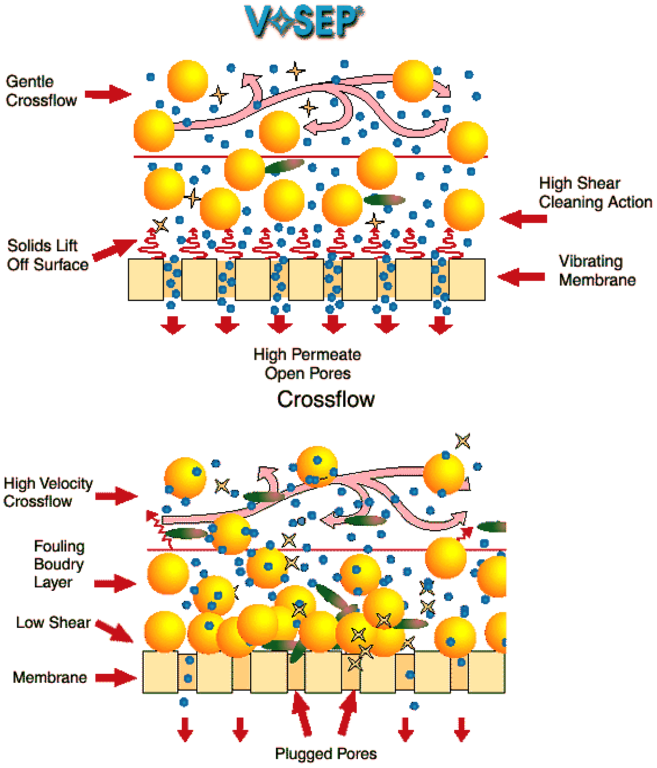
Cost Component	O&M Cost, $/yr
Power	$307,000
Labor	$90,000
Parts and Maintenance	$215,000
Chemicals and Consumables	$302,000
Total	**$914,000**

2.2 Vibratory Shear-Enhanced Processing

Conventional membranes are subject to colloidal fouling because suspended material can become polarized at the membrane surface and obstruct filtration. Vibratory Shear-Enhanced Processing (VSEP), a patented process of New Logic Research, Inc., was developed to reduce polarization of suspended colloids on the membrane surface by introducing shear to the membrane surface through vibration. Shear waves produced on the membrane surface keep the colloidal material in suspension, thereby minimizing fouling. As a result, high throughput and water recoveries above that of a conventional membrane system can be achieved.

VSEP employs torsional oscillation at a rate of 50 times per second (50 hertz) at the membrane surface to inhibit diffusion polarization of suspended colloids. The suspended colloids are helped in suspension where a tangential cross flow washes them away. Figure 2.3 compares cake formation on the membrane surfaces of conventional and VSEP membrane systems.

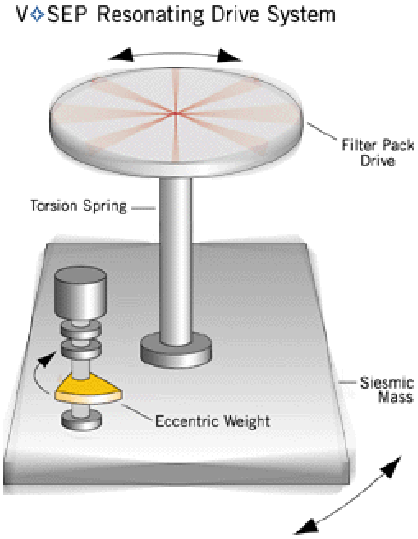
FIGURE 2.3 CAKE DEVELOPMENT IN VSEP VERSUS CONVENTIONAL CROSS-FLOW RO



Source: New Logic Research, Inc.

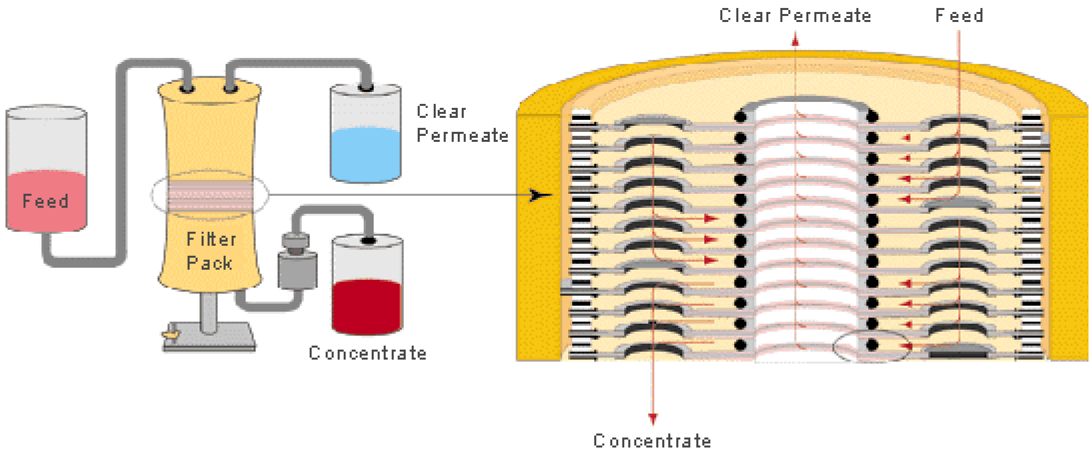
VSEP consists of four components—a driving system than generates vibration, a membrane module, a torsion spring that transfers vibration to the membrane module, and a system for controlling vibration. The vibration imparts a shear to the surface of the membrane to mitigate fouling and scaling that would occur in a conventional RO system (Figure 2.4). The membrane module houses a stack of flat membrane sheets (filter pack) in a plate-and-frame-type configuration as shown in Figures 2.4 and 2.5.

FIGURE 2.4 VSEP SYSTEM AND VIBRATING MECHANISM



Source: New Logic Research, Inc.

FIGURE 2.5 VSEP MEMBRANE FILTER PACK



Source: New Logic Research, Inc.

Unlike the conventional RO membranes, VSEP performance is not limited by the presence of colloidal material. The VSEP system can be configured employing either RO or nanofiltration (NF) membranes in a single-stage or multiple-stage arrangement. The configuration depends upon water quality goals for the VSEP permeate, as well as target water recovery. VSEP has not been used in a full-scale concentrate application; however, the process has been used in agricultural and industrial applications. Advantages associated with VSEP include:

- Potentially high recovery rates
- Production of high-quality water (similar to conventional RO)
- Minimal environmental issues associated with use (similar to traditional membrane systems)
- Potentially no requirement for pretreatment chemicals (such as antiscalant and feedwater pH adjustment)

Disadvantages associated with VSEP include:

- No experience in municipal applications
- Performance needs to be evaluated through pilot testing
- Potentially susceptible to amorphous fouling with aluminum, iron and manganese oxide deposits
- Much higher clean-in-place (CIP) frequencies than conventional RO (BBARWA, 2006) due to operating with much higher fluxes (i.e., 24-30 gfd vs. 9-12 gfd).
- Changing all membrane elements in a stack is required if one membrane plate needs replacement
- Higher capital and O&M costs than traditional RO
- Proprietary technology from a single vendor
- Sound attenuation technology typically required

Capital costs for a VSEP unit capable of handling 1 mgd of flow range from approximately $5.7 million for a flow with a TDS of 5,000 ppm and a silica concentration of 60 mg/L. These estimates are based on information provided by New Logic Research, Inc., the developer of VSEP technology. Capital cost estimates for three different capacities, are provided in Table 2.3. Assumptions that were used to develop the cost estimates for VSEP include:

- A two-stage VSEP with a recovery of 75 percent (concentrate silica concentration exceeding 100 mg/L reduces recovery rate of VSEP to less than 65 percent which is not desirable. To improve recovery of the system, a pretreatment necessary to reduce silica level to 60 mg/L or less in the feed water).
- VSEP needs special equipment for maintenance including a 2-ton hoist for filter module replacement.
- A building to house the equipment.
- Unit size and power requirements were estimated assuming a 2,000-gallon per minute (gpm) (2.9-mgd) flow.

TABLE 2.3
VSEP CAPITAL COST MATRIX

	0.2 mgd	1.0 mgd	5.0 mgd
Total Capital Cost Including Equipment Installation and Building to House the Equipment, $	**$1,699,600**	**$5,698,000**	**$16,485,000**

Note:

Capital costs for 1.0-mgd system is according to the City of Santa Maria, 2009. Cost for other flow rates were estimated using the following formula:

Cost 2=(Flow 2/Flow 1)^0.66*Cost 1. (Flow 1 is 1.0 mgd).

A breakdown of annual O&M costs for a 1-mgd facility is shown in Table 2.4. The projected O&M costs include power, labor, feed water acidification, biannual membrane replacement, chemical cleaning and routine maintenance and replacement of parts.

TABLE 2.4
VSEP OPERATION AND MAINTENANCE COSTS

	O&M Cost, $/yr
Power	$182,704
Labor	$62,400
Parts and Maintenance	$610,695
Chemicals and Consumables	$52,560
Total	**$908,359**

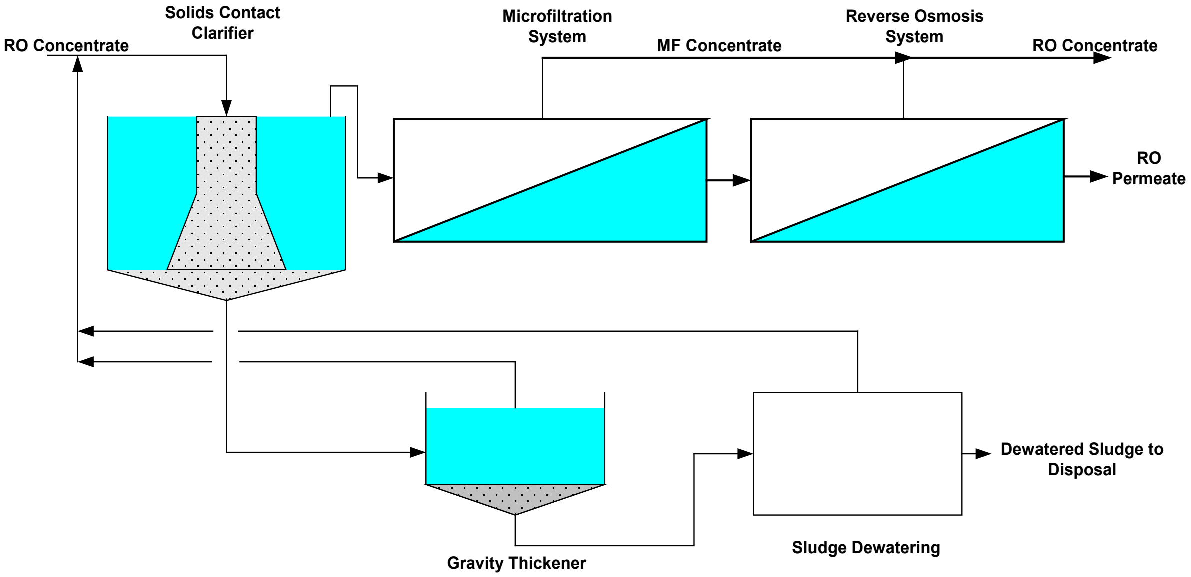
2.3 Precipitative Softening and Reverse Osmosis

Precipitative softening (PS) is a unit process that can be integrated with the RO system to increase recovery of concentrate as a volume-reduction process. PS works to increase the recovery rate of the RO process by controlled precipitation and removal of sparingly soluble inorganic salts. The PS unit process includes chemical addition and clarification for softening (that is, alkalinity and hardness removal) and pH adjustment for silica removal.

