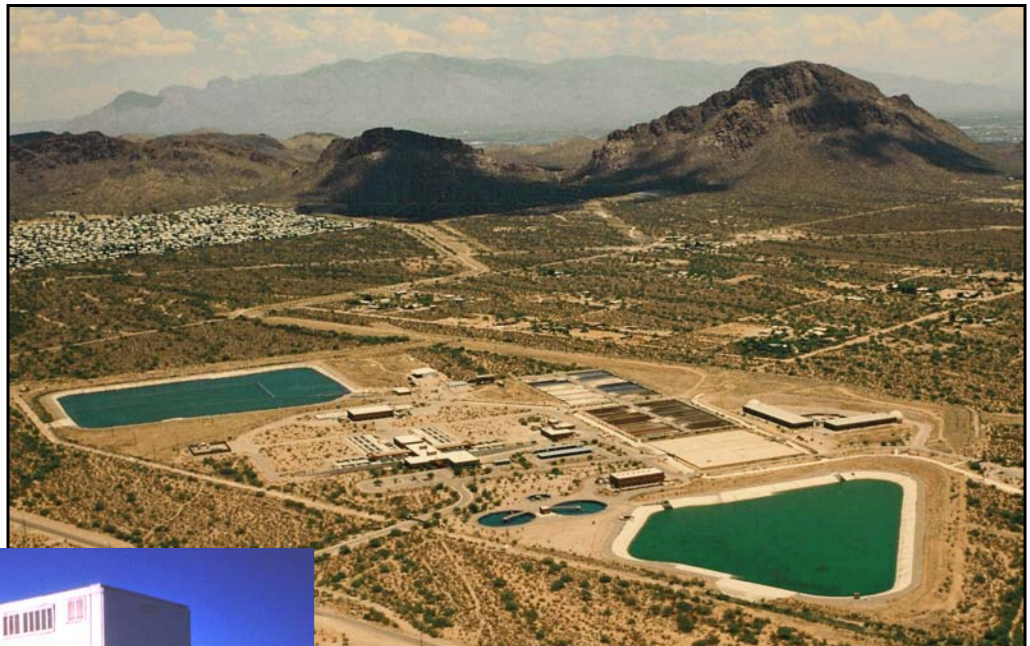
Reverse Osmosis Treatment of Central Arizona Project Water for the City of Tucson

Desalination Research and Development Program Report No. 36



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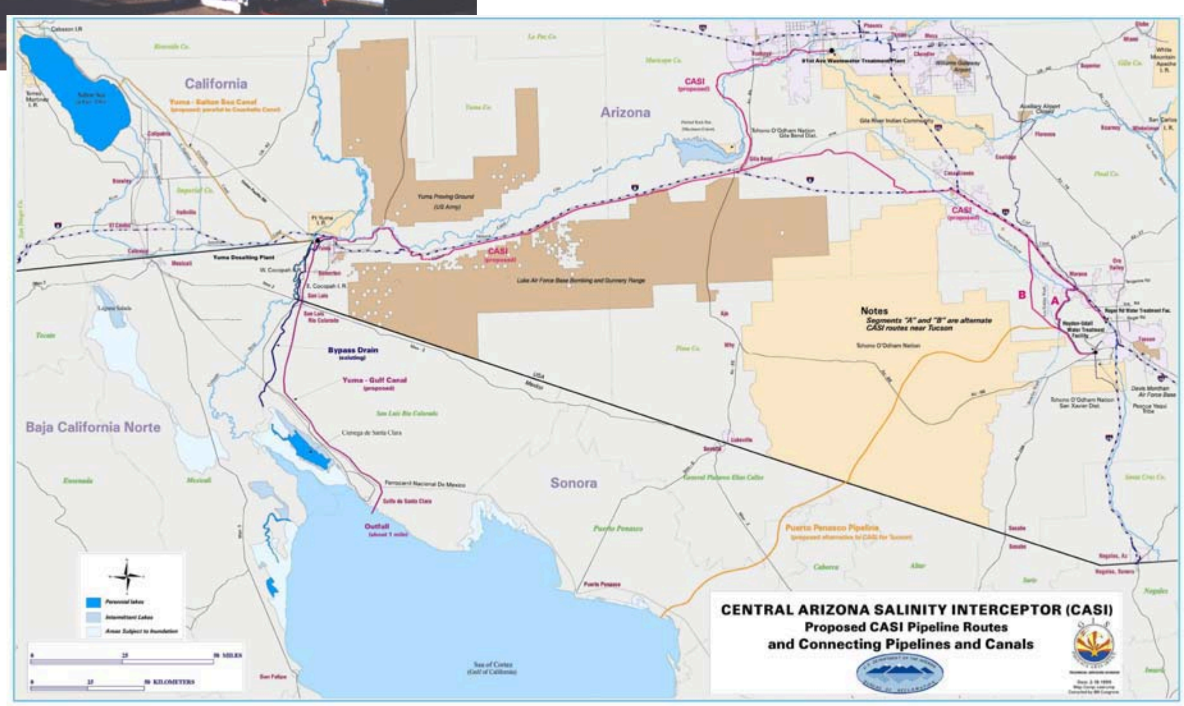

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The Water Desalination Research and Development Program is authorized by the Water Desalination Act of 1996 (Act). The Act is based on the fundamental need in the United States and world-wide for additional sources of water. The primary goal of this program is to develop more cost-effective, technologically efficient, and implementable means to desalinate water.

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Reverse Osmosis Treatment of Central Arizona Project Water for the City of Tucson

Appraisal Evaluation

prepared by the
Bureau of Reclamation
in cooperation with the
Tucson Water Department
under

Cooperative Agreement LC-96-2300-02

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13. ABSTRACT *(Maximum 200 words)*

The Bureau of Reclamation and the city of Tucson (City) evaluated conceptual designs and costs of reverse osmosis (RO) treatment of Central Arizona Project (CAP) water and disposal of the RO concentrate. RO treatment of CAP water with a TDS of 700 mg/L recovers 85 percent of the water as product with an average annual TDS of 56 mg/L (95 to 137 mg/L after post-treatment) and discharges 15 percent as brackish concentrate waste with a TDS of 4,400 mg/L. The desalted product meets the City's target levels of 210 mg/L TDS, 84 mg/L hardness, and 0.4 mg/L TOC. Pilot tests selected polyamide RO membranes operating at 17 gfd flux on microfiltration- or ultrafiltration-treated CAP water. For disposal of 16 MGD (18,100 af/yr) of brackish RO concentrate, the report selected discharge to the Gulf of California and recommended a regional salinity interceptor to transport central Arizona brackish waters to the Yuma, Arizona, area for beneficial use. For producing 33.5 billion gallons (102,500 af) per year of desalted water, the study estimates annual costs to upgrade the existing water treatment facility to include desalting and concentrate disposal as $33 to 41 million per year. These costs correspond to $1.00 to 1.24 per thousand gallons or, in terms of removed dissolved salts, $308 to 380 per ton of removed salts.

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Jim Miller of Process Optimization Services prepared the preliminary design and cost estimates for granular activated carbon (GAC) treatment. Dan Johnson of Cypress Sierrita performed extensive pilot tests to assess the value of reverse osmosis concentrate for flotation and leaching of mineral ores. Roger Jorden of Clear Corporation and John Franklin assisted with pilot tests.

Workgroup meetings were held approximately monthly. These meetings offered a valuable forum for public participation and included discussions and presentations of diverse technical opinions. The following individuals participated with the workgroup at one or more meetings: Mohsen Belyani, Tom Jefferson, Bill Vann, Keith Eagar, Clare Conley, Dennis Rule, Bill Wright, Bruce Masselt, Dave Johnson, John Pagliuso, Mike Metzinger, and Diane Elwood of Tucson Water; Michael Block and Thomas Caito of the Metropolitan Domestic Water Improvement District, Jim Riley of the University of Arizona Environmental Research Laboratory; Jerry Juliani of the Pure Water Coalition; Brent Cluff and Raydene Cluff of Clean Water Products, Mohamad Amin Saad of MASAR Technologies; Mike Caporaso and John Bodenchuk of the Arizona Department of Water Resources; Kathleen Chavez, Prakash Rao, and Don Armstrong of Pima County Wastewater Management; Mike Fleury and Scott Toland of Camp Dresser and McKee; Chuck Freitas of Falcon Pools; Russ Howard and Bob Navigato of the Central Arizona Water Conservation District; Lois Kulakowski of the Tucson Regional Water Council; Cornelius Steelink, Prof. Emeritus of Chemistry of the University of Arizona; Ron Wong of BKW Farms; Steve Davis, Warren Swanson, George Maseeh, and Zaid Chowdhury of Malcolm Pirnie; Jim Lozier of CH2M Hill; John Bratby of Brown and Caldwell; Michael McGuire of McGuidre Environmental Consultants; Ted Curtis; Dave Gudgel; Ron Soroka of U.S. Filter; Ed Lowell; Mort Seymour; Shirley Clouse; Jim King; Kevin Adam of the Office of Senator John McCain; Vicente Sanchez-Martinez of the Pima County Development Services Department.

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Acronyms and Abbreviations

af	Acre-foot volume of water; multiply by 325,851 to convert to gallons
af/yr	Acre-feet per year water flow; multiply by 0.620 to convert to gallons per minute; divide by 724 to convert to cubic feet per second
AMWUA	Arizona Municipal Water Users Association
ASR	Aquifer storage and recovery
AWWARF	American Water Works Association Research Foundation
CA	Cellulose acetate
CAP	Central Arizona Project
CASI	Central Arizona Salinity Interceptor (proposed pipeline or canal from Tucson and Phoenix to Yuma)
CAVSRP	Central Avra Valley Storage and Recovery Project
CF	Cartridge filtration
City	City of Tucson
CT	Conventional treatment
CRA	Colorado River Aqueduct
DBP	Disinfection byproduct
DRIP	Desalination Research and Innovation Partnership
GAC	Granular activated carbon
gal/min	Gallons per minute
gfd	Gallons per square foot per day membrane water flux; divide by 2.12 to convert to 10^{-6} m/s
gpd	Gallons per day plant capacity
HDPE	High-density polyethylene
HUWTF	Hayden Udall Water Treatment Facility
IBWC	International Boundary and Water Commission
kgal	Thousand gallons
MF	Microfiltration
MF/UF	Microfiltration or ultrafiltration
MGD	Million gallons per day; multiply by 1,121 to convert to acre-feet per year; multiply by 1.547 to convert to cubic feet per second
mg/L	Milligrams per liter concentration; multiply by 0.00136 to convert to tons per acre-foot
MTBE	Methyl Tertiary-Butyl Ether
NF	Nanofiltration
NF/RO	Nanofiltration or reverse osmosis
PA	Polyamide

PP	Pilot plant
ppt	parts per thousand
psi	Pounds per square inch pressure; divide by 14.5 to convert to bars; multiply by 6.895 to convert to kPa
psig	Pounds per square inch gauge
Reclamation	Bureau of Reclamation
RO	Reverse osmosis
SARI	Santa Ana Regional Interceptor
SDI	Silt Density Index measurement (ASTM Method D 4189)
SROG	Arizona Municipal Water Users Association Subregional Operating Group
SSF	Slowsand filtration
TARP	Tucson Airport Remediation Program
TDS	Total dissolved solids concentration, the measure of salinity,mg/L. TDS is measured by evaporation at 180 °C. It is also calculated from the concentrations of solutes in the water by the equation: TDS = 0.6* alkalinity + Na + K + CA + Mg + SO_4 + SiO_3 + NO_3 + F
TDS, RO sum	RO membrane manufacturers frequently refer to the sum of all solutes as TDS. TDS, RO sum, does not subtract any alkalinity, includes alkalinity as carbonate and bicarbonate, and includes silicon as SiO_2 mg/L
TOC	Total organic carbon concentration, mg/L
UF	Ultrafiltration
WCPA	Water Consumer Protection Act
WQIC	Bureau of Reclamation Water Quality Improvement Center inYuma, Arizona
WTF	Water treatment facility
WWTP	Wastewater treatment plant

Executive Summary

This report addresses the feasibility and estimated costs of reverse osmosis (RO) treatment of Central Arizona Project (CAP) canal water. The study was sponsored by the Science and Technology Program and Phoenix Area Office of the Bureau of Reclamation and by the City of Tucson.

Reverse Osmosis

RO is a water treatment process that cleans and purifies water by using pressure to push water, but not dissolved salts and many other contaminants, through membranes. The low-salinity RO finished product water has economic benefits, including reduced corrosion of water fixtures and appliances. RO treatment provides public health benefits, including serving as an effective barrier for removal of waterborne microorganisms, such as cryptosporidium and giardia, and producing water that meets all primary and secondary drinking water standards.

Another advantage is that with the low-total organic carbon (TOC) levels in the RO product, chlorine disinfection can be used instead of chloramine disinfection. RO is very effective at removing TOC compounds that react with free chlorine to form toxic disinfection byproducts (DBPs) regulated under the Disinfectants/Disinfection Byproducts Rule of the Safe Drinking Water Act. The use of free chlorine with RO-treated CAP water may improve its compatibility with the existing chlorinated groundwaters by avoiding mixing chloraminated and chlorinated waters. Such mixing may create taste and odors in the combined water supply. The ability to carry a free chlorine residual with RO-treated CAP water avoids this problem or avoids the potential need to chloraminate existing groundwater supplies.

In addition to producing high-quality, low-salinity product water, the RO process also produces a salty waste stream or “concentrate.” All RO desalting plants require concentrate disposal, which is generally problematic because the concentrate contains all the constituents removed from the source water.