Inorganic salt precipitation can be controlled at lower recoveries by using an appropriate antiscalant and by lowering the pH of feedwater. At higher recoveries, antiscalants are not as effective and pH control does not prevent precipitation of problematic minerals such as barium sulfate and calcium sulfate, which are difficult to remove by chemical cleaning. In addition, silica scaling is problematic at lower pH values, the opposite of calcium carbonate scale, which precipitates more readily at high pH values (Johnson, 2001). The PS process is effective at removing calcium, barium, and strontium (primary scale-forming ions). Silica removal also can be performed by PS if the pH is elevated by adding magnesium and/or sodium hydroxide to increase the pH to 10.3 or higher.[2]

A process flow diagram for a PS process is presented in Figure 2.6, and an example of a typical solids contact clarifier is shown in Figure 2.7. Alternatively, a high-rate contact clarifier/thickener (Figure 2.8) could be used to treat the sludge in the PS step, eliminating the need for separate gravity thickening.

FIGURE 2.6 PS/RO PROCESS FLOW DIAGRAM



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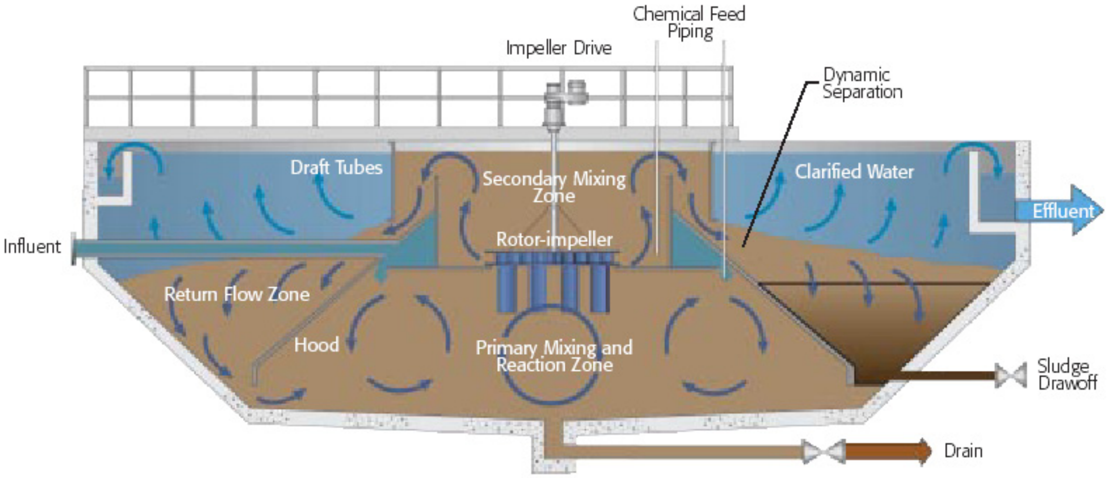
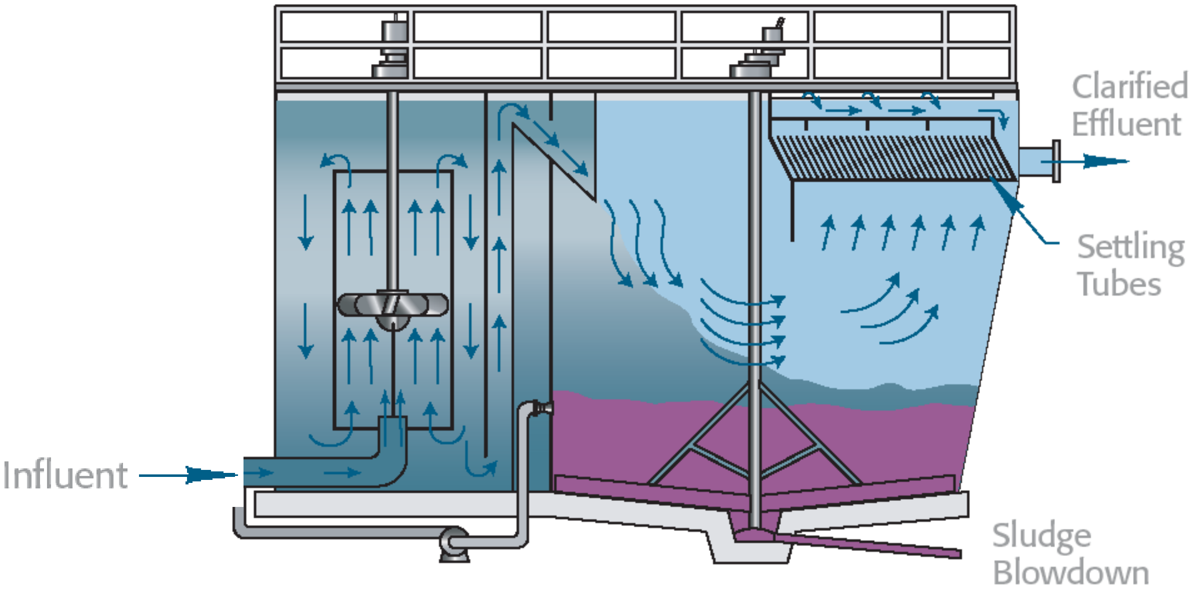
[2] Based on Ft. Irwin Concentrate Recovery Jar Testing Results

FIGURE 2.7 TYPICAL SOLIDS CONTACT CLARIFIER



Source: Infilco Degremont Accelerator

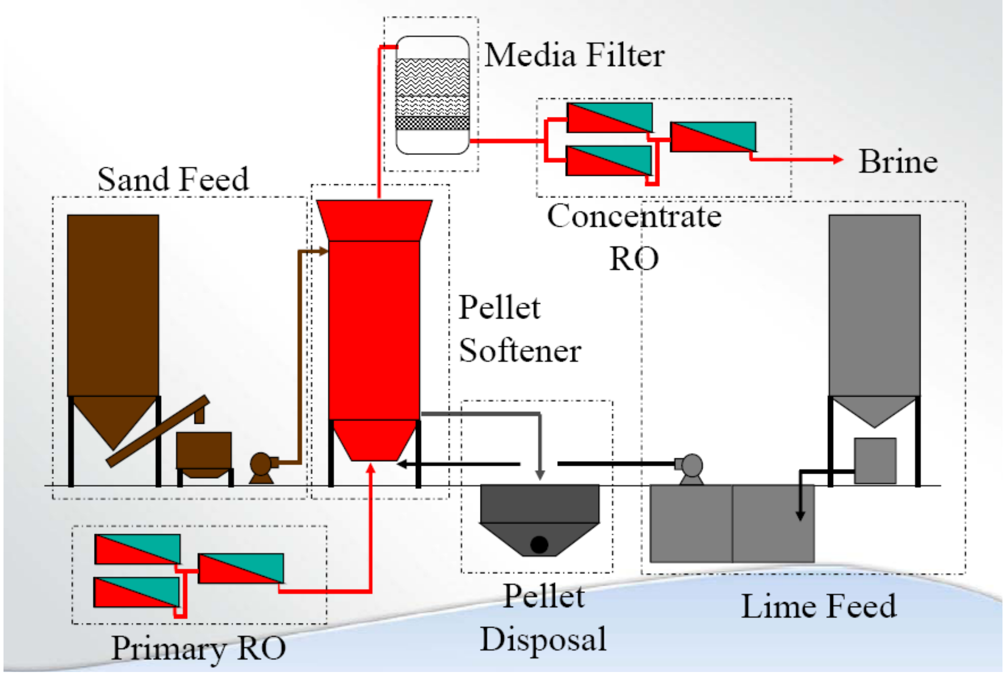
FIGURE 2.8 TYPICAL THICKENING CLARIFIER



Source: Infilco Degremont DensaDeg High Rate

An alternative technology to softening step of conventional PS/RO is the pellet softening. In this process, hardness can be removed from the water by growth of calcium carbonate crystals in a fluidized bed reactor, or pellet reactor. With the use of sand and grains as seeds, the removal efficiency of hardness can be increased. Unlike the sludge produced from the conventional softening plant, a crystallization process in a fluidized reactor produces solid grain of calcite. These pellets have an economic value that can be used in agricultural and industrial fields. Western Municipal Water District (WMWD) successfully pilot tested this technology at the Arlington Desalter in Riverside County, California. The purpose of testing was to show if this technology reduces the scale forming mineral thereby reducing scale formation in SARI line. Figure 2.9 illustrates the process flow diagram of a pilot pellet softening facility at the Arlington Desalter. Figure 2.10 illustrates the pilot unit and pellets formed.

FIGURE 2.9 PROCESS FLOW DIAGRAM OF PILOT PELLET SOFTENING



Source: Safely, 2009

FIGURE 2.10 PROCESS FLOW DIAGRAM OF PILOT PELLET SOFTENING

Source: Safely, 2009

The PS/RO process is a proven technology for municipal and industrial applications and can be installed in existing chemical- and sludge-handling facilities. Combined PS/RO systems are manufactured by a number of companies and have similar regulatory requirements to traditional RO systems. However, the combined PS/RO systems have a large overall footprint and might require additional chemical and sludge dewatering facilities. Environmental impacts include high usage of chemicals based on the feed quality and management of sludge disposal. Advantages associated with PS/RO include:

- Proven technology treatment train – many installations with RO following PS or lime softening
- Applicable to concentrate with high silica content
- Regulatory issues similar to RO

Disadvantages associated with PS/RO include:

- Large overall footprint
- Additional space required for chemical facilities and dewatering of sludge
- High usage of chemicals depending on feedwater quality
- Management of sludge disposal required
- Overall recovery limited by RO system osmotic pressure constraints

Estimates for the cost of a combined PS/RO system include capital costs for sludge dewatering and for chemical facilities, and are based on information provided by Infilco Degremont. The projected capital costs for a PS/RO unit are $13 million for a 1-mgd PS/RO unit. However, this cost can be reduced if sludge dewatering is not required. Table 2.5 summarizes the capital costs for the PS/RO system.

TABLE 2.5
PS/RO CAPITAL COST MATRIX

	0.2 mgd	1.0 mgd	5.0 mgd
Total Capital Cost Including Equipment Installation and Building to House the Equipment, $	**$4,495,000**	**$13,000,000**	**$33,608,000**

Note:

Capital costs for 1.0-mgd system is according to the City of Santa Maria, 2009. Cost for other flow rates were estimated using the following formula:

Cost 2=(Flow 2/Flow 1)^0.66*Cost 1. (Flow 1 is 1.0 mgd).

A breakdown of annual O&M costs for a 1-mgd facility treating is shown in Table 2.6. O&M costs include power, labor, sludge disposal, chemicals for softening, pH adjustment and for CIP, membrane replacement costs (every 3 years), routine maintenance and other replacement of system parts.

TABLE 2.6
PS/RO OPERATION AND MAINTENANCE COSTS

Component	O&M Cost, $/year
Power	$274,000
Parts	$150,000
Chemicals	$350,000
Maintenance	$121,000
Sludge Disposal	$51,000
Labor	$90,000
Total O&M Cost, $/year	**$1,036,000**

2.4 Enhanced Membrane Systems

An Enhanced Membrane System (EMS) is used to reduce the volume of reject concentrate by increasing the recovery of the RO process. One type of EMS is the patented High-Efficiency Reverse Osmosis (HERO) system (Figure 2.11). This process involves IX softening of reject from a first-phase membrane system to reduce the scaling potential of the concentrate fed to the HERO system, a degasification step to remove carbon dioxide, and addition of a caustic that would increase pH (about 11) to retard silica scaling and biofouling. The process combines a two-phase RO process with chemical pretreatment of primary RO, intermediate IX treatment of primary RO concentrate, and high pH operation of secondary RO. The secondary RO step operates at high efficiency due to IX pretreatment and operations at a high pH. This process results in a higher recovery than standard RO systems.

EMS is a relatively new type of membrane system and might require detailed pilot testing prior to implementation. Pilot testing could be complex due to the need to generate concentrate from a mainstream feedwater RO unit for the EMS pilot unit.

Advantages associated with EMS include:

- Applicable to concentrate flows with high silica content
- Relatively small foot-print
- Higher recovery achievable than with conventional RO because feed hardness is removed
- Small aesthetic profile (no tall stacks)

Disadvantages associated with EMS include:

- Inefficiency due to TDS limitations
- High capital and O&M costs
- Highly skilled operations staff required
- Complex process control system runs the IX, pH adjustment, and RO systems
- Produces two concentrated waste streams, IX regenerate, and HERO reject
- Waste streams form voluminous precipitate when combined

FIGURE 2.11 HIGH-EFFICIENCY REVERSE OSMOSIS (HERO) SYSTEM

Source: Aquatech, 2009

Estimated capital costs are summarized in Table 2.7. Capital costs for an EMS unit capable of handling 1-mgd flow range from approximately $7.8 million for a flow with TDS of 3,000 ppm to approximately $9 million for a flow with TDS of 8,000 ppm.

TABLE 2.7
EMS CAPITAL COST MATRIX

	0.2 mgd	1.0 mgd	5.0 mgd
Total Capital Cost Including Equipment Installation and Building to House the Equipment, $	**$4,636,000**	**$15,540,000**	**$37,018,000**

Note:

Capital costs for 0.2-mgd system is according to BBARWA, 2006. Cost for other flow rates were estimated using the following formula:

Cost 2=(Flow 2/Flow 1)^0.66*Cost 1. (Flow 1 is 0.2 mgd).

Table 2.8 summarizes the O&M costs for a facility with 1 mgd of feedwater flow and 8,000 mg/L TDS. O&M cost information is based on “Evaluation of RO Concentrate Management Options for Big Bear Area Regional Wastewater Agency” CH2M HILL, 2005. O&M costs include power, labor, chemicals for pH adjustment and for CIP, membrane replacement costs (every 5 years), and ion exchange resin replacement costs (every year).

TABLE 2.8
EMS OPERATION AND MAINTENANCE COSTS

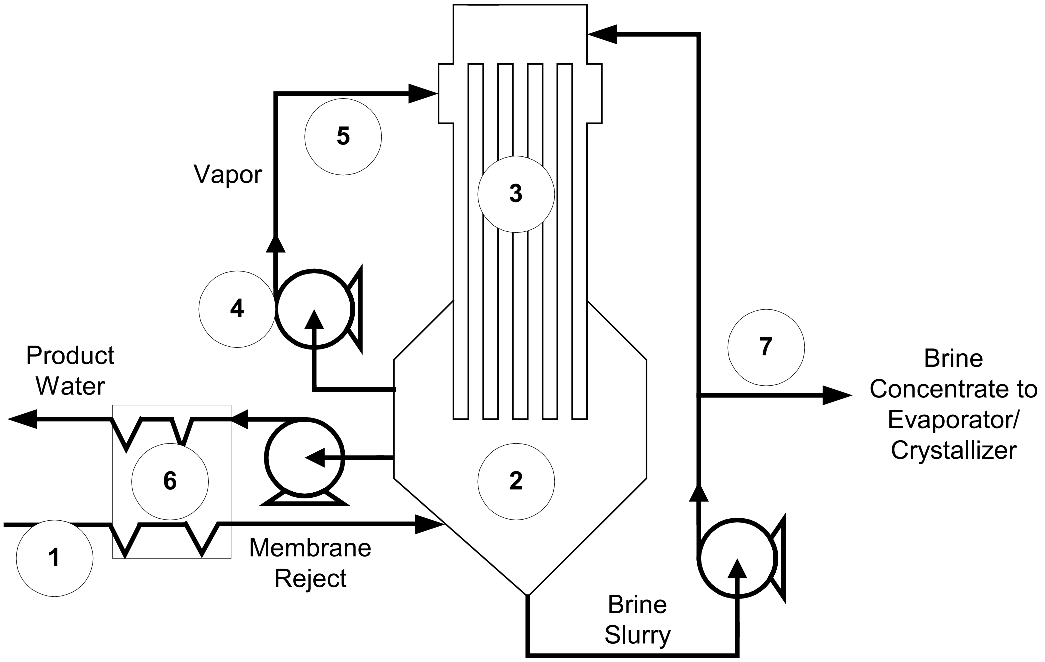
Component	O&M Cost, $/year
Power	$263,000
Parts	$163,000
Chemicals	$263,000
Maintenance	$148,000
Labor	$90,000
Total O&M Cost, $/year	**$927,000**

2.5 Mechanical and Thermal Evaporation

Mechanical and thermal evaporation devices are energy-intensive processes used to reduce the volume of concentrate by boiling the liquid and recover purified distillate. For mechanical evaporation, heat is added to the concentrate by a mechanical adiabatic heating process. For thermal evaporation, steam is used to heat the concentrate. The absorbed heat causes water to vaporize, which reduces the concentrate volume. The vapor is condensed, becoming distillate for reuse.

A number of different configurations of evaporators are supplied by different vendors. Evaporators are classified according to the arrangement of their heat transfer surfaces and the method used to impart heat to the feed solution. Common types of evaporators include single or multiple effect, vapor compression, vertical-tube falling-film, horizontal-tube spray-film, and forced circulation types. Figure 2.12 is a flow process diagram for a vertical tube, falling film, vapor compression evaporator (brine concentrator). A distinction is also made between conventional mechanical evaporation and slurry-seeded systems.

FIGURE 2.12 VERTICAL-TUBE FALLING-FILM VAPOR COMPRESSION SLURRY SEEDED EVAPORATION PROCESS FLOW DIAGRAM



Note: Numbers correspond with description in text.

The following process steps are numbered to correspond with the numbers in the process diagram.

The following process steps are numbered to correspond with the numbers in the process diagram.

1. Membrane reject is pumped through a feed-distillate heat exchanger that raises the temperature of the membrane reject and cools the distillate.
2. The hot membrane reject combines with the concentrate slurry (solid phase is anhydrous calcium sulfate) in the sump. The concentrate slurry is circulated constantly from the sump to the floodbox at the top of a bundle of heat transfer tubes. Calcium sulfate crystals that precipitate as feed is concentrated act as precipitation nuclei to prevent scaling on the heat transfer surfaces.
3. Some of the concentrate evaporates as it flows in a falling film through the tubes and back into the sump.

4. The vapor passes through mist eliminators and enters the vapor compressor, which heats the vapor. The compressed vapor is desuperheated with hot distillate and condenses into liquid water on to the outside of the heat transfer tubes. Mechanical compressors are used in most applications. The mechanical vapor compressor is responsible for about 80 percent of the 70- to 90-kilowatt-hour (kWh) energy usage per 1,000 gallons of brine concentrator feed.
5. Water vapor condenses on the surface of heat transfer tubes, transferring heat to the slightly cooler concentrate falling inside the tubes. Transferred heat causes more of the concentrate to evaporate, thereby sustaining the cycle.
6. As the compressed vapor gives up heat, the vapor condenses into distilled water. The distillate is relatively uncontaminated and typically has a TDS concentration of 5 to 10 mg/L, making the distillate an excellent source of water.
7. The high-purity distillate is pumped through the feed-distillate heat exchanger, where the distillate gives up heat to the incoming membrane reject water and the distillate is cooled. Total recovery of product water across the concentrator may range from less than 90 to over 99 percent, depending on water chemistry.
8. From less than 1 to over 10 percent of the concentrate slurry is blown down from the sump to maintain the concentrate Total Solids (TS) (dissolved and suspended) between 20 and 30 percent (200,000 to 300,000 mg/L). Blowdown may be sent to a crystallizer feed tank and then sent to the forced circulation crystallizer. Alternatively, the blowdown can be sent to an evaporation pond.

Mechanical evaporators are a proven technology for reduction of concentrate volume in industrial applications and can handle a range of feedwater compositions. Mechanical evaporators have a small site footprint with a tall tower profile that could affect its location due to height restrictions or aesthetic issues. Mechanical evaporators are complex and require specialized labor skills for operation and maintenance. The total solids concentration of the MTE brine is typically between 200,000 and 300,000 mg/L TS.

Advantages associated with mechanical evaporators include:

- Proven technology for brine concentrate volume reduction in industrial applications
- A small site footprint
- Most organic and inorganic constituents removed and high-quality water produced

Disadvantages associated with mechanical evaporators include:

- High capital and O&M costs due to mechanical complexity and high energy demands
- Sound enclosures possibly needed
- Aesthetics associated with tall tower profile
- Not feasible for projects with specific height limits (i.e., 50 ft or less).

Estimated capital costs for a mechanical evaporation unit are summarized in Table 2.9. Capital cost estimates are based on vendor data for the brine concentrator produced by Ionics (now part of GE Water). Capital costs for a 1-mgd MTE unit are approximately $17.7 million. Capital costs are independent of the TDS concentration.

TABLE 2.9
MTE CAPITAL COST MATRIX

	0.2 mgd	1.0 mgd	5.0 mgd
Total Capital Cost Including Equipment Installation , $	**$5,280,000**	**$17,698,000**	**$51,196,000**

Note:

Capital costs for 0.2-mgd system is according to BBARWA, 2006. Cost for other flow rates were estimated using the following formula:

Cost 2=(Flow 2/Flow 1)^0.66*Cost 1. (Flow 1 is 0.2 mgd.)

Table 2.10 provides O&M cost estimates for a MTE unit. O&M costs include power, labor, chemicals, maintenance, and replacement costs for key equipment components (i.e., compressor, heat exchanger). These estimates were provided by Ionics and are based on a 1-mgd feed flow.