Procedures

The Bureau of Reclamation (Reclamation) and the City of Tucson (City) cooperatively evaluated conceptual designs and costs of RO treatment of CAP water and disposal of the RO concentrate. The evaluation process consisted of workgroup meetings, pilot plant water treatment tests, appraisal level conceptual design analyses of pretreatment and desalting systems, and the development and evaluation of concentrate disposal alternatives.

The November 1998 draft report contained cost estimates for treatments and concentrate disposal, as well as appendices A - E with design and cost information. In May 1999, City and Reclamation representatives refined the focus of the conceptual designs for plant size and concentrate disposal and proceeded with additional pilot tests to confirm the effectiveness and reliability of the selected treatment processes. This report applies November 1998 cost information for the two plant sizes, four treatment alternatives, and six concentrate disposal alternatives selected at the May 1999 meeting, as well as results from all pilot tests. The design does not include interim (1998 - 2003) developments and information regarding water treatment technologies, and costs remain in 1998 dollars.

Water Treatment Results

Pilot plant tests were used to establish acceptable conceptual design parameters, including pretreatment, RO membrane type and rejection, water recovery, membrane water flux, and concentrate stabilization. Based on these tests, RO treatment of CAP water with total dissolved solids (TDS) of 700 milligrams per liter (mg/L) recovers 85 percent of the water as product with an average annual TDS of 56 mg/L and discharges 15 percent as brackish concentrate waste with a TDS of 4,400 mg/L.

The average annual expected RO product water quality levels are 56 mg/L TDS, 5.4 mg/L hardness, and 0.14 mg/L TOC. Projected post treatment stabilization with low-turbidity lime and carbon dioxide raises the average annual TDS level to 95 to 137 mg/L and hardness concentration to 44 to 86 mg/L (2.6 to 5.0 grains/gallon).

In the summer when salt rejection is lowest in a constant-flux RO plant, the expected RO product water quality levels are 69 mg/L TDS, 6.9 mg/L hardness, and 0.14 mg/L TOC. Projected post treatment stabilization with low-turbidity lime and carbon dioxide raises the summer TDS level to 108 to 166 mg/L and hardness concentration to 46 to 104 mg/L (2.7 to 6.1

grains/gallon). Caustic soda can replace some of the lime to reduce the added hardness.

These levels can meet the requirements of the City's 1995 Water Consumer Protection Act (WCPA) criteria of 210 mg/L TDS, 84 mg/L hardness, and 0.4 mg/L TOC.

To keep RO operating costs low with low operating pressures and long membrane lives, fouling must be kept low. To avoid fouling and coating of the RO membranes with particulates, the study evaluated conventional treatment (CT) and microfiltration or ultrafiltration (MF/UF). Because pilot studies indicated that the CT was much less reliable than MF/UF in producing foulant- and scalant-free water for RO operation, the study selected MF/UF with or without existing Hayden Udall Water Treatment Facility (HUWTF) rapid sand filters operating upstream of the MF/UF equipment.

The study evaluated treatment by granular activated carbon (GAC) in parallel to RO, but estimated that the GAC process would not result in lower costs and would add complexity and produce lower-quality water.

To produce 33.4 billion gallons per year at a daily average of 91.5 million gallons per day, the study considered two RO plant capacities—96.3 and 150 MGD as desalted RO product. The constant-production 96.3-MGD size plant incorporates existing City wells into an aquifer storage and recovery (ASR) system to meet peak demands in the summer. The variable-production 150-MGD size plant meets summer peak-day flows without ASR. The study estimates that the 96.3-MGD size plant with ASR costs less than the 150-MGD size plant by $9.5 million per year. This cost difference corresponds to approximately 25 percent of the cost to incorporate a 150-MGD desalting plant with concentrate disposal. Until issues of potential degradation of water quality during aquifer storage and recovery (ASR) can be resolved, however, the authors recommend the higher-cost 150-MGD plant capacity.

Concentrate Disposal Results

Disposal of the brackish RO concentrate at Tucson's inland site presents a serious challenge. With an average RO product flow of 91.5 MGD, the average concentrate flow of 16.1 MGD (18,100 af/yr) contains 108,600 tons/yr of dissolved salts at a concentration of 4,400 mg/L (6.0 tons/af) TDS. Study participants explored and evaluated a host of alternatives, including discharge to the Gulf of California, deep well injection, reuse at a local mine, fossil fuel evaporator/crystallizer, solar ponds, evaporation ponds, halophyte irrigation, and discharge to wetlands or brackish water reservoir. Study participants selected discharge to the Gulf of California as the most promising concentrate disposal alternative based on the criteria of effectiveness, implementability, and cost.

Discharge to the Gulf of California can follow either of two gravity flow routes. With no partners to share in the disposal costs, the lower-cost route runs from Tucson southwest to Mexico discharging into the Gulf of California east of Puerto Penasco where the brackish water is expected to have several beneficial uses. The estimated cost to upgrade the existing HUWTF to include 150-MGD of RO desalting capacity and dispose of the concentrate in a pipeline to Puerto Penasco (alternative 150:UF-RO-PP16) is $41 million per year corresponding to $1.24 per thousand gallons of desalted product water or $380 per ton of removed salts

The authors recommend a second, potentially more economical, concentrate disposal alternative that offers a regional solution to projected needs throughout central Arizona for the discharge of brackish residual waters from desalting plants, water reuse plants, and urban and agricultural irrigation. The proposed Central Arizona Salinity Interceptor (CASI) consists of pipeline and canal sections to collect and transport brackish waters by gravity from the Tucson and Phoenix areas to Yuma.

At Yuma, the brackish water has several potential beneficial uses, including supplying additional brackish water to the Cienega de Santa Clara (Santa Clara Wetland) in Mexico, supplying additional freshwater through desalting at the Yuma Desalting Plant, supplying relatively fresh water to lower the salinity of the Salton Sea, and supplying brackish water to restore and maintain the ecology of frequently-dry stretches of the Colorado River and Colorado Delta in Mexico. CASI could be operated by the Central Arizona Water Conservation District in the same manner that the Santa Ana Watershed Protection Authority operates the Santa Ana Regional Interceptor (SARI) pipeline for Los Angeles, California, and its suburbs.

With cost-sharing associated with 20-MGD or greater flow from the Phoenix area, CASI becomes more economical than a pipeline to Puerto Penasco. With participation in a 36-MGD low-volume CASI canal, the estimated cost to upgrade the HUWTF to include 150-MGD of RO desalting capacity and dispose of the concentrate (alternative 150:HU-UF-RO-CC36) is about the same as with an unpartnered pipeline to Puerto Penasco: $41 million per year corresponding to $1.23 per thousand gallons of desalted product water and $380 per ton of removed salts. Up to 20 percent lower costs can be achieved by participating in the construction and operation of a high-volume CASI canal for discharging up to approximately 270 MGD (300,000 acre-feet per year), the projected accumulation of brackish water in Central Arizona.

Conclusion

In summary, the study finds that MF/UF and RO treatment with concentrate disposal offers a technically feasible process for producing 33.5 billion gallons (102,500 af) per year of desalted water. The study estimates annual costs to upgrade HUWTF to include desalting and concentrate disposal to be $33 to $41 million per year ($1.00 to $1.24 per thousand gallons), depending on the concentrate disposal selected.

Introduction

The city of Tucson (City) is evaluating nanofiltration (NF) and reverse osmosis (RO) membrane treatment as part of its efforts to use its water resources in the most efficient manner possible and to maintain its historically high quality water.

The economic benefits of maintaining low salinity waters are significant. Two recent studies (Dames and Moore, 1995, and Bookman-Edmonston, 1998) estimated different, but nevertheless considerable, economic benefits of using low salinity waters. The benefits are based on a range of effects including, for example, salinity effects on the effectiveness of laundry detergents, repairs and replacement of plumbing fixtures and home appliances, car radiator life, and the extent to which customers individually seek to avoid salinity effects by installing water softeners and home filtration systems and purchasing bottled water.

Delivery of low-total dissolved solids (TDS), low-total organic carbon (TOC) RO-treated Central Arizona Project (CAP) waters has other advantages, including providing a barrier for increased removal of waterborne microorganisms, including viruses, cryptosporidium, and giardia (see figure 1); removal of organic precursors to disinfection byproducts (e.g., trihalomethanes); and removal of many inorganic contaminants and some organic contaminants. For example, RO effectively removes two contaminants found in Colorado River water: perchlorate (Riley, 1998; Liang, et al. 1999) and methyl tertiary-butyl ether (MTBE) (Liang, et al. 1999).

Another advantage is that with the low-total organic carbon (TOC) levels in the RO product, chlorine disinfection can be used instead of chloramine disinfection. RO is very effective at removing TOC compounds that react with free chlorine to form toxic disinfection byproducts (DBPs) regulated under the Disinfectants/Disinfection Byproducts Rule of the Safe Drinking Water Act. The use of free chlorine with RO-treated CAP water may greatly improve its compatibility with the existing chlorinated groundwaters by avoiding mixing chloraminated and chlorinated waters. Logsdon et al. (1999) report it inadvisable to mix waters, such as chloraminated CAP water and well waters containing free chlorine, because at the interface of the two supplies, the free chorine may react with the monochloramines, thereby reducing the free chlorine level and possibly forming dichloramine or nitrogen trichloride compounds. All three results may create taste and odors in the combined water supply. The ability to carry a free chlorine residual

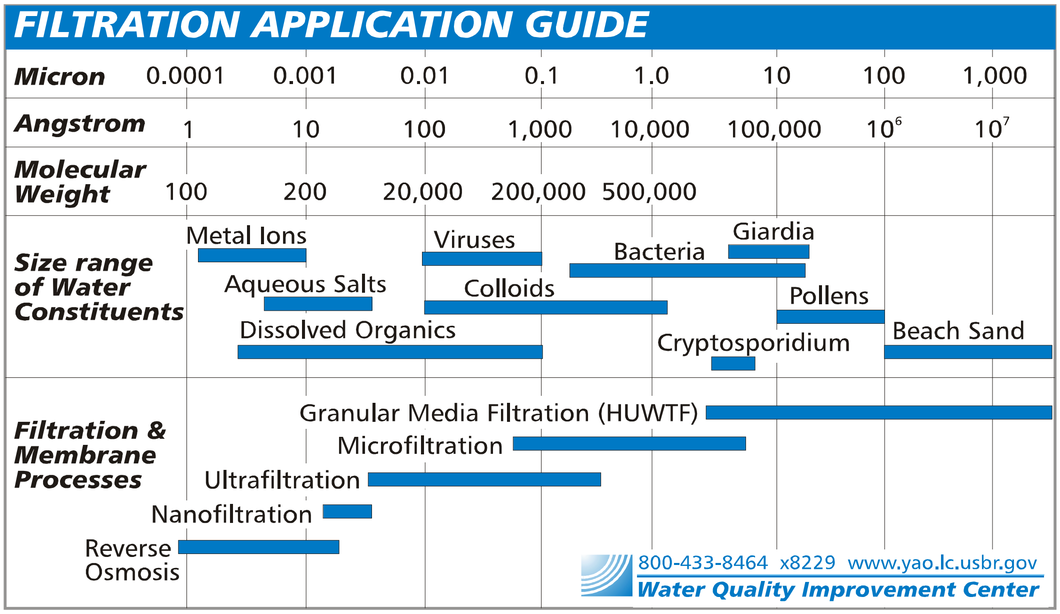

Figure 1.—Filtration application guide.

with RO-treated CAP water avoids this problem or avoids the potential need to chloraminate existing groundwater supplies.

To ensure that Colorado (and Agua Fria) River water delivered to Tucson customers from Reclamation's Central Arizona Project are sufficiently treated to be as high quality as Tucson's historical groundwater supplies, the City established the Water Consumer Protection Act (WCPA) in 1995. Under the WCPA, ". . .CAP water may be directly delivered as a potable water supply only if it is treated in a manner sufficient to ensure that the quality of the delivered water is equal to or better in salinity, hardness, and dissolved organic material than the quality of the groundwater being delivered from Tucson's Avra Valley well field. . .."

The City lists the target Avra Valley water quality values as 210 mg/L TDS, 83.8 mg/L hardness as $CaCO_3$, and less than 0.4 mg/L TOC (Mapes, 1996). Although the CAP water quality varies, it exceeds the target Avra Valley values with respect to all three parameters.

Study Objectives

To estimate the costs and viability of membrane treatment of CAP water, the study addresses the following questions:

1. What NF or RO membrane types are most appropriate and cost effective?

2. What is the maximum product water recovery that can be achieved while avoiding membrane scaling by the precipitation of low-solubility salts? These estimated maximum water recoveries were verified during onsite pilot operations.

3. Do the City's existing filtration and chloramine disinfection provide adequate pretreatment for the membrane process as evaluated during onsite pilot operations to measure membrane fouling and degradation. If the City's existing treatment does not provide adequate pretreatment, what are the recommended modifications and estimated costs of these modifications?

4. What are the quantity and composition of the membrane concentrate? Can the membrane concentrate be utilized for beneficial use? If not, what are the estimated costs to dispose of this brackish water?

5. What are the estimated costs (per preappraisal-grade estimates with an accuracy of plus 50 and minus 30 percent) to implement this advanced treatment option including cost of pretreatment modifications, membrane treatment, and the use or disposal of the membrane concentrate?

6. If the estimated costs appear potentially affordable, what additional pilot plant, regulatory, and cost questions need to be answered in the next evaluation stage of this water treatment option?