TABLE 2.10
MTE OPERATION AND MAINTENANCE COSTS

Component	O&M Cost, $/year
Power	$4,000,000
Parts	$885,000
Chemicals	$250,000
Maintenance	$531,000
Labor	$180,000
Total O&M Cost, $/year	**$5,846,000**

2.6 Natural Treatment Systems

Natural treatment systems are an established technology for polishing and treatment of wastewater effluent but have not been used widely as a method of RO concentrate disposal. Several pilot studies have been developed in Oxnard, California, as well as in Brisbane, Australia, and Goodyear, Arizona. There are two configurations of NTS that are evaluated in this report:

- Halophytes in a closed system to uptake the concentrate prior to final disposal
- Constructed wetlands to treat the concentrate stream prior to final disposal

Both of these systems use natural processes to remove salt and other constituents from the concentrate as a cleaning step before final disposal.

2.6.1 Halophytes

Halophytes are broadly defined as plants with an unusually high tolerance to salinity; however, the lower limit of salt tolerance is poorly defined (Glenn, 1999). Halophytes thrive in saline conditions, such as in marine estuaries and salt marshes, through cellular, tissue, and whole plant adaptations (Glenn, 1999). Many of these plants have adapted to a saline environment by absorbing large amounts of salt with water, while others have exclusion mechanisms of adaptation. Halophytes tolerate salinity largely via the controlled uptake of sodium (balanced by chloride and other anions) into cell vacuoles to produce an electrochemical gradient that drives water into the plant when external water potential is low (Glenn, 1999). Other secondary tolerance mechanisms include presence of salt glands, salt bladders, or succulent tissues; and whole plant reduction of stomatal conductance, thereby increasing water use efficiency in response to salt. However, individual plants will vary in the traits that they possess to the extent in which they are used (Seaman, 2004).

Halophytes can be used as a brine/concentrate management technology in the same manner as an NTS (wetland). The use of wetlands and halophytes for brine/concentrate management is an emerging technology; however, both are accepted treatment technologies for stormwater and wastewater applications. The salinity threshold of salt tolerant plants varies depending on plant type, with halophytes having an extremely high salinity threshold. Examples of salt tolerant and halophytic plants are shown in Table 2.11. Salinity thresholds are provided as electrical conductivity (EC_e). At moderate salinity levels, EC can be related to TDS through the following relationship:

$$\text{TDS (mg/L)} = 640 \times \text{EC (dS/m)}$$

TABLE 2.11
EXAMPLES OF HALOPHYTIC SHRUBS, TREES, AND GROUND COVER

Common Name[a]	Botanical Name	Max Permissible[b] ECe; dS/m
Moderately Tolerant -		
Weeping bottlebrush	*Callistemon viminalis*	6-8
Oleander	*Nerium oleander*	6-8
European fan palm	*Chamaerops humilis*	6-8
Blue dracaena	*Cordyline indivisa*	6-8
Rosemary	*Rosmarinus officinalis*	6-8
Aleppo pine	*Pinus halepensis*	6-8
Sweet gum	*Liquidamabar styraciflua*	6-8
Tolerant -		
Brush cherry	*Syzygium paniculatum*	>8 [c]
Ceniza	*Leucophyllum frutescens*	>8 [c]
Natal plum	*Carissa grandiflora*	>8 [c]
Evergreen Pear	*Pyrus kawakamii*	>8 [c]
Bougainvillea	*Bougainvillea spectabilis*	>8 [c]
Italian stone pine	*Pinus pinea*	>8 [c]
Very Tolerant -		
White iceplant	*Desloperma alba*	>10 [c]
Rosea iceplant	*Drosanthemum hispidum*	>10 [c]
Purple iceplant	*Lampranthus productus*	>10[c]
Croceum iceplant	*Hymenocyclus croceus*	>10[c]

Notes:

[a] Species are listed in order of increasing tolerance based on appearance and growth reduction.

[b] Salinities exceeding the maximum permissible ECe could cause leaf burn, loss of leaves, and/or excessive stunting.

[c] Maximum permissible ECe is unknown. No injury symptoms or growth reduction was apparent at 7 dS/m. The growth of all iceplant was increased by soil salinity of 7 dS/m.

Source: Maas, 1990.

Irrigation of Halophytes

Halophyte irrigation is one of the areas recommended for additional research and development effort by the AWWA subcommittee on concentrate management (AWWA, 2004). Halophyte applications include landscaping, wildlife habitat, dust barriers, windbreaks, livestock grazing, and production of grains, oilseeds, and fodder (Ahuja, 2005). Internationally, the United Arab Emirates has extensively investigated halophyte systems for landscaping, crop, and livestock production, golf course irrigation, landscaping, and creating nature preserves (Child, 2005).

There are numerous implementation issues that require consideration when irrigating with brine, including

- Overall irrigation strategy and distribution techniques
- Opportunities for blending irrigation water sources
- Chemical characteristics of the brine and ultimate fate of chemical constituents
- Hydraulic and nutrient loading
- Site and plant selection
- Site drainage characteristics
- Leaching requirement and potential groundwater impacts
- Seasonal storage requirements/discharge alternatives (Jordahl, 2006)

Plant limitations and need for substantial leaching, water quality considerations and regulatory restrictions for both surface and ground waters, and cost all limit the feasibility for large-scale implementation of brine irrigation projects. Some of these are described in more detail below.

Plant Species

Halophytes generally perform best when the soil solution salinity is ≤ 20 grams per liter (g L^{-1}), which is less saline that the brine concentrate produced with some treatment technologies (Miyamoto, 1996). Certain halophyte plant species, however, such as *Salicornia* spp., can tolerate irrigation with seawater (about 35 g L^{-1}). When TDS of the concentrate is above the highest value that can be tolerated by vegetation, irrigation is not a feasible alternative without blending. If the plant species can tolerate the concentrate salinity and is otherwise suitable for the geographic area and soil conditions, then irrigation may be a viable alternative for disposing of membrane concentrate (Jordahl, 2006).

Individual halophyte species may show differences in salt tolerance, depending on growth stage. For example, many halophytes show a 50 percent reduction in seed germination when solution salinity is about 10 g L^{-1}, which is similar to the germination reduction that is observed with many conventional crops (Miyamoto, 1996). On the other hand, *Salicornia* spp. will germinate readily in seawater (Miyamoto, 1996). Therefore, it is important to consider plant salinity thresholds at all life stages that would be affected by brine irrigation, and to use blending or other water sources when necessary to prevent adverse salinity impacts.

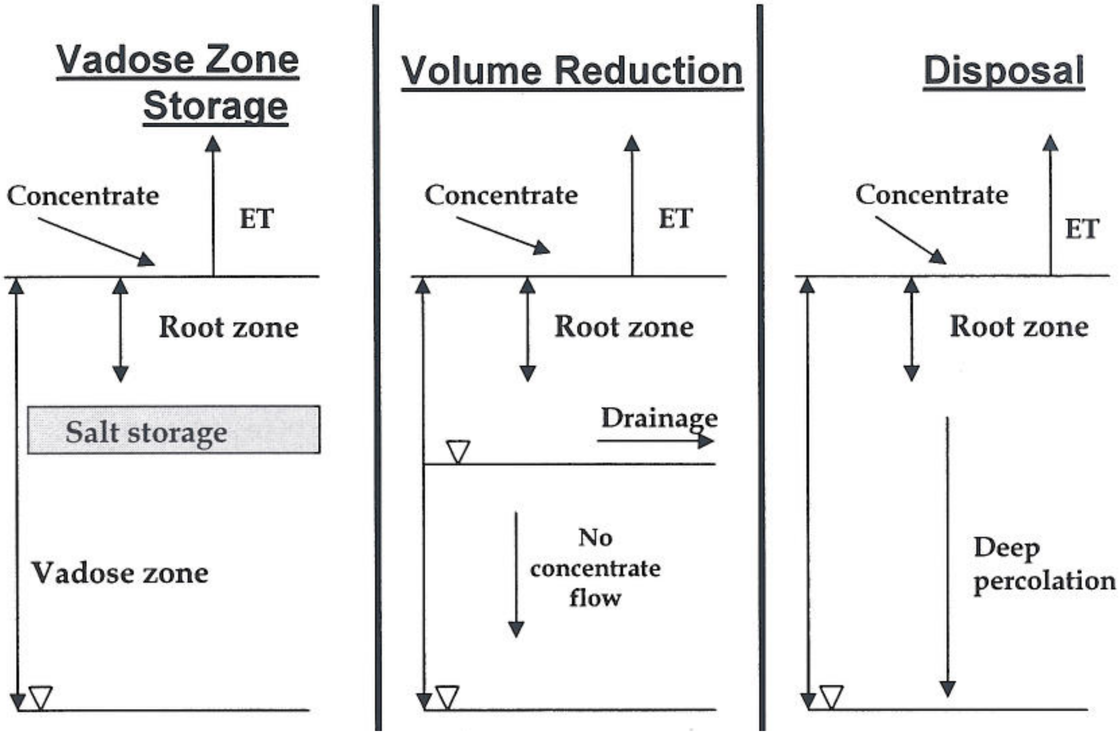
During the rainy season, halophytes would likely obtain most of their needed water from precipitation; and plant capacity to use brine flows may differ from the volume of flows that is produced. Installation of detention ponds may be necessary to detain excess water when the rate of brine production exceeds the allowable hydraulic loading rate (Jordahl, 2006).

Irrigation Management Strategy

Three methods of managing brine irrigation could be considered (Jordahl, 2006) and are illustrated in Figure 2.13:

- **Storage in the vadose zone.** This method requires a deep water table and careful management to apply a limited leaching fraction, and effectively store salts in the vadose zone. Problems can arise if salts precipitate and form a slowly permeable layer that would retard drainage (e.g., a caliche layer). Riley et al. (1998) calculated that with a 3 to 5 percent leaching fraction applied to halophytic vegetation, it would taken 100 years of irrigation for percolation to reach half-way to the depth of the water table at a site in southern Arizona (Riley, 1998).
- **Volume Reduction.** This irrigation method reduces the concentrate volume through evapotranspiration, and requires a subsurface drainage system to recapture the concentrate. To ensure protection of groundwater quality, presence of slowly permeable subsoil underlying subsurface drainage is high desirable (Jordahl, 2006). Additional treatment of flows from the drainage system may include diversion to evaporation ponds or ZLD (brine concentrator) system.
- **Disposal.** If the underlying aquifer is already of poor quality (i.e., >10,000 mg/L TDS), then substantial leaching of salts to groundwater may be permissible, and little advanced site design operations may be required.

FIGURE 2.13 IRRIGATION MANAGEMENT STRATEGIES USING CONCENTRATE



Leaching Capacity

Plant irrigation, including irrigation of halophytes, typically requires some amount of irrigation above plant requirements in order to flush excess salts through the root zone. Leaching requirements vary with plant species, salinity of irrigation water, and climate. Without leaching, salts will accumulate in the plant root zone and eventually cause adverse effects to plant growth—even with halophytes. Leaching of salts into underlying groundwater may violate State water quality standards, especially where the groundwater aquifer is of higher quality than the water being land applied. Therefore, regulatory constraints may limit the feasibility of irrigating with brine concentrate.

Chemical Characteristics

- **Sodium Adsorption Ratio**. When sodium concentration in the soil is high relative to calcium and magnesium, destruction of soil structure and reduced soil permeability can result. The sodium hazard is evaluated by the sodium adsorption ratio (SAR), defined as:

$$SAR = \frac{[Na]}{\sqrt{\frac{([Ca]+[Mg])}{2}}}$$

Where

Na, Ca and Mg concentrations are expressed in milliequivalents per liter (meq/L). SAR greater than 9 in irrigation water may adversely affect soil permeability (Ayers, 1985). The sodium hazard is usually not substantial when bulk salinity is high; however, if better quality water is received, through rainfall or alternative water sources, then sodium hazard may increase. Also, if alkalinity causes precipitation of calcium and magnesium carbonate in the soil, this would likewise increase the SAR, and potentially cause permeability problems.

- **Specific Ion Toxicity.** Sodium, chlorine and boron in irrigation water can cause toxic responses in sensitive plants. When plants are sprinkler irrigated, sodium and chloride can cause foliar damage, and a concentration of 3 meq/L for either sodium or chloride is typically used as a toxicity threshold. Boron concentrations above 0.7 mg/L may produce toxicity symptoms in sensitive plants, and leaching of boron is more difficult than leaching other salts. However, specific ion toxicity is very different for halophytes and therefore halophytes have a much higher toxicity threshold.

Land Requirements

Land area required for brine irrigation depends on the volume of brine concentrate produced and plant water requirements. Evapotranspiration rate varies with climate (i.e., plants in hot, arid climates have higher transpiration rates than plants in cool, coastal areas). Table 2.12 shows differences in evaporation rates for various regions in the State.

Land required for irrigation in a high ET region (Perris, California) and a relatively low ET region (Irvine, California) was determined, assuming irrigation of salt grass with 1 mgd of brine. Other assumptions included the following:

- Soil: Irvine: Sorrento soils with 0.19 in/in of available water
- Perris: Willows soils with 0.10 in/in of available water
- No leaching fraction; irrigation at agronomic rate only
- Reference ET and monthly precipitation from the California Irrigation Management Information System (CIMIS) stations located in Irvine and at UC Riverside, respectively, for regional evaluation
- Sprinkler irrigation with 85 percent irrigation efficiency
- Halophyte: Saltgrass, using crop coefficients previously determined for each month of the year

TABLE 2.12
AVERAGE SEASONAL AND ANNUAL CLASS-A PAN EVAPORATION

Station	May-Oct	Nov-Apr	Annual	Beginning of Record	Latest Data
	in	in	in	mo/yr	mo\yr
Arvin-Edison WSD	66.2	21.3	87.5	Mar-67	Dec-77
Backus Ranch	85.6	30.5	116.1	Jun-36	Jun-62
Baldwin Park	40.9	18.5	59.5	Jul-32	Dec-53
Beaumont Pumping Plant	49.7	23.0	73.0	Jan-55	Sep-75
Casitas Dam	40.2	20.3	60.5	Sep-59	Sep-77
Castaic Dam Headquarters	51.8	29.0	81.0	Jun-68	Dec-78
Chula Vista	39.7	23.6	63.4	18-Sep	Dec-79
Fullerton Airport	41.9	21.9	63.9	Jan-35	May-77
Henshaw Reservoir	49.4	18.5	67.9	Jul-59	Apr-79
Huntington Beach – Heil	39.6	18.1	57.6	Sep-34	Dec-45
Irvine Co Automatic	38.0	20.9	58.8	Feb-46	Jun-72
Lake Bard	49.0	33.0	82.0	Mar-67	Sep-77
Mockingbird Reservoir	34.3	20.8	55.0	Jul-41	Feb-79
Perris Reservoir Evaporation	60.4	27.0	87.4	Dec-63	Jan-79
Prado Dam	50.6	25.4	76.0	30-Jul	Jan-69
Riverside Citrus Experimental Station	46.7	22.7	69.4	25-Jan	Apr-78
San Bernardino Flood Control	52.2	23.8	76.0	Jun-59	Oct-73
San Jacinto Reservoir MWD	58.4	23.7	82.1	Jul-39	Sep-71
Silver Lake Reservoir	42.8	23.0	65.8	Jan-52	Dec-67
Tujunga Spreading Grounds – Evaporation	48.6	26.2	74.8	Dec-32	Dec-44
Vail Lake – USGS	54.6	25.9	80.5	Apr-52	Jun-76
Van Nuys Flood Control 15B	25.9	11.8	37.7	Jan-30	Jul-48

Notes:

These values represent the sum of the monthly means.

Based on an average concentrate production of 1 mgd, approximately 553 acres of land would be required in Perris, and approximately 695 acres of land would be required in Irvine, California (Attachment A). Little to no irrigation of saltgrass would be required between November and March, when precipitation alone largely meets plant transpirational water demand. During the rainy season, rainfall would at least partially leach salts through the plant root zone, and this could potentially be supplemented with irrigation to achieve greater leaching. However, storage and/or alternative disposal options would need to be considered during those months.

Groundwater levels in Irvine may be relatively high, which would potentially present a problem with respect to salt migration into groundwater. Furthermore, while the calculated land requirement assumes no leaching fraction, in practice the absence of leaching would likely result in adverse salinity impacts to plants over time as excess salts accumulate in the root zone. The estimated acreages, however, are useful for comparing relative land requirements in areas with different climates.

Irrigation Costs

Cost of brine irrigation of halophytes is highly specific to project location and depends on following:

- Volume and quality of concentrate
- Distance to land application site
- Irrigated acreage
- Geographic location
- Storage requirements
- Land cost

For example, the capital and O&M costs for treating 1.0-mgd concentrate flow with a TDS range of 10,000 to 20,000 mg/L are $43,000,000 and $390,000 per year, respectively. This estimate is based on evaporation and rain fall data for Irvine, California.

2.6.2 Constructed Wetlands

Constructed wetlands (CWs) use plants to biologically and chemically remove constituents from water and reduce micropollutant concentrations in the concentrate. Depending upon the application objective, the CWs can be configured as vertical flow, surface flow (SF), and submerged aquatic vegetation (SAV). An example of surface flow and submerged aquatic CW is presented in Figure 2.14.

Recent pilot testing conducted by the City of Oxnard (City of Oxnard, 2003; City of Oxnard, 2004; Jordahl, 2006) and a study by the WateReuse Foundation (Jordahl, 2006) indicate that brackish marshes can be constructed to significantly reduce the volume of concentrate through evapotranspiration. These studies also found that chemical constituents of concern in the membrane concentrate can be reduced to levels safe for biota in wetlands, thereby providing valuable habitat as an additional benefit.[3]

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[3] Testing was conducted on combined concentrate from the NF, RO, and EDR trains used at the Port Hueneme, California, desalination facility.

FIGURE 2.14 EXAMPLE OF SURFACE FLOW AND SUBMERGED AQUATIC CONSTRUCTED WETLANDS

For concentrate applications, a CW consists of high-salt-tolerant plant species that can be used to remove or concentrate constituents in the root zone of the plant or in sediments, allowing evapotranspiration to reduce the volume of flow while increasing the salinity of the concentrate stream. Halophytes are one type of plants that can be utilized in CWs for treating high TDS-containing RO concentrate (that is, TDS concentrations of more than 10,000 mg/L). Halophytes are distinguished by the ability of the plants to grow in a saline environment as either obligate or facultative. Obligatory halophytes are plants in need of salt, and facultative halophytes can live in saline and in freshwater conditions. Examples of halophyte systems include saline semi-deserts, mangrove swamps, marshes and sloughs, and seashores. Salt marsh grass (*Spartina alterniflora*) is an example of a halophyte and is shown in Figure 2.15.

FIGURE 2.15 SALT MARSH GRASS GROWING NATURALLY

Advantages associated with constructed wetlands include:

- Uses a natural treatment process
- Creates aesthetic, educational, and recreational opportunities
- Provides habitat value
- Greatly reduces power needs compared to mechanical systems
- Has a proven record of treating municipal and industrial wastewater and stormwater runoff, including wastewater with high organic loading
- Provides specific constituent removal and polishes brine concentrate flows

Disadvantages associated with constructed wetlands include:

- Large footprint
- No full-scale project for brine concentrate treatment
- Potential exposure of wildlife to hazardous chemicals
- Potential impact to an underground source of drinking water (USDW) (if no liner used)
- Loss of potentially reusable product water through evapotranspiration
- Reduction of brine concentrate volume limited by the salt tolerance of NTS plant

Water quality and temperature strongly affect performance (both microbial uptake and evapotranspiration rates) of CWs.

Factors affecting the feasibility of implementing constructed wetlands for RO concentrate disposal include RO concentrate quality and flow rate, geographical location, hydrology, water balance, and site location. Many times, a volume-reduction technology would be necessary to reduce the RO concentrate volume if constructed wetlands were implemented. Wetlands are ecological systems; therefore, water quality has a strong impact on the type of microorganism that dominates. In addition, the TDS content of the water will determine the suitability of plants for wetland application.

Capital and O&M costs for an NTS were based on the assumption that the NTS is modeled after the sequence of wetlands being tested by the City of Oxnard Water Division for treatment of brine concentrate, as described on the City of Oxnard Web site (www.oxnardwater.org/ great/wetlands.asp) and as described in *Draft Results for the City of Oxnard GREAT Program Membrane Concentrate Pilot Wetland Project* (City of Oxnard, 2004). However, this testing was performed using concentrate from a groundwater RO facility.

Table 2.13 provides an example of an estimated volume reduction of 50 percent provided under an NTS sequence during the summer for a 1-mgd brine concentrate feed flow. The system area is estimated to be 68 acres (32 acres of wetlands plus 36 acres of winter pond storage) for 1 mgd of brine concentrate flow. Capital costs for an NTS capable of handling a 1-mgd flow is $9,600,000.

TABLE 2.13
EXAMPLE OF VOLUME REDUCTION FOR NTS SYSTEM DURING SUMMER

Type of NTS	Fractional Area (%)	Area (acres)	Inflow (mgd)	ET[a] rate (cm/d)	Outflow (mgd)	Volume Reduction (%)
VF	15	5	1.00	0.75	0.97	4
SF	36	12	0.97	1.58	0.77	21
SAV	49	16	0.77	1.15	0.57	26
Total	100	32	-	-	-	50

Note:

[a] Estimated rate of ET in Oxnard, Ventura County

cm/d	centimeters per day
VF	peat-based vertical flow
SF	surface flow
SAV	submerged aquatic vegetation

O&M activities will consist of the following periodic activities:

- Weekly inlet and control structure and flow inspection
- Monthly water quality monitoring
- Periodic vector management
- Annual vegetation management

The annual O&M cost of an NTS that treats a flow of 1 mgd is approximately $286,500. The unit treatment cost is $0.40 per 1,000 gallons of concentrate, which is near the upper range of operational costs described by Kadlec and Knight (Kadlec, 1996) and compares favorably with a unit cost of $0.43 per 1,000 gallons of treated capacity for the Laguna Niguel Wetland Capture and Treatment Network (City of Laguna Niguel Public Works Department, 2004).