Procedure

In November 1996, Tucson Water and the Bureau of Reclamation (Reclamation) entered into a cooperative agreement to evaluate the costs and viability of membrane treatment of CAP water. The evaluation process consisted of workgroup meetings, pilot plant water treatment tests, appraisal-level conceptual design analyses, and the development and evaluation of concentrate disposal alternatives.

The initial draft report was published in November 1998. In May 1999[1], Tucson Water and Reclamation representatives refined the focus of and outlined additional information needed for the conceptual designs. The original design and cost information remain as originally listed in Appendices A - E. Each appendix is followed by the first revision of that appendix, "Revision 1," that contains design and cost information to address the directions of the May 1999 meeting. To address uncertainties regarding the effectiveness of pretreatment to RO equipment, additional pilot tests were conducted in 1999. Appendix F describes pilot tests and test results.

The revised evaluations of designs and costs include:

1. A reduction in the number of RO plant sizes from three sizes: 50, 100, and 150 million gallons per day (MGD) to two sizes: 96.3 MGD with aquifer storage and recovery (ASR) and 150 MGD, sized to meet peak-day demand in the summer without ASR.

2. Based on successful pilot tests, the selection of microfiltration or ultrafiltration (MF/UF) as pretreatment to desalting by reverse osmosis (RO) (see table 2, treatment alternatives 7 and 10).

3. To achieve lower treatment costs, treatment designs incorporating nondesalted "blend" water treated by granular activated carbon (GAC) to remove total organic carbon (see table 2, treatment alternatives 7a and 10a).

4. A description of and cost estimates for post-treatment stabilization of the desalted water.

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[1]Attendance at this May 19, 1999, meeting were:

From Tucson Water—David Modeer, John Nachbar, Marie Pearthree, Bruce Johnson, Barbara Buus, David Cormier, Jim Lozier (CH2M Hill consultant).

From Reclamation—Chuck Moody, Eric Holler, Stan Hightower, Tom Wotring

5. Further evaluation of the recommended concentrate disposal alternative: Discharge to the Gulf of California for six alternatives, involving two routes with and without cost-sharing from partnering municipalities.

This report revision describes the conceptual designs and estimated costs for the 48 combinations of two plant sizes, four treatment alternatives, and six concentrate disposal alternatives.

Workgroup Meetings

City and Reclamation workgroup members met 20 times (approximately monthly) to coordinate activities, monitor pilot tests, and review and discuss progress. Interested parties and representatives from State and local agencies were invited. Average meeting attendance included 14 nonwork-group members.

In addition to presentations and discussions by workgroup members, workgroup meetings included the following presentations and/or reports:

Jim Lozier (CH2M Hill), *Plugging Factor Tests at Phoenix-Area CAP Water Plants*. Silt density index (SDI) levels at four plants ranged from 2.3 to 5.3, low enough to consider for RO operation, which requires SDI levels less than 5.

Michael McGuire (McGuire Environmental Consultants), *Customer Focus on Water Quality Program.*

Brent Cluff (Clean Water Products) described slowsand filtration (SSF) as pretreatment to nanofiltration (NF) and exhibited his SSF-NF pilot plant equipment.

Mohammed Amin Saad (MASAR Technologies) demonstrated software for monitoring RO plant performance.

Dr. James Riley and Dr. Edward Glenn (University of Arizona Environmental Research Laboratory), *Acceptability of Potential Water Supplies to the Santa Clara Wetlands with Respect to Salinity and Selenium* (see appendix D for report). Water presently entering the Santa Clara Wetland in the MODE and Riito canals is beyond the salinity optimum for the dominant vegetation, and the selenium concentration puts it in the high risk category for wetlands. Nevertheless, this water supports a valuable and unique wetland in the Colorado River delta. Preserving the size, wetland values, and safety of the wetland will require that water of equal or better quality with respect to salinity and selenium should make up the inflow source. The models show that water of higher quality can be substituted in lower volume for water presently entering the Santa Clara Wetland at 3.1 parts per thousand (ppt) (3,100 mg/L) TDS. Conversely, water of higher salinity can substitute in higher volume, but the upper salinity limit of 6 ppt (6,000 mg/L) for the vegetation and the possibly greater selenium risk associated with higher-salinity water, place constraints on this option (Tanner et al., 1997).

Bob Riley (Separation Systems International) described RO element materials and fabrication and RO element autopsy procedures.

Steve Davis (Malcolm Pirnie), *Central Avra Valley Storage and Recovery Project Task 6 - Water Quality Management Program. Bench-Scale Iron Release Testing Program: Phase I Results.*

Mike Miller (Reclamation), *Geological Assessment of Deep Well Injection in the Tucson and Avra Valley Basins* (see appendix D for report).

Herman Bouwer (U.S. Water Conservation Laboratory), *Arizona's Long-Term Water Outlook: From NIMTO to AMTO*. Dr. Bouwer described the need to remove and dispose of salts brought into the Central Arizona area from the Colorado and Salt Rivers (Bouwer, 1997).

Brett Andrews (PermaCare) described the use of antiscalants to prevent RO scaling from low solubility solutes.

Bob Ning (King Lee Technologies) described the use of antiscalants to prevent RO scaling from low solubility solutes and antifoulants to reduce RO fouling.

Maggie Wolfe (PerLorica) described Colorado River water RO pilot tests being conducted by the Metropolitan Water District of Southern California as part of the Desalination Research and Innovation Partnership (DRIP).

Dan Johnson (Cyprus Sierrita Corporation) presented results of bench-scale evaluations of different waters (including RO concentrate) for use in the flotation recovery of copper and molybdenum from mined ores.

Pilot Tests

Pilot tests were conducted using Reclamation's Mobile Treatment Plant and the City's Hayden Udall Pilot Plant (PP), constructed during the study (see appendix F for detailed descriptions of test and test results).

The 16-gallon per minute (gal/min) Hayden Udall PP, modeled after the full-scale Hayden Udall Water Treatment Facility (WTF), includes ozonation, coagulation, chlorine disinfection, and gravity filtration. Sedimentation tanks were added upstream of the filters to lengthen the periods between filter backwashes (filter runs).

The Mobile Treatment Plant contains a pilot 6-gal/min nanofiltration/reverse osmosis (NF/RO) unit operating with 2.5-inch diameter NF/RO elements in a 2:1 array. Associated chemical feed systems and controls are provided for pH, chlorine, ammonia, and antiscalants.

A 6-gallon-per-minute Zenon unit equipped with microfiltration (MF) membranes for some tests and ultrafiltration (UF) membranes for other tests was tested to evaluate the effectiveness of MF/UF pretreatment for reverse osmosis.

An automatic silt density index (SDI) instrument (Chemetek FPA-3300) was used to monitor particulate levels in pretreatment products and RO feedwater. SDI (by ASTM Method D 4189) uses the flow rate through 0.45-µm pore size filter paper as a measure of particulate content. SDI measurements are better than turbidity measurements for determining the potential for colloidal and particulate fouling and simpler than particle analysis measurements.

Concentrate Disposal

For the disposal or reuse of the concentrate flow from the RO system, the workgroup originally developed and conducted a screening evaluation of 11 alternatives (see table 3) and selected 4 alternatives for detailed analyses (see appendix D for descriptions and cost analyses of the alternatives and analyses).

In May 1999, City and Reclamation representatives selected six concentrate disposal alternatives for cost analyses (see appendix D, revision 1). This report revision presents the costs of the following six concentrate disposal alternatives.

a. PP16. Pipeline to Puerto Peñasco with a flow of 16 MGD

b. CP16. CASI pipeline to Yuma with a flow of 16 MGD

c. CC16. CASI canal to Yuma with a flow of 16 MGD

d. CP36. CASI pipeline to Yuma with 20 MGD from the Arizona Municipal Water Users Association Subregional Operating Group (SROG) for a total of 36 MGD

e. CC36. CASI canal to Yuma with 20 MGD from SROG for a total of 36 MGD

f. CC270. CASI canal to Yuma with maximum multiple Central Arizona partners and a flow of 270 MGD (300,000 af/yr)

Results

The results are summarized in this section and presented in detail in the appendices.

Conceptual Design Basis

Tucson Water Deliveries

For the period 1995-97, Tucson Water Department delivered an average of 33.4 billion gallons (104,300 acre-feet) of water each year (Tucson Water Department, 1996, 1997, 1998). The average monthly water deliveries range from 64 million gallons per day (MGD) in March to 123 MGD in July.

Projected future annual deliveries to the city of Tucson are 55.6 billion gallons (173,900 acre-feet) (Bureau of Reclamation [Reclamation], 1998a). The average projected future monthly deliveries range from 109.6 MGD in January to 177.5 MGD in September.

The average daily flows are 91.5 MGD for 1995-97 and 155.1 MGD in the future.

Reverse Osmosis Plant Capacities

This report considers two reverse osmosis (RO) plant sizes: 96.3 and 150 MGD as RO product water.

The 96.3-MGD capacity plant operates year-round at an assumed plant factor of 95 percent at constant production of 91.5 MGD. Incorporating aquifer storage and recovery, from October through May excess RO product is conveyed through the existing water distribution systems to recharge wells in the central wellfield. From June through September, the water is recovered to supplement the RO plant production and meet peak demand.

The 150-MGD capacity plant is sized to meet the peak day demand needs in the summer. At other times of the year, it operates at less-than-full capacity with an average operating factor of 61 percent. Both RO plant sizes produce an average of 91.5 MGD and a total annual production of 33.4 billion gallons.

Pilot Tests and RO Conceptual Design

RO membrane equipment requires very low suspended particulate concentrations to avoid coating or "fouling" the membrane surfaces with clay and organic particulates. RO can often operate directly on groundwater with minimum "pretreatment" (e.g., cartridge filters, pH adjustment, and addition of antiscalant). For surface waters, including CAP water, however, RO requires extensive filtration pretreatment. Such pretreatment can be accomplished to varying degrees of quality by conventional treatment consisting of coagulation and media filtration, by slowsand filtration (SSF), or by MF. In separate studies, the city of Tucson (Chowdhury, et al., 2003) and the Bureau of Reclamation (Moody,et al., 2002) evaluated SSF pretreatment of CAP water for RO desalting. Pilot tests for this study used the Hayden Udall PP modeled after the existing Hayden Udall WTF for most of the testing. A Zenon unit with MF and UF membranes was used for several pilot activities.

Table 1 summarizes existing and proposed water treatment components for the two available water supplies: groundwater and CAP water. Not listed is disinfection treatment, which is required for both water supplies.

Table 1.—Water treatment components

Water source	Filtration I	Filtration II	Advanced treatment
Groundwater	Existing: None	Existing: None	Existing: Air stripping on TARP supply only
CAP	Existing: HUWTF	Existing: None	Existing: None
	Proposed: CAVSRP SSF MF/UF	Proposed: CF SSF MF/UF	Proposed: RO GAC

TARP = Tucson Airport Remediation Program; CAVSRP = Central Avra Valley Storage and Recovery Project; CF = Cartridge filtration

Table 2 lists water treatment alternatives using the water treatment components in table 1. This study considered alternative 2 as the "no action" alternative against which to compare other alternatives. The study did not evaluate alternatives 6, 6a, 8, or 9. The study evaluated alternatives 3, 4, 5, 7, 7a, 10, and 10a.

Table 2.—Water treatment alternatives

Alt. no.	Water source	Filtration I	Filtration II	Advanced treatment	Comments
1	[Groundwater]				Existing, but water table is falling.
2	[CAP]	[HUWTF]			Existing, but does not meet WCPA. TDS = 700 mg/L, TOC = 2.2 mg/L.
3	[CAP]	[HUWTF]	[CF]	[RO]	Uncertainty remains regarding adequacy of HUWTF particulate removal for RO operation. Pilot tested in 1998. TDS = 60 mg/L, TOC = 0.14 mg/L.
4	[CAP]	[HUWTF]	[CF]	[RO]	Blends HUWTF product with RO product.
5	[CAP]	[HUWTF]	[CF]	[RO] [GAC]	Blends GAC-treated HUWTF product with RO product. TDS = 210 mg/L, TOC = 0.17 mg/L.
6	[CAP]	[CAVSRP]	[CF]	[RO]	CAVSRP surface recharge removes particulates and TOC. Requires a pipeline to keep particulates out of CAVSRP product.
6a	[CAP]	[CAVSRP]	[CF]	[RO]	Blends CAVSRP water with RO product.
7	[CAP]	[MF/UF]		[RO]	Pilot tested in this study and at Yuma's WQIC. Provides excellent RO pretreatment.
7a	[CAP]	[MF/UF]		[RO] [GAC]	Blends GAC-treated MF/UF product with RO product. TDS = 140 mg/L, TOC = 0.17 mg/L.
8	[CAP]	[SSF]	[CF]	[RO]	Not evaluated in this study, but two subsequent pilot studies (Chowdhury, et al., 2002; Moody, et al., 2002) evaluated SSF pretreatment of CAP water for RO as effective and lower cost than MF/UF.
9	[CAP]	[HUWTF]	[SSF & CF]	[RO]	Existing HUWTF rapid-sand filters w/o ozone serve as "roughing filters" to SSF.
10	[CAP]	[HUWTF]	[MF/UF]	[RO]	Existing HUWTF rapid-sand filters w/o ozone serve as "roughing filters" to MF/UF. Both MF/UF and RO operate at high membrane flux on low-fouling feedwaters. TDS = 60 mg/L, TOC = 0.14 mg/L.
10a	[CAP]	[HUWTF]	[MF/UF]	[RO] [GAC]	Blends GAC-treated MF/UF product with RO product. TDS = 140 mg/L, TOC = 0.17 mg/L.
11	[CAP]	[SSF]	[MF/UF]	[RO]	MF serves as polishing filter to SSF.