Environmental Concerns

Species protection is a large concern driving regulation of solids residual-producing processes using NTSs. Large wetland ponds are attractive to many birds that frequent water. In some cases, high concentrations of metals and other constituents in the ponds have caused birth defects in waterfowl inhabiting ponds. Control of waterfowl can be handled using several different methods. One technique is to fire cannons periodically, creating a loud noise to scare waterfowl away from the evaporation ponds. However, the sound from the cannons generally carries a long distance and can be a nuisance to neighboring residential areas. Another technique is to broadcast the sound of natural predators over a loudspeaker system. This type of control is in use at fruit orchards across the country and has been proven to be quite effective. The sound emitted from these systems does not carry as far as the cannons, minimizing the potential for public complaints; however, birds frequently become immune to these methods. In addition, these methods do not protect reptiles, amphibians, or small mammals that enter ponds even when ponds have fences.

In addition, natural treatment systems must be lined to prevent seepage into the groundwater; otherwise, ponds would be considered a Class V injection well. Permitting of a Class V injection well, which can be extremely difficult, will be discussed in the deep well injection section of this report. Given proper lining, permitting an evaporation pond is a relatively simple process involving specific state and local regulations. If misting equipment is included to reduce the required area of the ponds, regulatory approval could be slightly more.

2.7 Two-Pass Nanofiltration

The Long Beach Water Department (LBWD) has developed and patented a two-pass NF process to produce drinking water from seawater. The two-pass, multistage nanofiltration membrane process treats water at a lower operating pressure and energy than a conventional single-pass seawater reverse osmosis (SWRO) desalination process. SWRO processes typically use thin-film composite membranes. A key component of the two-pass NF is the second-pass concentrate recycle loop, which dilutes feedwater and makes NF membranes feasible. The first pass removes approximately 90 percent of salinity, and the second pass removes 93 percent resulting in a total salt rejection of approximately 99 percent. The LBWD pilot unit is shown in Figure 2.16.

FIGURE 2.16 LBWD TWO-PASS NF PILOT PROJECT

The presence of two-passes of the NF increases reliability. In addition, the second pass can be operated at a higher pH by chemical addition to improve boron rejection. The overall recovery from the process is approximately 30 to 45 percent, which is lower than conventional RO desalination. Although two-pass NF was developed in late 2001, no full-scale application of this process exists. This could be due to concerns over lower water recoveries. No capital and O&M costs information is available for this technology because a full-scale application has not been implemented.

Advantages associated with two-pass NF include:

- Application to brine concentrate flows high in silica content with pH adjustment
- Small site footprint
- Lower energy cost

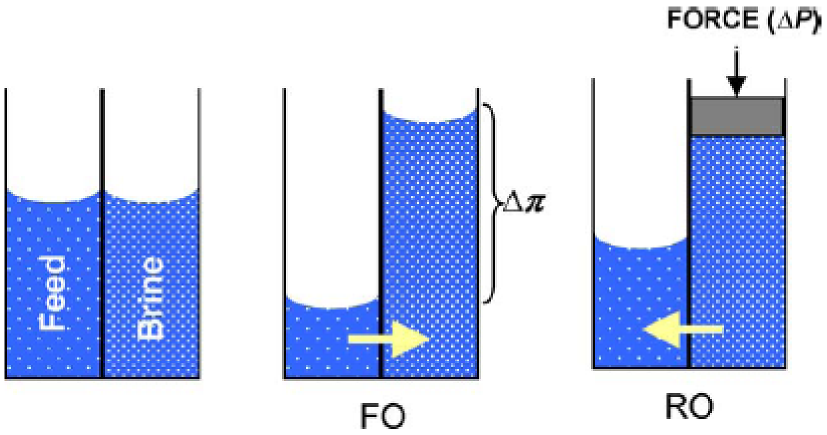
Disadvantages associated with two-pass NF include:

- Lower water recoveries than conventional RO
- No experience, requires detailed pilot testing to demonstrate performance and optimize operating conditions
- Complex, requires highly skilled operation

2.8 Forward Osmosis

Forward osmosis (FO) is an osmotic process that uses a semi-permeable membrane to separate salts from water. FO uses an osmotic pressure gradient instead of hydraulic pressure, which is used in RO, to create the driving force for water transport through the membrane. Figure 2.17 illustrates the FO process.

FIGURE 2.17 SCHEMATIC ILLUSTRATION OF RO AND FO



The concentrated solution, or draw solution on the permeate side of the membrane, is the source of the driving force in the FO process. Osmotic driving forces in FO can be significantly greater than hydraulic driving forces in RO. This results in the potential for higher water flux rates and recoveries. The selection of an appropriate draw solution is the key to FO performance. The draw solution should:

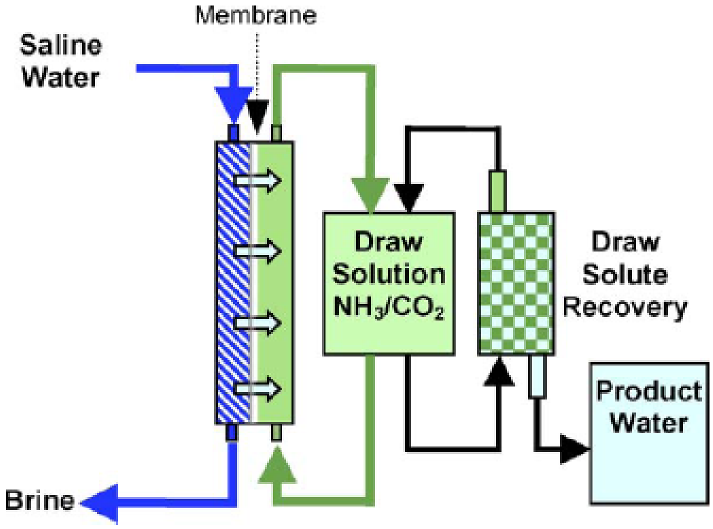
- Have a high osmotic efficiency(that is, have a high solubility in water and have a low molecular weight)
- Be non-toxic; trace amounts of chemicals in product water might be acceptable
- Have chemical compatibility with the membranes

When potable water production is considered via FO, the draw solute should be separated from water easily and economically. Example draw solutions include magnesium chloride, calcium chloride, sodium chloride, potassium chloride, ammonium carbonate and sucrose. A simplified process schematic of an FO process is presented in Figure 2.18.

There are two major limitations of using FO:

- High-performance membranes do not exist for FO process
- A draw solution that is easily separable has not been identified

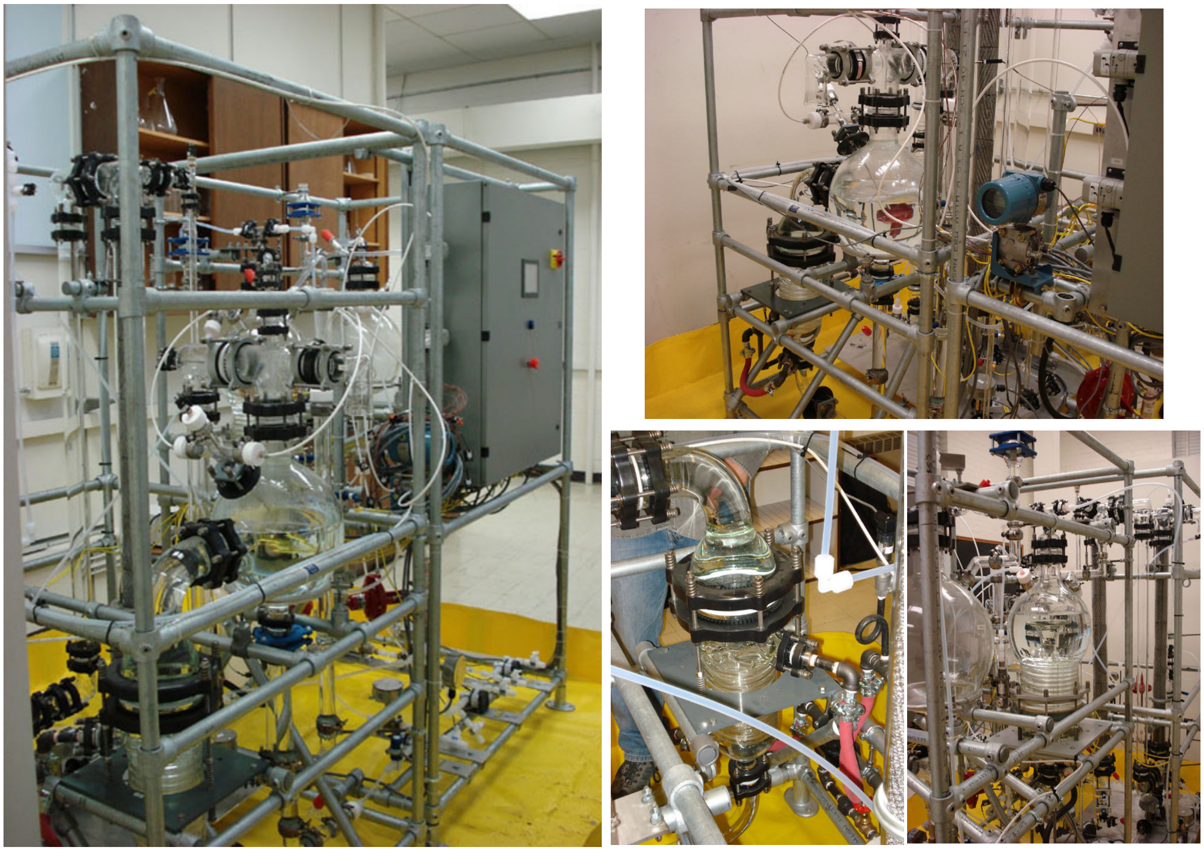
FIGURE 2.18 SIMPLIFIED PROCESS SCHEMATIC OF FORWARD OSMOSIS



Existing commercially available RO membranes are not suitable for FO because such membranes have a relatively low product water flux, which can be attributed to severe internal concentration polarization in the porous support and fabric layers of RO membranes. For this reason, existing membranes cannot support the flux required in FO.

FO is promising, but the process is still under development. A bench-scale FO unit was built and has been operated at Yale University laboratory since 2005; the unit is shown in Figure 2.19. However, FO cannot be used in large-scale applications until a membrane is developed that has high salt rejection and low internal concentration polarization. Since this technology is in the developmental stage, information regarding its advantages, disadvantages, and cost is not available.

FIGURE 2.19 BENCH-SCALE FORWARD OSMOSIS UNIT AT YALE UNIVERSITY



Source: Elimelech Lab, 2009

2.9 Membrane Distillation

Membrane distillation (MD) combines membrane technology and evaporation processing in a single unit. MD transports water vapor through the pores of hydrophobic membranes using the temperature difference across the membrane. The membrane allows water vapor to penetrate the hydrophobic surface while repelling the liquid. The clean vapor is carried away from the membrane and condensed as pure water, either within the membrane package or in a separate condenser system.

MD differs from other membrane technologies because the driving force that pushes the water through the membrane is not feed pressure but temperature. In MD units, vapor production is enhanced by heating the feedwater, which increases the vapor pressure and penetration rate. MD requires the same amount of energy input to heat and condense vapor as traditional evaporation; however, it does not require boiling water and is operated at ambient pressure. The energy requirement for MD is lower than conventional evaporation requires. MD is most efficient on low-grade or waste heat, such as industrial heat streams or even solar energy (Scott, 2007). Also, efficiency of the unit can be improved with heat recovery.