In these alternatives, the term "MF/UF" refers to either of the two similar microfiltration (MF) or ultrafiltration (UF) processes (refer to figure 1 for MF and UF particulate removal ranges). For brevity, the abbreviated notation uses "UF." All selected alternatives use MF/UF pretreatment. Alternatives 10 and 10a use the existing HUWTF rapid-sand filters as roughing filters, and 7a and 10a add GAC treatment parallel to RO so that "blended" water has low TOC levels. Appendices A and C describe conceptual designs and costs of these treatment alternatives. Alternatives 7a and 10a include an evaluation of cost savings with granulated activated carbon (GAC) filters.

Pilot tests evaluated treatment alternatives 3, 7, and 9. Seven pilot test activities were conducted from October 1997 to September 1998 and from February 1999 to August 1999 (see appendix F).

All pilot tests utilized reverse osmosis (RO) treatment to produce desalted water that meets the City of Tucson's Water Consumer Protection Act for total dissolved solids (TDS), hardness, and total organic carbon (TOC).

The pilot test activities evaluated the effects of the following major design components: RO pretreatment (HUPP [coagulation, flocculation, and media filtration], MF/UF, and HUPP together with MF/UF), RO membrane type (cellulose acetate (CA) and polyamide (PA)), and water recovery (70 to 90 percent). The major performance criteria were RO fouling and RO scaling.

The table below summarizes the operating conditions and performances for these criteria as well as including a general evaluation of costs.

Pilot test summary ratings

Activity no.	Treatment alternative number and pilot process components	HUPP Coagulant	Evaluation criteria		
			Fouling	Scaling	Cost
1	3. CAP - HUWTF - CF - RO (CA)	Alum	good	poor	fair
2,3,4	3. CAP - HUWTF - CF - RO (PA)	Alum	poor	good	good
5[1]	7. CAP - MF - CF - RO (PA)	n/a	good	good	fair
6	3. CAP - HUWTF - CF - RO (PA)	Ferric chloride	poor	tbd	good
7a[1]	7. CAP - UF - CF - RO (PA)	n/a	good	good	fair
7b - 7e[1]	10. CAP - HUPP - UF - CF - RO(PA)	Ferric chloride	good	good	fair

[1] Best combinations of performance and cost for full-scale desalting.

Fouling—Good = Little or no RO fouling; Poor = Severe particulate fouling observed requiring high pressure to maintain RO product flow

Scaling—Good = No scaling observed; Poor = Significant scaling observed requiring high pressure to maintain RO product flow;

Cost—Good = Uses existing water treatment facilities to supply RO feedwater; Fair = Adds MF or UF to supply RO feedwater

The study initially focused on the use of processes in the existing water treatment facility in treatment alternative 3: CAP-HUWTF-CF-RO and 4: CAP-HUWTF-CF-(RO & GAC). Pilot tests produced mixed results (see appendix F) but were generally unsuccessful in demonstrating that the existing HUWTF processes would adequately and consistently produce water that would not coat and plug the fouling-sensitive polyamide RO equipment with particulates or scale from alum or iron coagulants.

In contrast, alternatives 7 and 10 produced water with low RO fouling rates both during 1999 pilot tests (refer to Appendix F) and in pilot treatment of Colorado River water at Reclamation's Water Quality Improvement Center (WQIC) in Yuma AZ (McAleese, et al., 1999).

Based on these pilot tests, the authors recommend CAP treatment with either of the following alternatives:

Treatment alternative 7. CAP - MF/UF - RO
Treatment alternative 10. CAP - HUWTF - MF/UF - RO

In May 1999, City and Reclamation representatives selected the following four treatment alternatives for the purposes of preparing conceptual designs and preappraisal cost estimates.

Selected treatment alternatives

Treatment alternative number	Symbolic process description on Table 2	Abbreviated symbolic process notation for figures
7	CAP - MF/UF - RO	UF-RO
7a	CAP - MF/UF - (RO & GAC)	UF-RO&GAC
10	CAP - HUWTF - MF/UF - RO	HU-UF-RO
10a	CAP - HUWTF - MF/UF - (RO & GAC)	HU-UF-RO&GAC

RO conceptual design information obtained in large part from the 1997-99 pilot tests at the Hayden Udall WTF include:

1. Selecting polyamide (PA) membranes over cellulose acetate (CA) membranes to minimize adding sulfuric acid that increases supersaturation levels of barium sulfate.

2. Selecting RO membranes instead of NF membranes because NF membranes (with sodium chloride rejections less than 80 percent) do not meet the target product TDS level of 210 mg/L in the summer.

3. Selecting a design water recovery of 85 percent. Water recovery is critical because a water recovery of 85 percent means that 85 percent of the water is converted to low-TDS product and 15 percent remains as brackish concentrate to be disposed. The pilot unit operated successfully at 90-percent recovery on MF pretreatment (and the absence of alum) but at a lower feedwater TDS than the CAP design. At Reclamation's Water Quality Improvement Center in Yuma, a pilot RO unit operated with MF pretreatment on Colorado River water at 85 percent recovery for several months with no evidence of scaling (McAleese, et al., 1999).

4. Selecting a conceptual design RO membrane flux of 17 gallons per square foot per day (gfd) based on successful pilot test operation with MF/UF pretreatment. Membrane water flux is important because the number of RO elements and capital costs vary inversely with water flux.

5. Selecting barium sulfate crystallization as a potentially effective and economical process for removing supersaturated barium sulfate from the brackish concentrate. Preliminary jar tests indicate that, by using barium sulfate seed crystals, a crystallizer can remove barium sulfate that might scale pipelines or canals used for concentrate disposal. (See appendix D, figures 5 and 6). Although preliminary pilot test efforts found no removal and although barium sulfate removal may not be necessary, to provide a conservative and comprehensive cost estimate, the design presented in this report includes the estimated size and costs of barium sulfate crystallizers.

6. Calibrating three manufacturers' conceptual design projections for operating pressures and product TDS to match pilot test results. After calibration and including allowances for additional increases in operating pressure and product TDS with age, the average of the three calibrated performance projections form the basis for the RO conceptual design in this study.

7. To achieve 85-percent and higher water recoveries, the RO conceptual design that was chosen consists of three RO equipment stages (see figure 2). Stage 1 concentrate is stage 2 feed. Stage 2 concentrate is stage 3 feed. The RO feed pumps include both single-speed and variable-speed centrifugal pumps where the variable-speed pumps provide operational flexibility. Interstage booster pumps maintain uniform 17-gfd water flux for each of the three stages. Energy recovery turbines recover energy from the pressurized stage 3 concentrate and transfer it by direct couple to feed pumps (alternatively, energy recovery could power the interstage pumps).

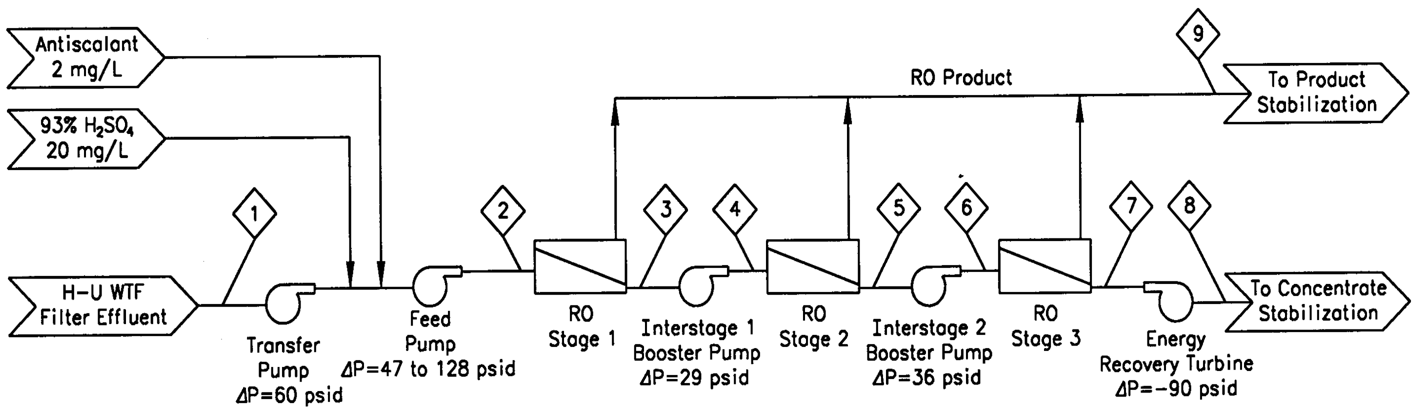


Figure 2.—Process flow schematic for a three-stage reverse osmosis plant.

At 17-gfd water flux and 85-percent water recovery, a two-stage design may offer a lower-cost alternative to the selected three-stage design. The selected three-stage design, however, offers the flexibility of operating at higher water recovery (e.g., 90 percent). The three-stage design can also operate at lower water flux (e.g., 10-12 gfd) if needed to reduce fouling, as well as to obtain significant power savings with a variable-production plant in the winter with cold water and low demand.

RO treatment of CAP water with total dissolved solids (TDS) of 700 milligrams per liter (mg/L) recovers 85 percent of the water as product with an average TDS of 56 mg/L and discharges 15 percent as brackish concentrate waste with a TDS of 4,400 mg/L.

The average expected RO product water quality levels are 56 mg/L TDS, 5.4 mg/L hardness, and 0.14 mg/L TOC. Projected post treatment stabilization with low-turbidity lime and carbon dioxide raises the average TDS level to 95 to 137 mg/L and hardness concentration to 44 to 86 mg/L (2.6 to 5.0 grains/gallon).

In the summer when salt rejection is lowest, the expected RO product water quality levels are 69 mg/L TDS, 6.9 mg/L hardness, and 0.14 mg/L total organic carbon (TOC). Projected post treatment stabilization with low-turbidity lime and carbon dioxide raises the summer TDS level to 108 to 166 mg/L and hardness concentration to 46 to 104 mg/L (2.7 to 6.1 grains/gallon). Caustic soda can replace some of the lime to reduce the added hardness.

These levels can meet the requirements of the City's 1995 Water Consumer Protection Act (WCPA) criteria of 210 mg/L TDS, 84 mg/L hardness, and 0.4 mg/L TOC.

With a 13-percent “blend” of GAC-treated water (refer to table 2, alternatives 7a and 10a), the average annual blend water has a TDS of 140 mg/L and a hardness of 47 mg/L. The post-treated blend has an estimated TDS of 173 mg/L and a hardness of 81 mg/L (see appendix A, revision 1).

Figures 3a and 3b illustrate the integration of 96.3- and 150-MGD RO plants into the City's water system. Listed are the available capacities from both the RO plants and the existing well field. For year-round full capacity operation of the 96.3-MGD RO plant, the well fields can serve for winter storage and summer recovery of excess winter RO production.

Concentrate Disposal

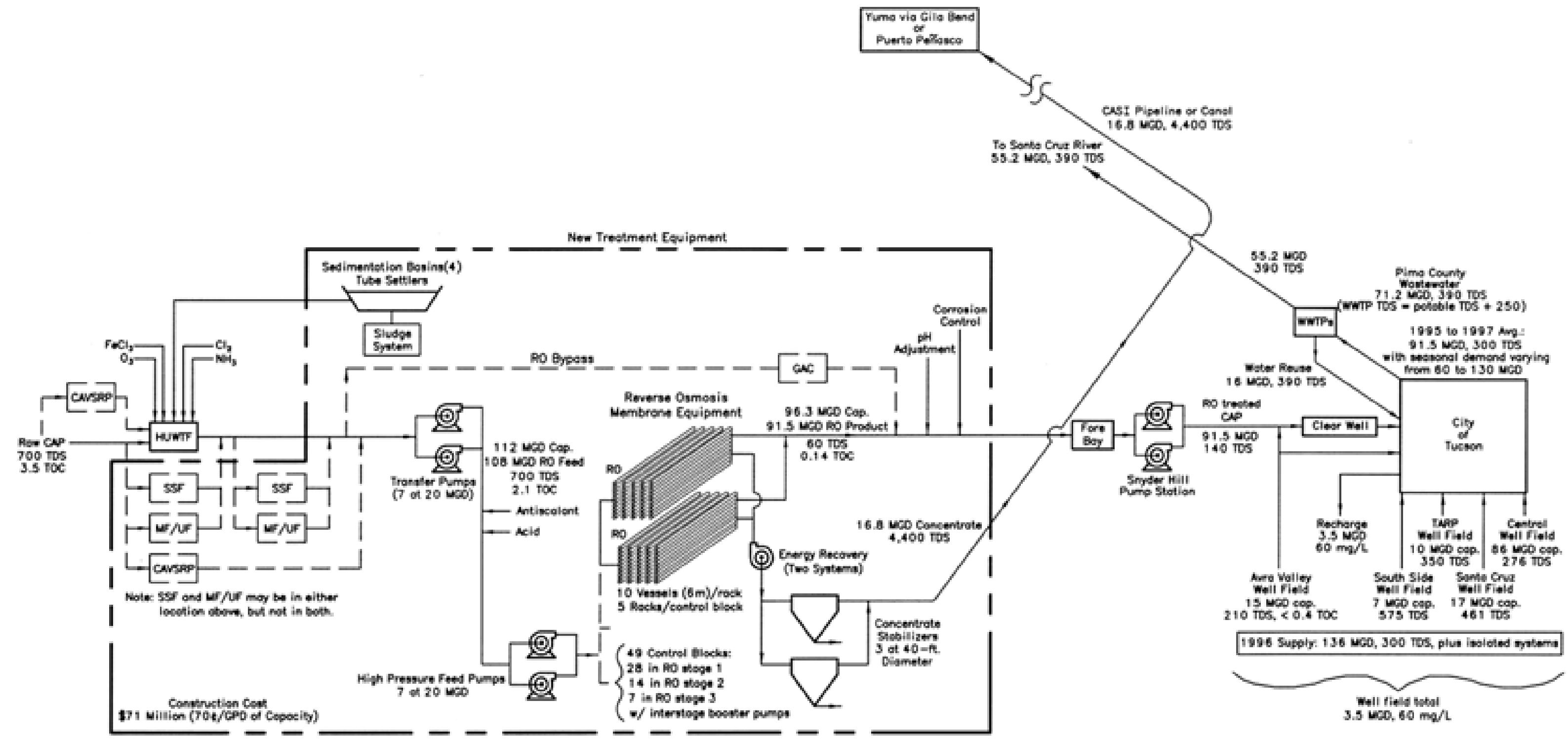
The work group studied and prepared a long list of alternatives for the disposal or reuse of 8.8 to 26.5 MGD (4,400 TDS) concentrate flow from the RO system. The work group conducted a screening evaluation in which it selected and ranked ten alternatives (see table 3, where costs are per thousand gallons [kgal] of RO concentrate). The work group selected the following top four alternatives for a more detailed analysis:

- Deep well injection
- Discharge to the Gulf of California
  - 162-mile pipeline to discharge east of Puerto Penasco, Sonora, Mexico
  - Central Arizona Salinity Interceptor (CASI) 245-mile canal/pipeline to Yuma for use as a water supply for the Santa Clara wetland in Sonora, Mexico
- Reuse at Cyprus Sierrita Mine
- Blend with effluent from Pima County Wastewater Management's Wastewater Treatment Plant

After a detailed analysis of the above four alternatives, the work group recommended Discharge to the Gulf of California via a Central Arizona Salinity Interceptor (CASI) to collect and transport brackish waters by gravity from the Tucson and Phoenix areas to Yuma (see the Central Arizona Salinity Interceptor map [figure 4]). CASI offers a regional solution to projected needs throughout central Arizona for the discharge of brackish residual waters from desalting plants, water reuse plants, and urban and agricultural irrigation. The proposed Central Arizona Salinity Interceptor consists of pipeline and canal sections to collect and transport brackish waters by gravity from the Tucson and Phoenix areas to Yuma.

At Yuma, the brackish water has several potential beneficial uses.

- Supply additional brackish water to the Cienega de Santa Clara (Santa Clara Wetland) in Mexico. This isolated wetland area is the largest remaining wetland in the Colorado Delta and provides habitat for migratory waterfowl and shorebirds. Agricultural return flow with a TDS of about 3,000 mg/L from the Yuma area created and presently supplies brackish water to the wetland.



96.3 MGD RO PLANT TO MEET 91.5–MGD 1995–97 TUCSON WATER CUSTOMER DEMAND
Process Flow Schematic
(At 95% plant factor, average RO production is 91.5 MGD)

LEGEND

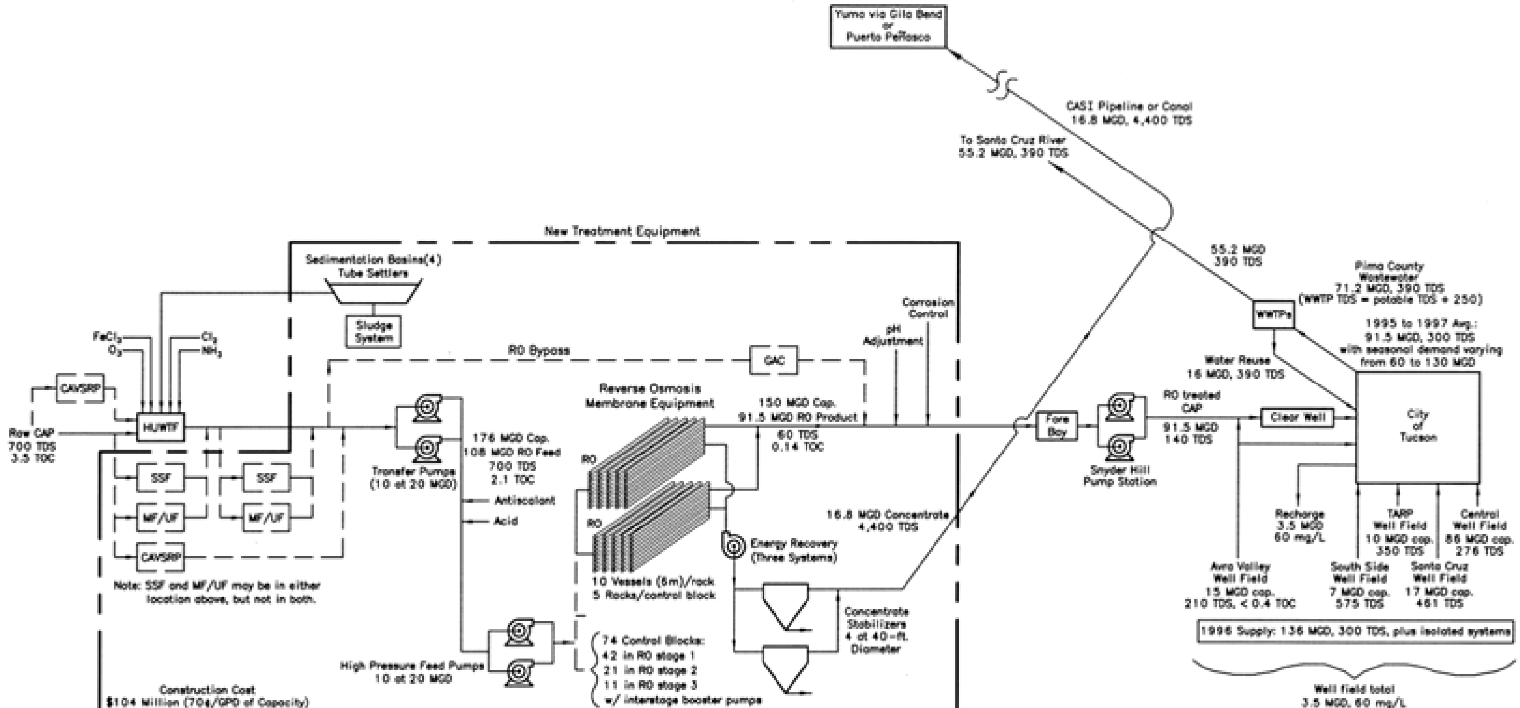
TDS= mg/L Total Dissolved Solids, determined by Gravimetric Analysis (180° C)

TOC= mg/L Total Organic Carbon

Prepared By: Bruce Garrett and Chuck Moody

Drawn by: Robert Rodriguez

Figure 3a.—Process flow schematic for 96.3–MGD RO plant and well field to meet 91.5–MGD 1995–97 Tucson water customer demand. Solid lines are for the existing water supply system and the RO treatment design and costs described in this report. Dotted lines show the possible locations of other proposed treatment components.



150 MGD RO PLANT TO MEET 91.5-MGD 1995-97 TUCSON WATER CUSTOMER DEMAND
Process Flow Schematic
(At 61% plant factor, average RO production is 91.5 MGD)

LEGEND

TDS= mg/L Total Dissolved Solids, determined by Gravimetric Analysis (180° C)

TOC= mg/L Total Organic Carbon

Prepared By: Bruce Garrett and Chuck Moody

Drawn by: Robert Rodriguez

Figure 3b.—Process flow schematic for 150-MGD RO plant and well field to meet 91.5-MGD 1995-97 Tucson water customer demand. Solid lines are for the existing water supply system and the RO treatment design and costs described in this report. Dotted lines show the possible locations of other proposed treatment components.

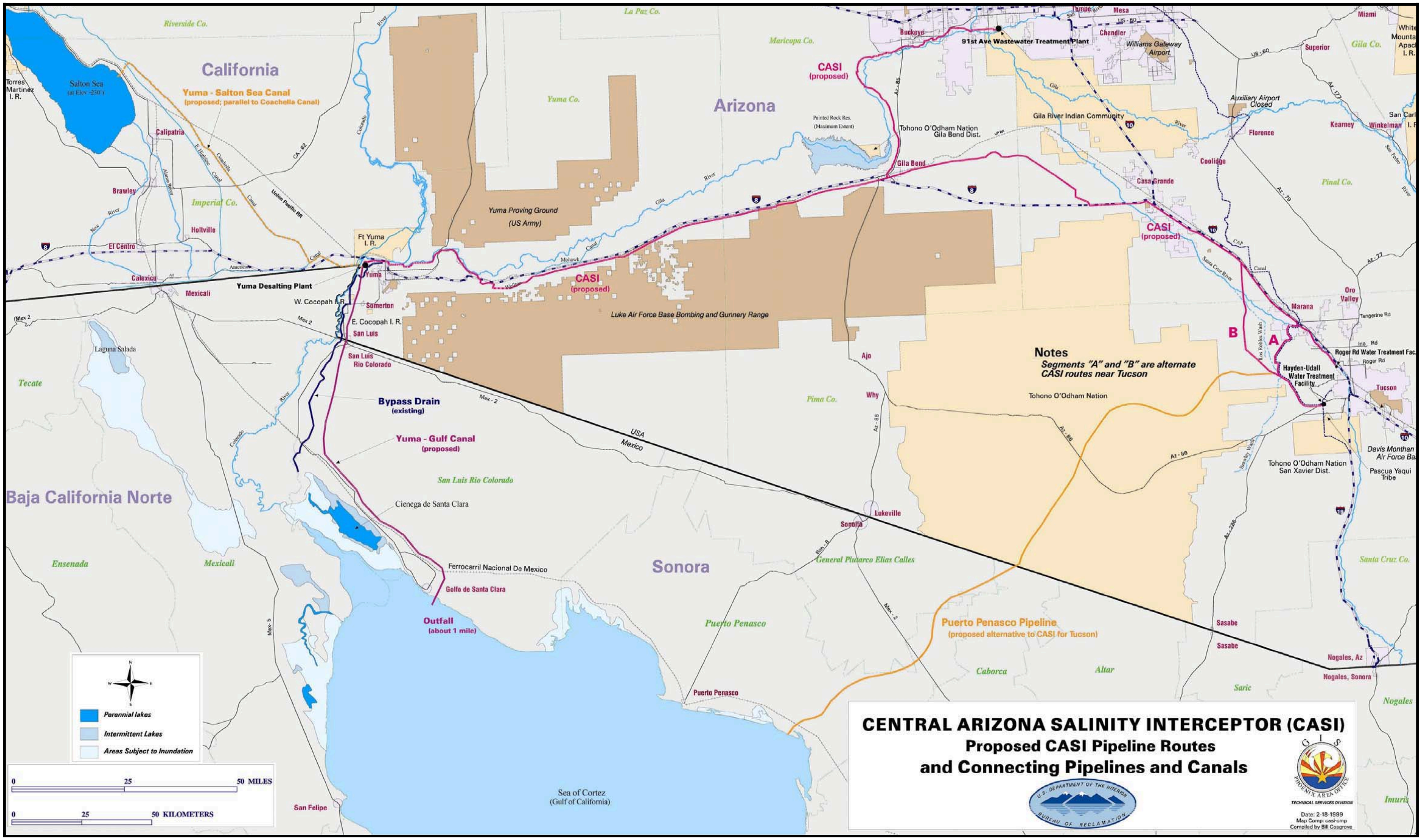

CENTRAL ARIZONA SALINITY INTERCEPTOR (CASI)
Proposed CASI Pipeline Routes
and Connecting Pipelines and Canals
California
Arizona
Baja California Norte
Sonora
Riverside Co.
La Paz Co.
Maricopa Co.
Yuma Co.
Imperial Co.
Pima Co.
Pinal Co.
Gila Co.
Santa Cruz Co.
Salton Sea
(at Elev. -230')
Torres Martinez I. R.
Yuma - Salton Sea Canal
(proposed; parallel to Coachella Canal)
Calipatria
Brawley
Holtville
El Centro
Calexico
Mexicali
Union Pacific RR
Ft Yuma I. R.
Yuma
Yuma Desalting Plant
W. Cocopah I. R.
E. Cocopah I. R.
Somerton
San Luis
San Luis Rio Colorado
Yuma Proving Ground
(US Army)
Luke Air Force Base Bombing and Gunnery Range
CASI
(proposed)
Painted Rock Res.
(Maximum Extent)
Tohono O'Odham Nation
Gila Bend Dist.
Gila Bend
Buckeye
91st Ave Wastewater Treatment Plant
Chandler
Mesa
Williams Gateway Airport
Gila River Indian Community
Auxiliary Airport Closed
Superior
Miami
Kearney
Winkelman
Florence
Coolidge
Casa Grande
Marana
Oro Valley
Tangerine Rd
Roger Rd Water Treatment Fac.
Hayden-Udall Water Treatment Facility
Tucson
Davis Monthan Air Force Base
Pascua Yaqui Tribe
Tohono O'Odham Nation San Xavier Dist.
Tohono O'Odham Nation
B
A
Notes
Segments "A" and "B" are alternate CASI routes near Tucson
Ajo
Why
Lukeville
Sonoyta
Sasabe
Nogales, Az
Nogales, Sonora
Nogales
Imuris
Saric
Altar
Caborca
General Plutarco Elias Calles
Puerto Penasco
Puerto Penasco Pipeline
(proposed alternative to CASI for Tucson)
Bypass Drain
(existing)
Yuma - Gulf Canal
(proposed)
San Luis Rio Colorado
Cienega de Santa Clara
Ferrocarril Nacional De Mexico
Golfo de Santa Clara
Outfall
(about 1 mile)
Laguna Salada
Tecate
Ensenada
Mexicali
San Felipe
Sea of Cortez
(Gulf of California)
USA
Mexico
Perennial lakes
Intermittent Lakes
Areas Subject to Inundation
0 25 50 MILES
0 25 50 KILOMETERS
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PHOENIX AREA OFFICE
TECHNICAL SERVICES DIVISION
Date: 2-18-1999
Map Comp: casi-cmp
Compiled by Bill Cosgrove