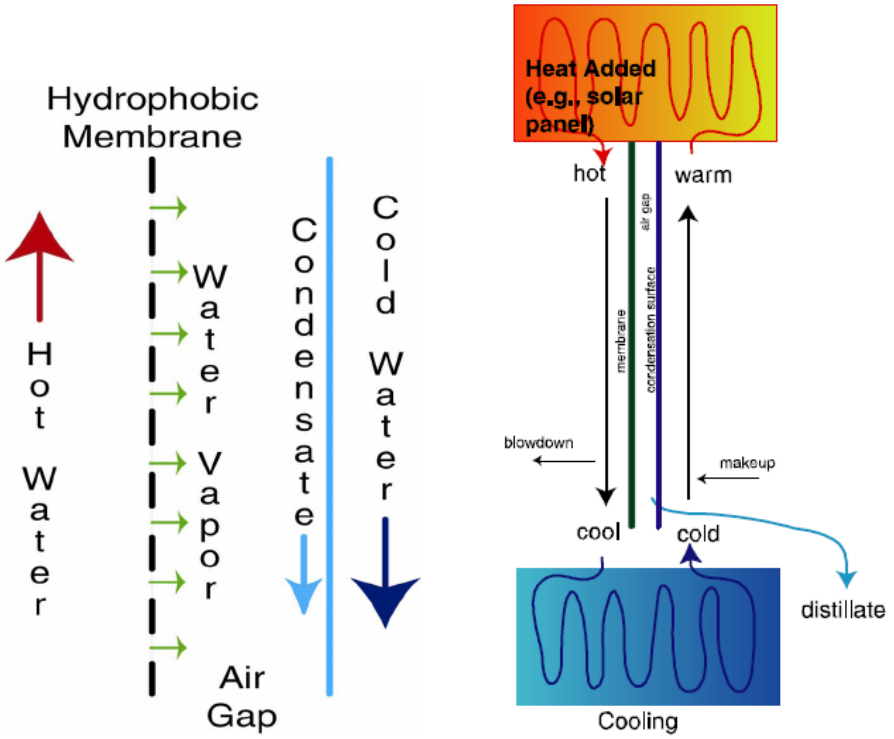
MD membranes must be microporous (pore diameters of 0.05 to 0.2 micrometer [µm]) and nonwettable by the feed. For MD applications, hydrophobic polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVF) membranes can be used either as flat sheets, or as hollow fibers. Thermal and chemical resistance, narrow pore-size distribution, high porosity, and low thermal conductivity are other desirable membrane qualities. Membrane modules have been developed in various configurations, including plate-and-frame, spiral-wound and hollow-fiber (Scott, 2007) for MD applications.

A variety of arrangements and configurations can be used to induce the vapor through the membrane and to condense penetrant gas; however, the feedwater must always be in direct contact with the membrane. Condensation is typically achieved via four process configurations (Daniel, 2004), which are:

- **Direct-Contact Membrane Distillation**: The cool condensing solution directly contacts the membrane and flows countercurrent to the raw water. This is the simplest configuration and is best suited for applications such as desalination and concentration of aqueous solutions (for example, juice concentrates).
- **Air-Gap Membrane Distillation**: An air gap followed by a cool surface. The use of an air gap configuration allows larger temperature differences to be applied across the membrane, which can compensate in part for the greater transfer resistances. The air gap configuration is the most general and can be used for any application, including desalination.
- **Sweep-Gas Membrane Distillation**: A sweep gas pulls the water vapor and/or volatiles out of the system. This is useful when volatiles are being removed from an aqueous solution.
- **Vacuum Membrane Distillation**: A vacuum is used to pull the water vapor out of the system. This is useful when volatiles are being removed from an aqueous solution.

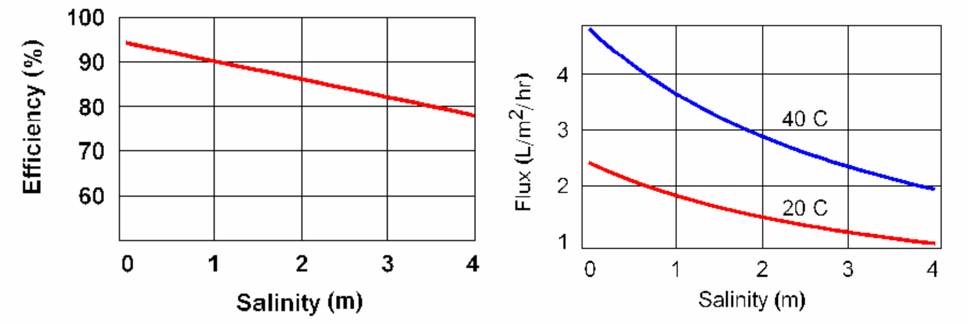
A schematic illustration of an air gap MD is shown in Figure 2.20.

FIGURE 2.20 SCHEMATIC OF AIR GAP MD AND AIR GAP MD WITH HEAT RECOVERY



Thermal efficiency of MD declines with salinity because highly saline water requires a greater temperature drop across the air gap, leading to greater losses of heat conduction through the air gap. Similarly, as salinity is increased, lower fluxes can be achieved due to reduced head transfer with highly saline water. The thermal efficiency and operating flux is estimated as a function of water salinity (Daniel, 2004). These relationships are presented in Figure 2.21, where the salinity has a molality (m) unit and 1 molal saline solution is equal to salt concentration of approximately 62,000 mg/L.

FIGURE 2.21 THERMAL EFFICIENCY AND FLUX AS FUNCTION OF SALINITY



A pilot test of MD using RO concentrate generated from a groundwater desalination facility operated by Eastern Municipal Water District (EMWD) was performed. The pilot test study showed that the operating flux was between 1.2 and 2.4 gallons per square foot per day (gfd) at feed and permeate temperatures of 40 and 20 degrees Celsius (°C), respectively. Increasing feed temperature to 60°C increased flux to 6.0 gfd. The water recoveries were between 60 and 81 percent, with an average of 70 percent during pilot testing. The pilot MD exhibited excellent salt rejections (that is, 99 percent or greater) during pilot testing. Potential advantages of MD include:

- High-quality water (distillate) is produced; however, distillate quality is dependent upon the extent of wetting of the membrane.
- MD is applicable for brine concentrate flows that are high in silica content.
- Low-grade energy and waste heat can be used.
- Little or no pretreatment may be required.
- MD requires relatively simple operation compared to other thermal processes.

Disadvantages associated with MD include:

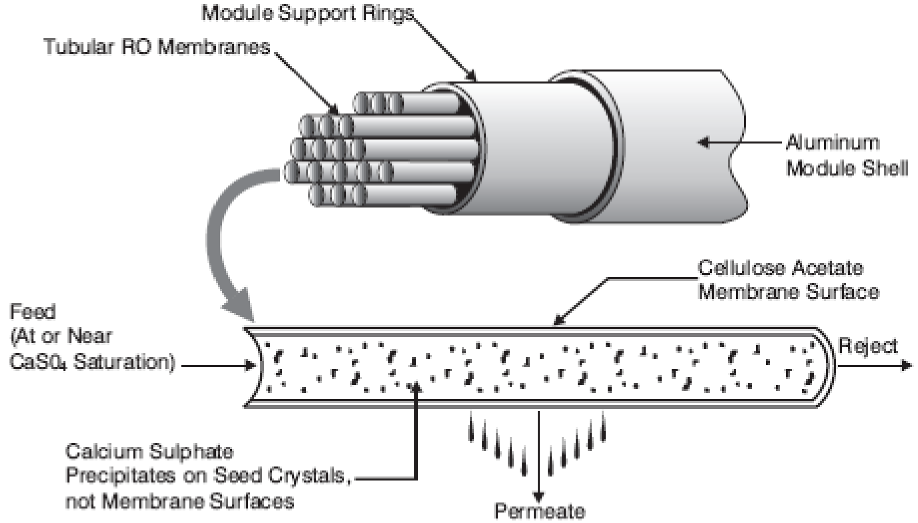
- The process is still under development; no-full-scale performance data are available.
- MD has relatively low recoveries and fluxes, based on EMWD pilot test results.
- The amount of energy required is high for a relatively low flux and recovery operation.
- High salinity limits mass transfer, which reduces flux through the system.
- Maintaining hydrophobic characteristics of membrane could be a challenge.
- No commercial membranes are available for MD applications. Membranes that are used in pilot and bench-scale MD demonstrations use microfiltration (MF) membranes that have a specific pore size and are made of hydrophobic materials.

MD is a technology still being developed. One key to the success of this technology will be the development of microporous membranes that have the desired porosity, hydrophobicity, low thermal conductivity, and a low potential for fouling. Development of these membranes would make MD an attractive and cost-effective technology in the future. There are no capital and O&M cost data available for this technology because it is still in the developmental stage.

2.10 Slurry Precipitation and Reverse Osmosis (SPARRO)

The major obstacle to operating an RO process at higher recoveries is the precipitation of sparingly soluble inorganic salts, most notably calcium sulfate ($CaSO_4$). Inorganic salt precipitation can be controlled at lower recoveries by using an appropriate antiscalant (AS) and by controlling feedwater pH. At higher recoveries (greater than 95 percent, as would be needed for large-scale RO), antiscalants are not effective, and pH control does not prevent precipitation of some problematic minerals such as barium sulfate and calcium sulfate, which cannot be removed by chemical cleaning. Slurry Precipitation and Reverse Osmosis (SPARRO) involves circulating a slurry of seed crystals within the RO system, which serve as preferential growth sites for calcium sulfate and other calcium salts and silicates. These seed crystals enable precipitate to begin as their solubility products are exceeded during the concentration process within the membrane tubes (GJG, 2000). The preferential growth of scale on the seed crystals prevents scale formation on the membrane surface. This process is confined to the use of membrane configurations that will not plug, such as tubular membrane systems, due to the need to circulate the slurry within the membranes. A conceptual schematic of SPARRO is presented in Figure 2.22.

FIGURE 2.22 CONCEPTUAL ILLUSTRATION OF SPARRO



In the SPARRO system, the water to be desalted is mixed with a stream of recycled concentrate containing the seed crystals and then fed to the RO process. The concentrate with seed crystals is processed in a cyclone separator to separate the crystals so that the desired concentration is maintained. This concentration is maintained in a reactor tank by controlling the rate of wasting the upflow and/or underflow streams from the separator. This technology has been tested for treating scale in a mine water (GJG, 2000), as well as on primary and secondary brine from the EMWD zero liquid discharge (ZLD) pilot project. The combined recovery of the process was greater than 90 percent (GJG, 2000). Although final pilot testing data have not been published, preliminary results from the EMWD study indicate that more than 80 percent recovery is achievable using the SPARRO process.

Potential advantages of SPARRO include:

- Low energy input compared to thermal processes.
- Less pretreatment needs than other hybrid technologies.

Disadvantages associated with SPARRO include:

- The process is still under development.
- SPARRO lacks full-scale performance, capital cost, and O&M data.
- Process has low rejection of salt (that is, 80 to 85 percent) compared to other RO-type processes (greater than 95 percent).
- Large footprint is necessary due to use of tubular membranes and large reaction tank required.
- Relatively complex operation is required.