Table 3.—Screening summary of concentrate disposal alternatives

ALTERNATIVE/ TECHNOLOGY[1]	EVALUATION CRITERIA		
	Effectiveness	Implementability	Cost[2]
Discharge to Gulf of California (D-23)	**Good**: Returns concentrate to its natural flow channel and provides a beneficial use to sustain the Santa Clara wetlands.	**Good**: Elevation drops 2400 feet from Tucson to Yuma which allows gravity flow. Discharge to Gulf requires permission from Mexico.	**Fair**: Preliminary estimate shows pipeline from Tucson to Yuma costs about $250 million or $2/kgal. Potential cost sharing.
Deep Well Injection (D-19)	**Fair**: Geology indicates fair potential, but more hydrogeological information is needed.	**Fair**: Rated fair pending hydrogeology analysis and consultations with the Environmental Protection Agency.	**Good**: Other deep well injection sites report costs of less than $1/kgal.
Reuse at Local Mine (D-24)	**Fair**: Concentrate salt load is minor compared to current precipitation loads. Short- and long-term reliability are uncertain.	**Fair**: Potential use for 5 to 20 MGD of concentrate pending outcome of laboratory bench studies by Cyprus Sierrita Co.	**Good**: Construct 30-mile pipeline with lift stations to deliver concentrate to mine at a cost of $35 million or $0.50/kgal.
Blend with Effluent from Wastewater Treatment Plant (WWTP) and Discharge to Santa Cruz River (D-22)	**Poor**: WWTPs do not treat or reduce concentrate contaminants. Effluent from WWTPs discharged to Santa Cruz River would increase salinity of aquifer.	**Poor to Fair**: Depending on flow volume, high TDS of concentrate could be toxic to ceriodaphnia and violate National Pollutant Discharge Elimination System (NPDES) permit. Also salt crust could form in river bed.	**Good**: Concentrate would bypass wastewater treatment to be blended with WWTP effluent at point of discharge into Santa Cruz River. Probably requires an equalization basin.
Evaporator/Crystallizer/ Landfill (D-10)	**Good**: Very effective and reliable for volume reduction. Minimal environmental impact.	**Good**: Proven technology currently utilized in many countries. No regulatory obstacles.	**Poor**: High capital and energy input required for evaporation. Total cost about $9/kgal.
Salinity Gradient Solar Ponds (D-9)	**Fair**: Volume reduction through evaporation. Solar ponds protect environment with double liner, leachate collection, and non-toxic surface layer; and solar energy provides beneficial use.	**Poor**: Pilot scale demonstration projects look promising, however, large projects yet to be built in U.S. for concentrate disposal and generation of energy revenues.	**Fair**: Solar ponds have higher capital and operation and maintenance costs than evaporation ponds, however revenues from heat extraction should offset these additional costs.
Evaporation Ponds/Landfill (D-6)	**Poor**: Effective volume reduction, but large pond surface area is potentially toxic to wildlife and carries risk of aquifer contamination.	**Poor**: Regulatory feasibility and land availability are unlikely for a 6,200-acre evaporation facility to treat 25 MGD.	**Fair**: Earthwork, lining, and land costs dominate. Preliminary cost estimate is $5/kgal.
Halophyte Irrigation (D-12)	**Fair**: Evapotranspiration reduces volume for further treatment. Potential infiltration problems and risk of contaminating aquifer.	**Poor**: Arizona Department of Environmental Quality (ADEQ) exempts irrigation from Aqui-fer Protection Permit (APP) program; how-ever, Arizona Department of Water Resources (ADWR) regulations prohibit irrigation of new acreage.	**Good**: Preliminary cost estimate for irrigation without drainage recovery is $1/kgal.
Discharge to Municipal Wastewater Treatment Plant (WWTP) (D-21)	**Poor**: WWTPs do not treat or reduce con-centrate contaminants. High TDS effluent would contaminate down-gradient aquifer.	**Poor**: High TDS could impair WWTP biological operations. Probable non-compliance with NPDES and APP permits.	**Fair**: Significant plant expansion would be required to accommodate the concentrate flow volume.
Rapid Infiltration (D-15)	**Poor**: High TDS of concentrate would contaminate underlying potable aquifer.	**Poor**: ADEQ would probably not grant an APP permit to protect aquifer.	**Good**: Construction cost of pipeline and infiltration basin would be relatively low.
Discharge to Wetlands or Brackish Water Reservoir (D- 16)	**Poor**: Evaporation would increase the concentration of various ions to levels that are unsafe to humans and wildlife.	**Poor**: Regulatory approval would probably not be granted due to expected violations of surface water quality standards.	**Fair**: Earthwork and liner costs would be similar to evaporation ponds, about $5/kgal.

[1]Ranked in order of decreasing feasibility. Refer to indicated page number for additional information.
[2]$/kgal refers to cost per 1,000 gallons of concentrate.

- Desalt the mixture of brackish waters conveyed to Yuma by CASI at the Yuma Desalting Plant (YDP). The YDP is designed to desalt brackish water in the anticipated CASI water salinity range.

- Supply relatively fresh water (4,400 mg/L TDS) to the Salton Sea to help lower its salinity from 44,000 mg/L to 40,000 mg/L or less.

- Supply brackish water to restore and maintain the river and riparian ecology of frequently-dry stretches of the Colorado River and Colorado Delta in Mexico in locations other than the Santa Clara Wetland.

Selenium levels in the concentrated Colorado River water present toxicity concerns for the beneficial ecology restorations described above. Although no selenium toxicity has been observed to date in the Santa Clara Wetland with 5 µg/L of selenium in its water supply, implementing these beneficial uses will require a thorough evaluation of selenium levels in the water supply and the potential selenium toxicities to the receiving ecologies.

The Central Arizona Water Conservation District could operate CASI in a manner similar to the Santa Ana Watershed Protection Authority's operation of the Santa Ana Regional Interceptor (SARI) pipeline in Orange County, California.

In the possible absence of partners to build and operate CASI, the work group evaluated a shorter route to transport the concentrate by pipeline to the Gulf of California at a discharge site east of Puerto Penasco, where the brackish water is expected to have several beneficial uses. This alternative is less costly than the a non-partnered low-volume, CASI pipeline.

The work group, however, considers CASI to represent a regional solution to brackish water disposal, and the November 1998 report estimated that additional CASI partners would decrease CASI costs to be less than for the Puerto Penasco route. Potential partners include the Arizona Municipal Water Users Association (AMWUA) Subregional Operating Group (SROG), that anticipates construction of several advanced RO wastewater treatment/water reuse plants in the Phoenix area during the next 20 years. In a comparison of evaporation ponds and CASI requested by AMWUA SROG, Irvine (2000) estimated CASI to have lower costs for disposing 20 MGD from AMWUA SROG water reuse plants.

The high-volume CASI canal (CC270) can transport the total projected need for brackish water discharge in central Arizona of 270 MGD (300,000 acre-feet per year). This is the estimated flow to achieve salt balance for central Arizona from agricultural, municipal, and industrial uses. It is based on Colorado River inflows of 1.5 million acre-feet/yr with 700 mg/L TDS, Salt

River inflows of 0.8 million acre-feet/yr with 400 mg/L TDS, and an assumed CASI TDS of 4,500 mg/L.

In May 1999, City and Reclamation representatives selected six variations of the "Discharge to the Gulf of California" alternative for cost estimating in conjunction with the two plant capacities (see table 4).

Table 4. --Six alternatives for concentrate disposal by discharge to the Gulf of California.

Description	Average flow (MGD)	Abbreviation
Pipeline to Puerto Penasco (without partners)	16	PP16
CASI pipeline to Yuma (without partners)	16	CP16
CASI canal to Yuma (without partners)	16	CC16
CASI pipeline to Yuma with 20 MGD from Phoenix-area SROG	36	CP36
CASI canal to Yuma with 20 MGD from Phoenix-area SROG	36	CC36
CASI canal to Yuma with maximum multiple Central Arizona partners and a total flow of 270 MGD (300,000 af/yr)	270	CC270

Average RO concentrate flow from Tucson is 16.1 MGD with RO alone and 13 percent less, 14.0 MGD for GAC replacing RO to process 13 percent of the water.

Figure 5a summarizes the capital costs associated with a 36-MGD CASI canal (CC36) transporting 16.1-MGD average flow (and 26.5-MGD summer peak flow) from a 150-MGD Tucson desalting plant and 20-MGD flow from Phoenix area water reuse plants to Yuma. Figure 5b summarizes the capital costs associated with the high-volume CASI canal. Costs of the pipeline alternatives are based on the use of polymer-lined steel pipe and high-density polyethylene (HDPE) pipe. Canal costs are for concrete-lined canals.

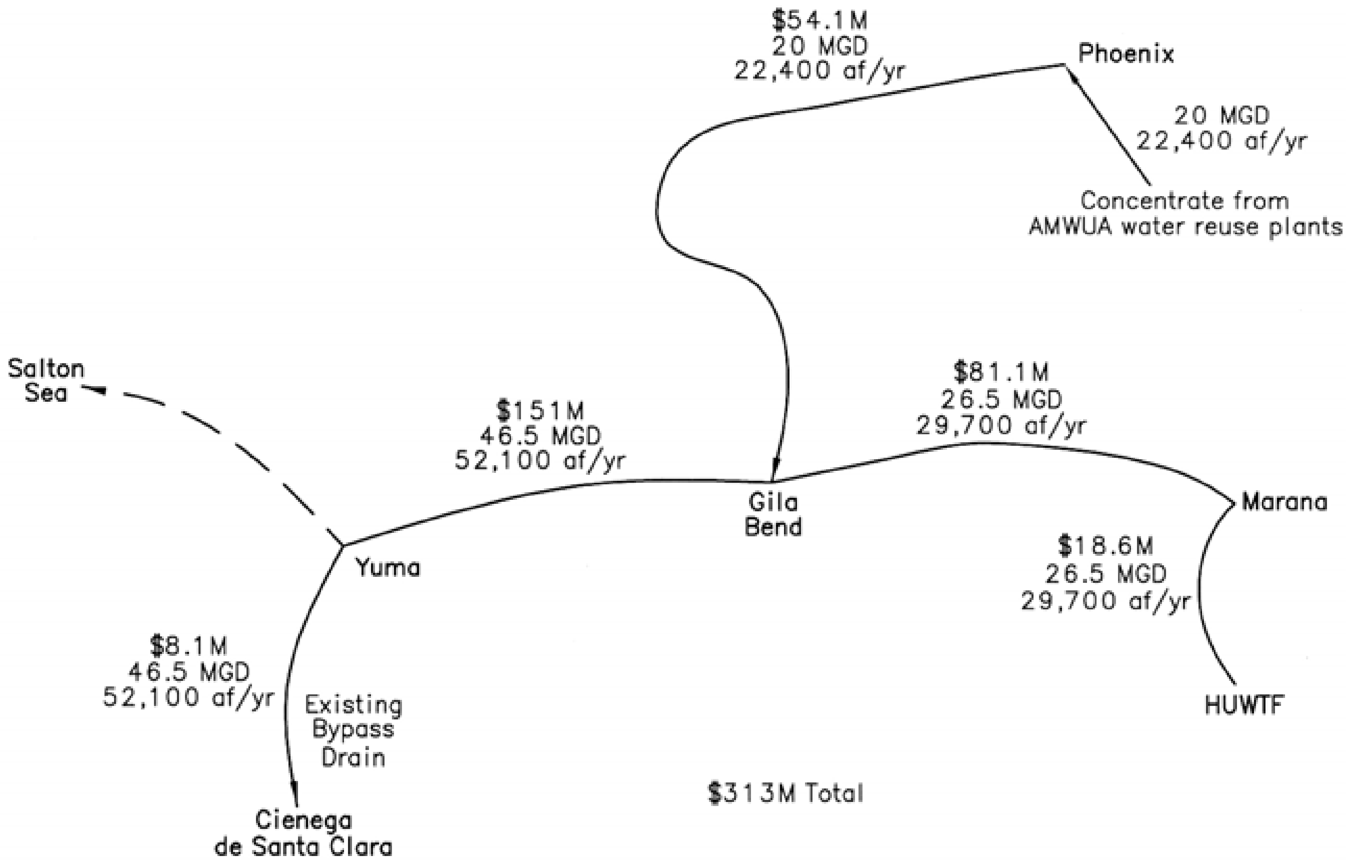


Figure 5a.—Canal capacities and capital costs for a 150-MGD Tucson RO plant capacity discharging RO concentrate to a low-volume CASI canal (CC36). With cost sharing of capital costs based on capacity, for the total cost of $313 million, Tucson's share is 57 percent (26.5 MGD / 46.5 MGD) = $178 million.

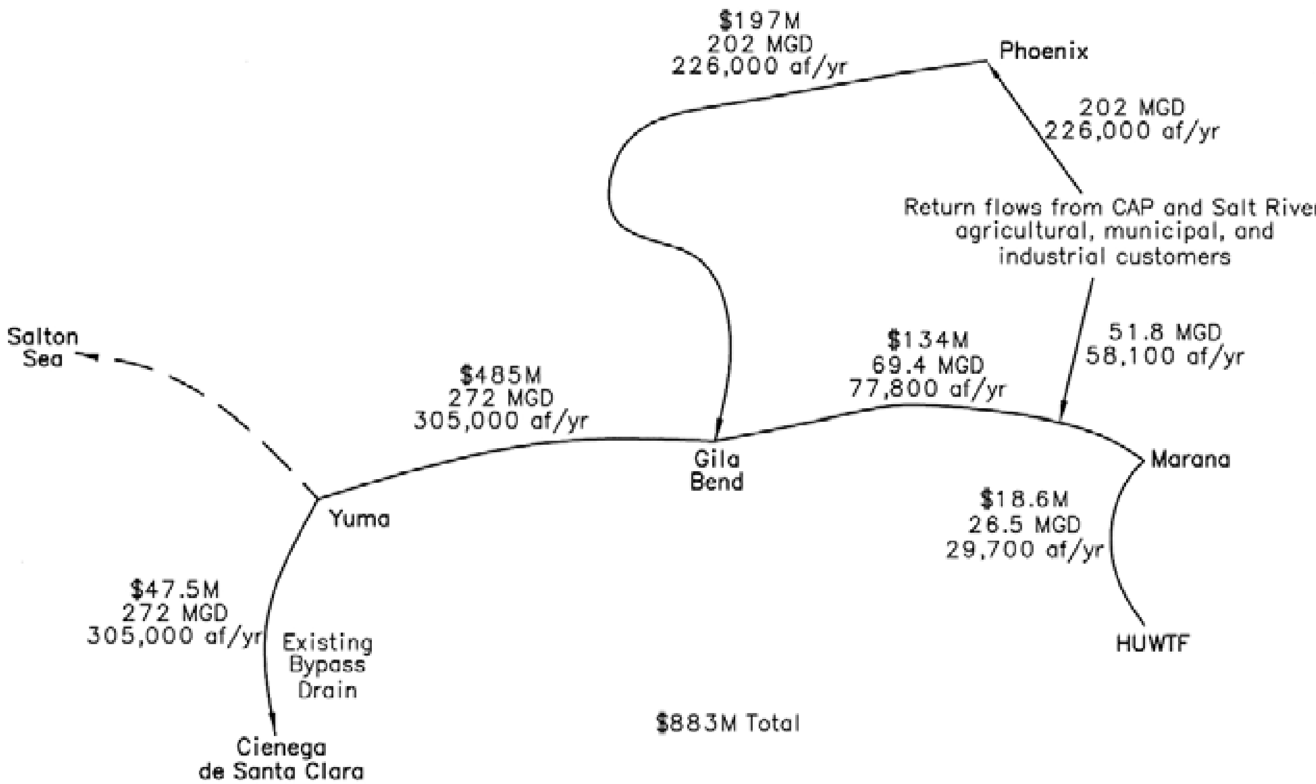


Figure 5b.—Canal capacities and capital costs for a 150-MGD Tucson RO plant capacity discharging RO concentrate to a high-volume CASI canal (CC270). With cost sharing of capital costs based on capacity, for the total cost of $883 million, Tucson's share is 9.7 percent (26.5 MGD / 272 MGD) = $86 million.

Costs and Selection of Recommended Alternatives

Cost estimates describe the costs of “advanced” treatment of CAP water and concentrate disposal. Costs described include:

1. Costs of operating existing HUWTF processes. This represents costs of the no action alternative for comparison with costs of advanced treatment and for use of the existing HUWTF processes in treatment alternatives 10 and 10a (see appendix E, revision 1).

2. Costs of MF/UF treatment of CAP water and Hayden Udall WTF-treated CAP water (see appendix C, Revision 1, and appendix E, Revision 1).

3. Costs of RO treatment of MF/UF product water (see appendix A, appendix C, and appendix E, revision 1). RO treatment consists of a three-stage design with interstage booster pumps to operate at 17-gfd water flux, 85-percent water recovery, energy recovery of the pressurized concentrate, pH adjustment to 7.2 with sulfuric acid, antiscalant chemical to prevent barium sulfate scaling, PA membrane elements at a cost of $400 for each 8-inch-diameter by 40-inch-long element, a 3-year membrane replacement frequency, no disinfection in the treatment processes, and nine RO cleanings per year.

4. Costs of granular activated carbon (GAC) treatment of MF/UF product and HUWTF-MF/UF product for possible blending with RO product water (see appendix B and appendix E, revision 1).

5. Costs for water stabilization of RO product water. The costs of post-treatment of RO product water are based on stabilization for corrosion control with carbon dioxide and low-turbidity lime and disinfection with sodium hypchlorite. (see appendix A, revision 1, and appendix E, revision 1).

6. Costs for disposal of RO concentrate (see appendix D and appendix E, revision 1).

7. Amortization of capital costs (see appendix E, revision 1). Capital costs of treatment are amortized at 6.25-percent interest for 25 years corresponding to a capital recovery factor of 0.0801. The interest rate and repayment period are based on the City's 1998 financial planning values for a municipal project. For concentrate disposal, capital costs are amortized at 7.125-percent interest for 40 years corresponding to a capital recovery factor of 0.0761. Assuming CASI construction under the existing CAP authority, Reclamation used the CAP 40-year repayment period for concentrate disposal. The actual interest rates will depend on the rates at the time of bonding.

8. "Upgrade" costs to incorporate advanced treatment and concentrate disposal at the HUWTF. Upgrade costs are the difference between annual (including amortized capital) costs of the advanced treatments and concentrate disposal minus O&M costs of the existing HUWTF.

This study focuses on the major costs associated with advanced treatment. Therefore, it does not describe:

1. Costs of the City's existing water supply, treatment, and distribution systems.

2. Costs saved by decreasing the production of existing water supply wells.

3. Cost comparisons with other alternatives proposed to meet the City's WCPA.

In the following discussion and comparison of alternatives, figures 6 - 9 describe the total costs of the alternatives including the operating costs of the “no action” alternative: HUWTF in its present design. Figures 10 - 13 show “upgrade” costs which are the total costs minus the cost of the no action alternative.

Comparing RO treatment with parallel RO and GAC treatments

As segmented barcharts, figures 6a and 6b present eight cost categories for the advanced water treatment alternatives with concentrate disposal. The existing HUWTF design has only three of these categories: CAP water delivery, HUWTF O&M (not including corrosion control O&M), and corrosion control O&M (although a subcategory of HUWTF O&M, corrosion control O&M is broken out as a separate category for the barcharts).

The advanced treatment alternatives have higher CAP water delivery costs than the existing design because the RO discharge of 15 percent of the delivered water as concentrate “waste” requires additional delivered water. The advanced treatment alternatives have lower HUWTF O&M costs because, compared to the existing HUWTF design they use no ozone, less sodium hypochlorite, no ammonium sulfate, and for two of the advanced treatment alternatives, no coagulant or coagulant aide (polymer). The advanced treatment alternatives have lower corrosion control O&M costs than for the existing design, based on preliminary estimates using the Rothberg, Tamburini, and Winsor (RTW) model for corrosion control, but the difference should not be considered significant at this appraisal level.

Figures 6a and 6b show that treatment alternatives with RO & GAC have no cost savings compared to treatments without GAC. Because of the absence of cost savings, increased complexity, and lower quality treatment associated with GAC, the authors do not recommend using GAC as a parallel treatment to RO. The remaining discussion focuses on treatment alternatives without GAC.

Figure 6a. --Comparison of treatment alternatives for 96-MGD desalting capacity. Concentrate disposal is by pipeline to Puerto Penasco (PP16).

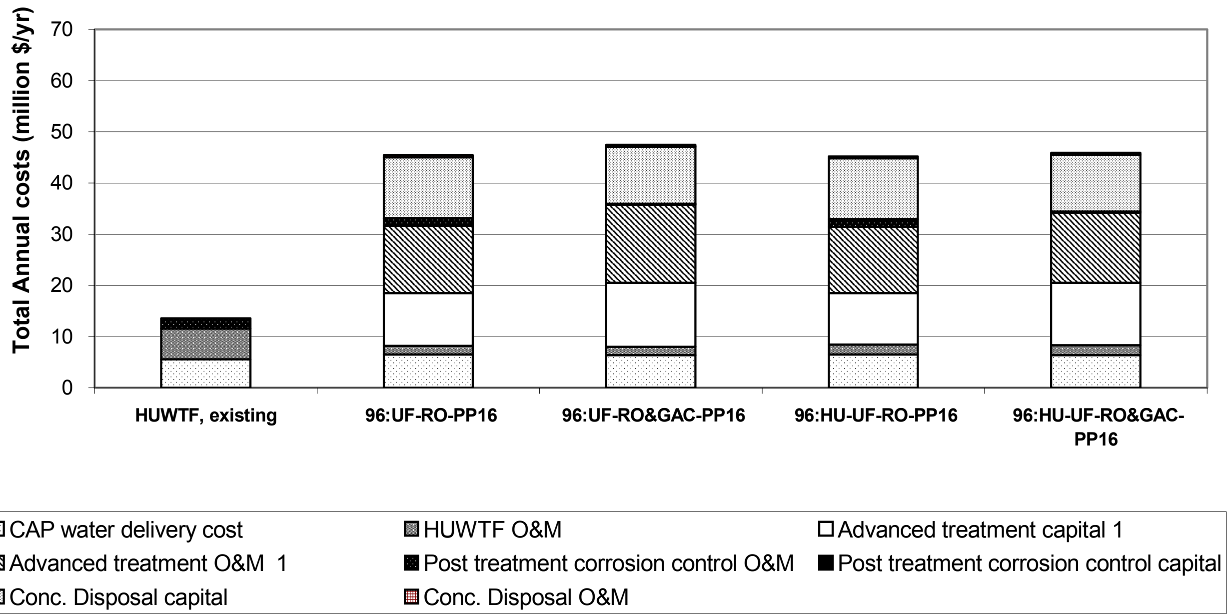
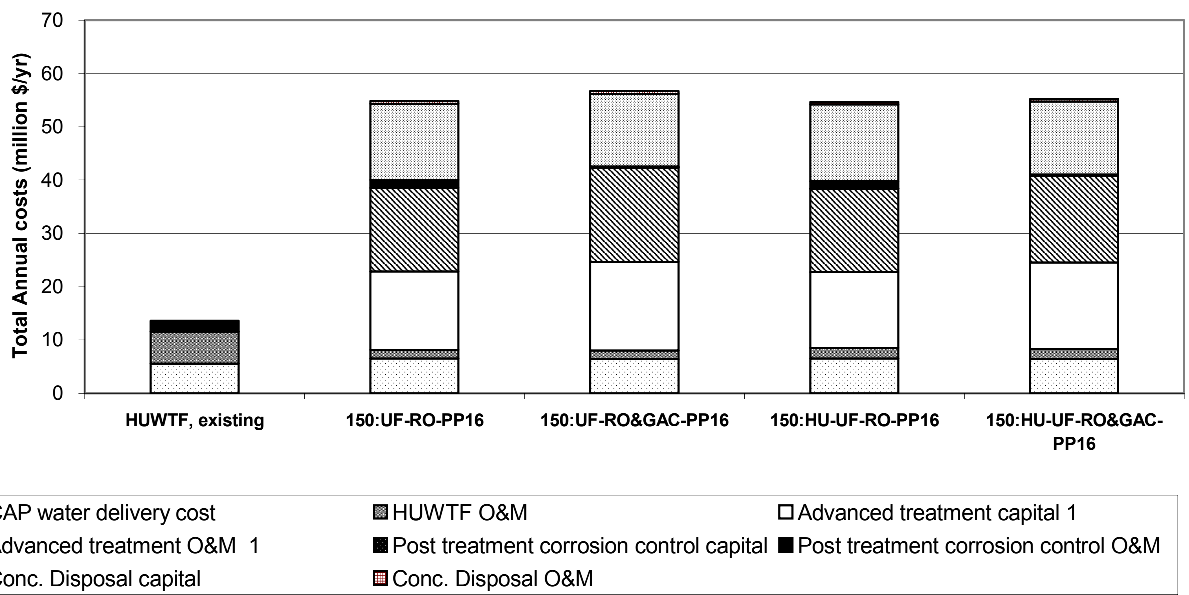


Figure 6b. --Comparison of treatment alternatives for 150-MGD desalting capacity. Concentrate disposal is by pipeline to Puerto Penasco (PP16).



Comparing treatment alternatives with and without existing treatment processes at the HUWTF

The difference in estimated costs of the remaining two treatment alternatives—MF/UF-RO and HU-MF/UF-RO—is not significant (refer to figure 6).

The HU-MF/UF-RO treatment alternative increases MF/UF operational reliability by employing the existing HUWTF rapid-sand gravity filters as roughing filters. This increased reliability comes at the expense of slightly greater complexity, because it requires operating and periodically backwashing the HUWTF rapid-sand filters. Although costs for the HU-MF/UF-RO alternative include the possible use of coagulant (e.g., ferric chloride) and coagulant aide, these are not expected to be needed. The alternative does not include the use of ozone.