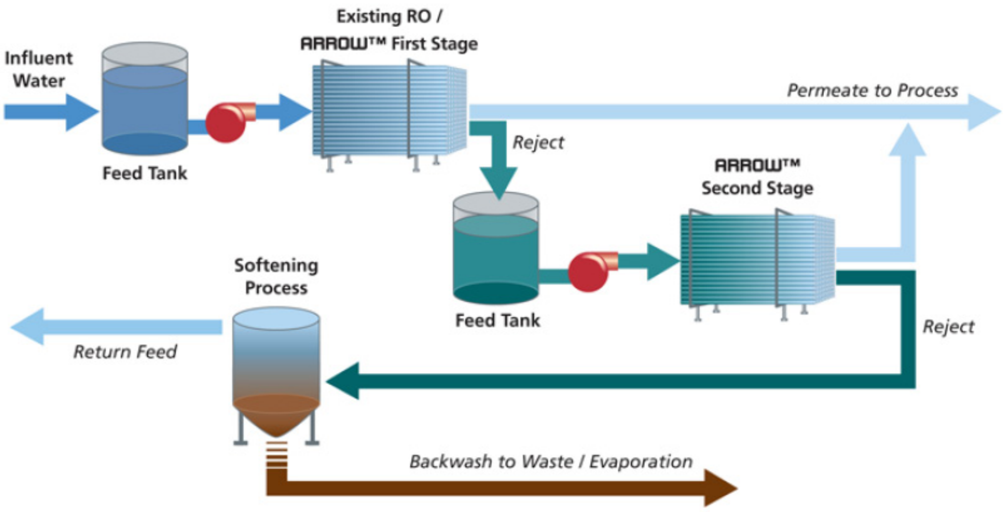
Although the SPARRO process is not new, it is still under development as a brine-concentrate management technology. This technology has relatively low energy costs but requires a large footprint to house the tubular RO membranes and requires the recovery and reuse of precipitated salts. No capital or O&M cost data are available for this technology.

2.11 Advanced Reject Recovery of Water

Advanced Reject Recovery of Water (ARROW) is a high-recovery, advanced membrane system that couples softening process with RO to increase water recovery. This is a proprietary technology marketed by Advanced Water Solutions and O’Brien & Gere. In RO and other desalination processes such as EDR, water recovery is limited by the concentration of scale precursors as well as by the concentration of colloidal and fouling material in the water. These compounds settle on the membrane surface or plates and reduce productivity. A common pretreatment to minimize scale fouling includes acidification of the feedwater and addition of an antiscalant. While calcium and magnesium hardness can be addressed by acidifying the feedwater, acidification is ineffective for reducing sulfate hardness. Silica also has a limited solubility, and acid addition further reduces solubility of silica. Increasing pH can push the solubility limit of silica, but it could result in deposition of calcium carbonate on the RO membrane surface or EDR plates. ARROW has a number of configurations that can be adjusted depending on flow rate, hardness, concentration of silica relative to other hardness precursors, and TDS concentration. The ARROW process is illustrated in Figure 2.23 and includes the following steps:

1. **Pretreatment:** Dual media or membrane filtration is used to minimize colloidal fouling. A silt density of less than 4 is targeted. Also, pretreatment includes the addition of acid (if necessary) and antiscalant.
2. **First-Stage RO:** ARROW produces a permeate stream of 60 to 75 percent of the flow, while 40 to 25 percent of the stream is RO concentrate.
3. **Second-Stage RO:** Concentrate from the first-stage RO is treated and combined with an appropriate flow of recycled stream from second-stage RO concentrate.
4. **Softening of RO Concentrate Stream from Second-Stage RO:** ARROW uses either chemical precipitation to reduce calcium, magnesium, and silica hardness or IX softening containing strongly acidic cation exchange resins, if silica hardness is not a concern. Chemical precipitation uses caustic soda or soda ash depending upon the ratio of alkalinity to calcium hardness.
5. **Recovery:** A small amount of flow from second–stage RO concentrate and a small reject stream either from the bottom of the clarifier or from the IX system is sent to a solar evaporator or thermal crystallizer. The combined volume of two reject streams is less than 5 percent giving an overall process recovery of greater than 95 percent.

FIGURE 2.23 PROCESS FLOW SCHEMATIC OF ARROW



To date, ARROW has only one full-scale application in the industrial water treatment field. This project is a 33-gpm unit in New Jersey, as pictured in Figure 2.24. Because the technology is very new, no capital and O&M cost data are available. However, the cost is expected to be similar to the EMS and PS/RO systems because the unit uses similar principles to increase RO recovery.

FIGURE 2.24 NEW JERSEY ARROW PROJECT FOR REJECT RECOVERY

Potential advantages of the ARROW system include:

- High-quality product water
- Applicable for brine concentrate flows that are high in silica content
- High water recovery (that is, 95 percent), which minimizes RO concentrate generation and disposal costs
- Compact skid-mounted system, which reduces not only footprint requirements but also equipment delivery and installation time (appropriate for applications of less than 0.25 mgd)

Potential disadvantages associated with ARROW include:

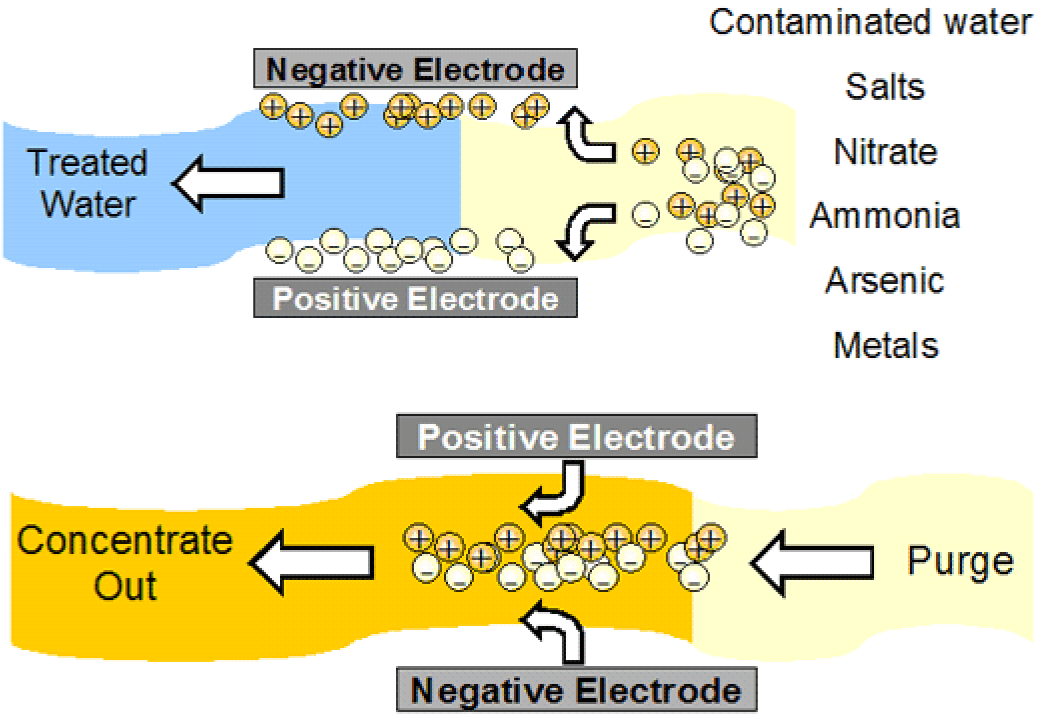
- Process is still under development; no full-scale applications exist in municipal water or wastewater treatment.
- High cost of chemicals used for pretreatment and softening of water.
- Combining the RO reject and IX regenerate would cause a precipitate to form that could reduce the crystallizer design or on-line factor.
- ARROW is a complex operation that requires skilled operators.
- Pilot testing is required to determine key design criteria.

- Sludge from precipitative softening might require separate disposal, which creates additional challenge and expense.
- Existing skid-mounted units are applicable only to very small systems (that is, systems up to 0.25 mgd). For larger systems, custom design, which increases construction time significantly, is required to reduce the capital cost.

2.12 Capacitive Deionization

Capacitive Deionization (CDI) is a low-pressure, non-membrane desalination technology that uses basic electrochemical principles to remove dissolved ions from solution. This process was developed and patented at Lawrence Livermore National Laboratory (Joseph, 1996). Aqueous solution of soluble salts are passed through pairs of porous, highly specific surface area (400 to 1,100 square meters per gram [m^2/g]) with very low electrical resistivity (less than 40 kilohm-meters) carbon aerogel electrodes that are held at a potential difference of 1.2 volts (V). Eventually, the electrodes become saturated with ions and must be regenerated. Using CDI, once the applied potential is removed, the ions attached to the electrodes are released and flushed from the system. This flushing produces a more concentrated brine stream, as illustrated in Figure 2.25.

FIGURE 2.25 CDI OPERATION (TOP) AND REGENERATION (BOTTOM)



CDI and EDR use similar electrochemical principles to remove ions from aqueous solutions. The difference between CDI and EDR is that CDI uses the reversible electrostatic adsorption in the electrical double layer close to the surface of the polarizable electrode, while EDR employs electrolysis on the surface of a nonpolarizable membrane. Surface adsorption requires much less energy than electrodialysis.

Although the power efficiency of CDI is nearly an order-of-magnitude better than RO and mechanical and thermal evaporative processes, it is plagued by a low ratio of water recovery (that is, 70 percent) with brackish water desalination. In addition, gel electrodes used in CDI are expensive. Also, the surface area of the electrodes is small, which reduces the salt capacity of the electrode and increases the number of electrodes required. TDA Research has developed a route to monolithic carbon electrodes with a combination of large (mesopores) and small pores (micropores), which are much less expensive than carbon aerogel electrodes. The benefit of the mesopores is that they allow the liquid to penetrate the carbon for easy access to the high-surface-area micropores while increasing capacity of salt uptake. Researchers at Massachusetts Institute of Technology (MIT) have proposed a CDI process with permeating flow discharge (PFD). In this modified approach, the brackish water is permeated through the porous electrodes rather than flowing between the electrodes, as is the case in the conventional axial flow discharge (AFD) process. This reduces discharge time and translates to an increase in water-recovery ratio by approximately 30 percent. However, increased recovery might not be applicable to brine-concentrate treatment because the MIT study used very low feedwater TDS values (600 to 990 mg/L).

Potential advantages of CDI include:

- CDI has low consumption of energy.
- No chemicals are used for regeneration of electrodes.
- Silica does not limit the recovery.

Potential disadvantages of CDI include:

- CDI is still under development.
- CDI lacks full-scale performance, capital, and O&M data.
- The process cannot remove all constituents (that is, boron, silica, and uncharged micropollutants).
- CDHS does not recognize CDI as a water treatment technology because CDI does not provide a barrier against pathogens.
- Multiple stages might be required for treatment of high-TDS feedwater, such as brine-concentrate, which increases capital and O&M costs.
- CDI recovers lower amounts of water than conventional membrane processes.