Both treatment alternatives operate with PA membrane elements with an estimated replacement frequency of 3 years in the RO equipment, no disinfection in the HUWTF, MF/UF, or RO equipment, and nine RO cleanings per year[1]. A downside to using PA membranes compared to CA membranes is that free chlorine disinfection cannot be used, because PA membranes can suffer significant losses in salt rejection in the presence of free chlorine. Although PA membranes operated successfully without degradation in short-term pilot tests in this study, in short-term pilot tests at Reclamation's WQIC, and for several years with chloramine disinfection at wastewater reuse plants, generally PA membranes operate with no disinfectant and rely on periodic cleanings to control biofouling.

The authors consider both treatment alternatives to have similar effectiveness. Because of their similar costs, the authors recommend both treatment alternatives.

Comparing concentrate disposal alternatives

Figures 7a and 7b show that from lowest to highest cost, the concentrate disposal alternatives cost order is:

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[1] Two major causes of loss in RO production and/or increase in required RO feed pressure are particulate fouling and "biofouling" caused by the growth of bacteria on the membrane surfaces. This study's RO pilot tests were conducted with chloramine disinfection to measure (in the absence of biofouling) particulate fouling and the effectiveness of different pretreatment tecnologies in preventing particulate fouling. Although the pilot tests were conducted with chloramine disinfection to evaluate RO pretreatment technologies, both the MF/UF-RO and HU-MF/UF-RO treatment alternatives incorporate PA membranes, no disinfection, and nine RO cleanings per year.

Figure 7a. --Comparison of concentrate disposal alternatives for 96-MGD capacity. Treatment is by MF/UF-RO.

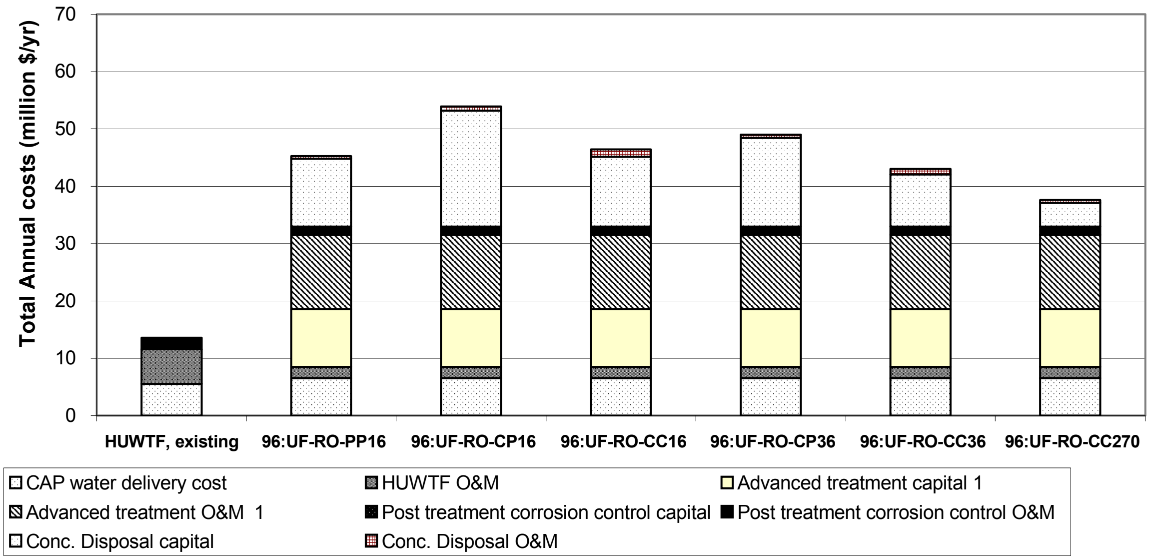
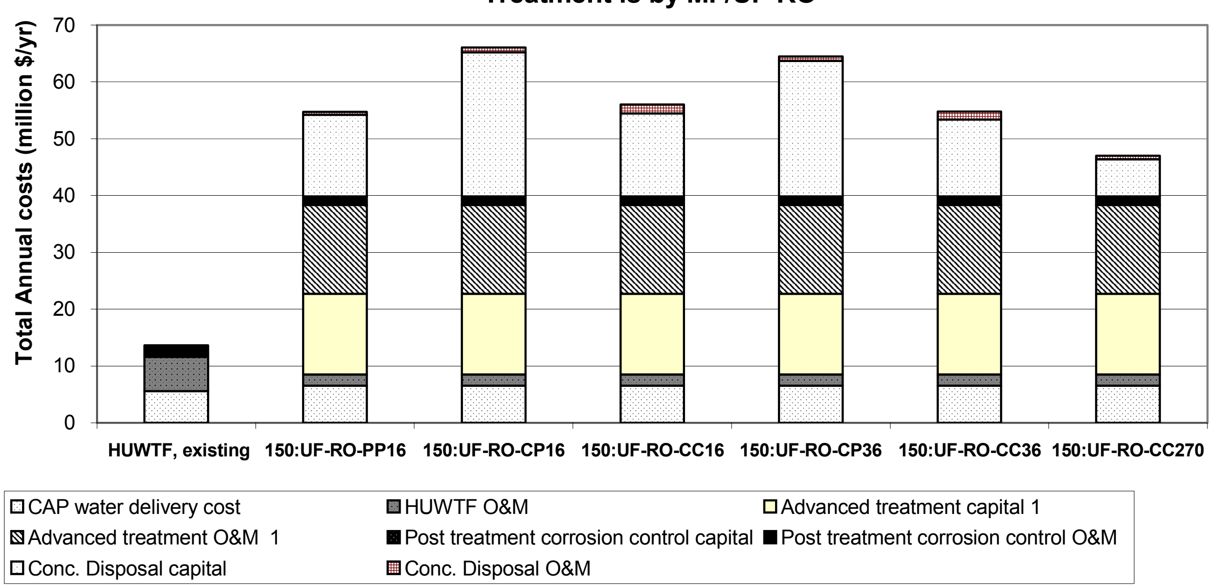


Figure 7b. --Comparison of concentrate disposal alternatives for 150-MGD capacity. Treatment is by MF/UF-RO



Lowest cost	CC270	CASI canal with 270-MGD capacity
	CC36	CASI canal with 36-MGD capacity
	PP16	Puerto Penasco pipeline with 16-MGD capacity
	CC16	CASI canal with 16-MGD capacity
	CP36	CASI pipeline with 36-MGD capacity
Highest cost	CP16	CASI pipeline with 16-MGD capacity

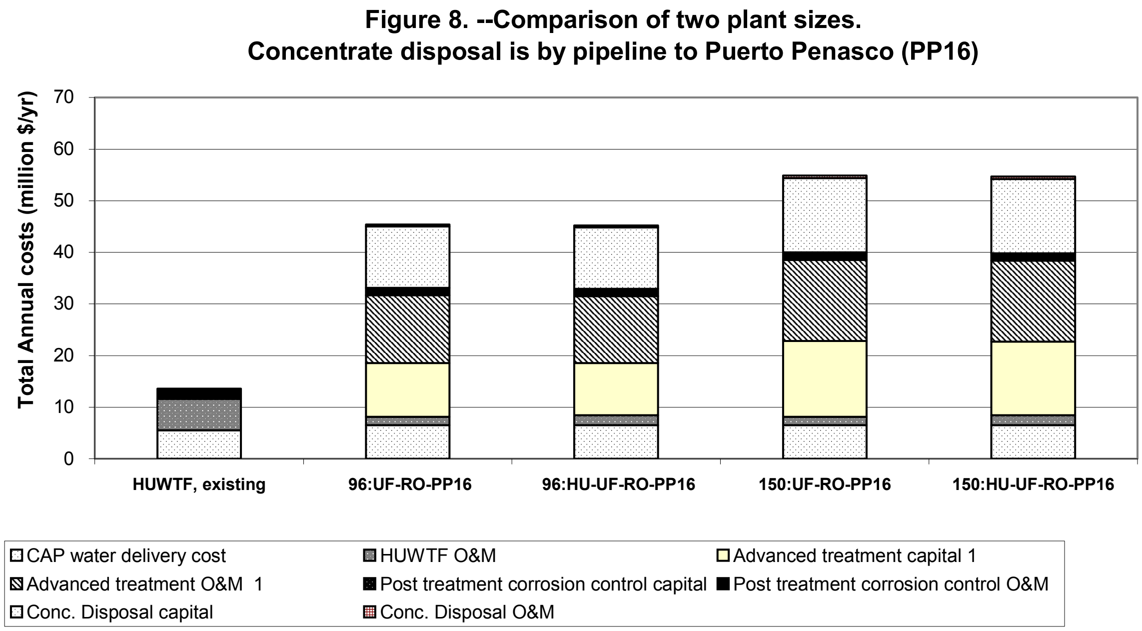
Of the alternatives without partners (PP16, CC16, and CP16), PP16 has the lowest estimated cost. PP16 also has a lower estimated cost than the partnered CP36. Therefore, assuming that PP16 can be implemented through agreements with the Tohono-Odham nation and with Mexico, then there is little incentive to consider further the three highest-cost alternatives: CC16, CP36, and CP16. If agreements to implement PP16 could not be achieved, then without partners, the similar-cost CC16 could be used.

Based on the costs shown in figures 7a and 7b, the authors recommend CC270, CC36, and PP16. Alternative CC270 has the lowest cost, but is contingent upon collecting and discharging essentially all of the brackish wastewaters from Central Arizona. Alternatives CC36 and PP16 rank second in costs. Alternative CC36 requires cost-sharing with 20 MGD of water from SROG or other source. Alternative PP16 requires no partners.

Compared to PP16 with no partners and CC36 with one partner, the significantly lower cost of CC270 provide an incentive to form regional partnerships. The remaining discussion focuses on these three concentrate disposal alternatives.

Comparing 96.3-MGD and 150-MGD RO plant capacities

Figure 8 compares the costs of the two plant capacities, where both have the same average daily production of 91.5 MGD and the same annual production of 33,400 million gallons per year. Figure 8 shows that compared to a capacity of 150 MGD, the 96-MGD capacity has a lower estimated cost of approximately 17 percent or $9.5 million per year ($45.4 versus 54.9 million/yr with UF-RO treatment and $45.2 versus 54.7 million per year with HU-UF-RO treatment). Until issues of potential degradation of water quality during aquifer storage and recovery can be resolved, however, the authors presently recommend the higher-cost 150-MGD plant capacity. The remaining discussion focuses on the 150-MGD plant capacity.



Recommended combinations of treatment and concentrate disposal alternatives

Figure 9 summarizes the component costs of the six recommended alternatives at the recommended 150-MGD plant capacity.

Costs to upgrade to desalting with the recommended alternatives

Figure 10 summarizes figure 9 information as estimated costs to upgrade HUWTF. For example, figure 10 lists the costs to upgrade to desalting with 150:UF-RO-CC270 as $33.6 million per year. This is the cost to upgrade from the existing HUWTF, with annual operating costs of $13.6 million per year, to alternative 150:UF-RO-CC270, with total costs of $47.2 million per year (refer to figure 9). Alternative 150:HU-UF-RO-CC270 has approximately the same estimated upgrade cost. The estimated upgrade costs for the recommended alternatives range from a low of $33.5 million per year to a high of $41.4 million per year.

Figure 9. --Costs with the recommended plant capacity and recommended treatment and concentrate disposal alternatives

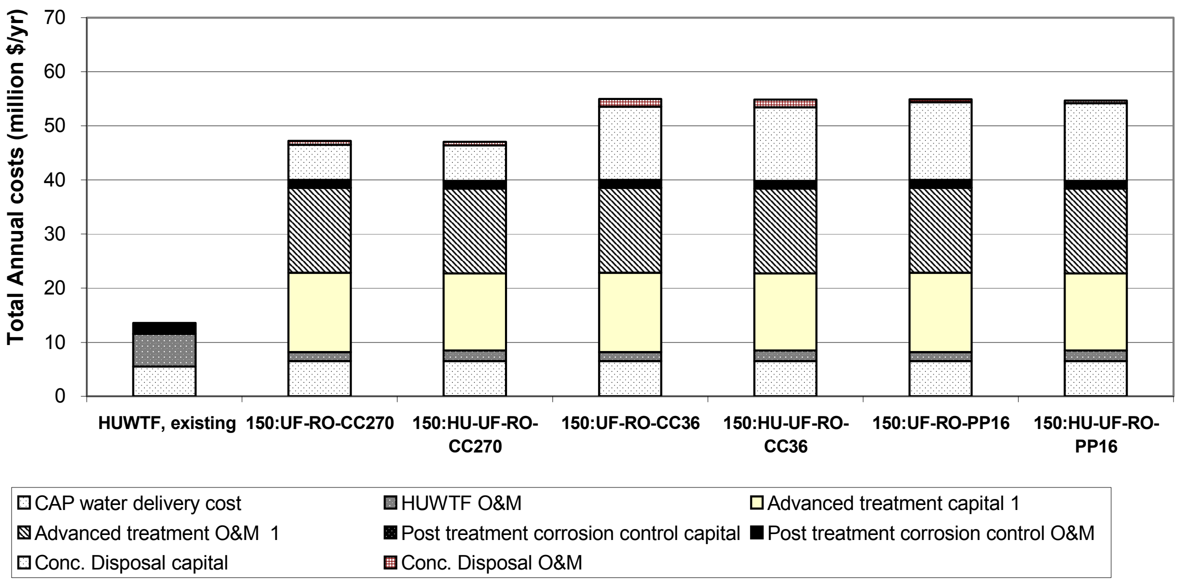


Figure 10. --Annual costs to upgrade HUWTF for the recommended plant capacity and recommended treatment and concentrate disposal alternatives

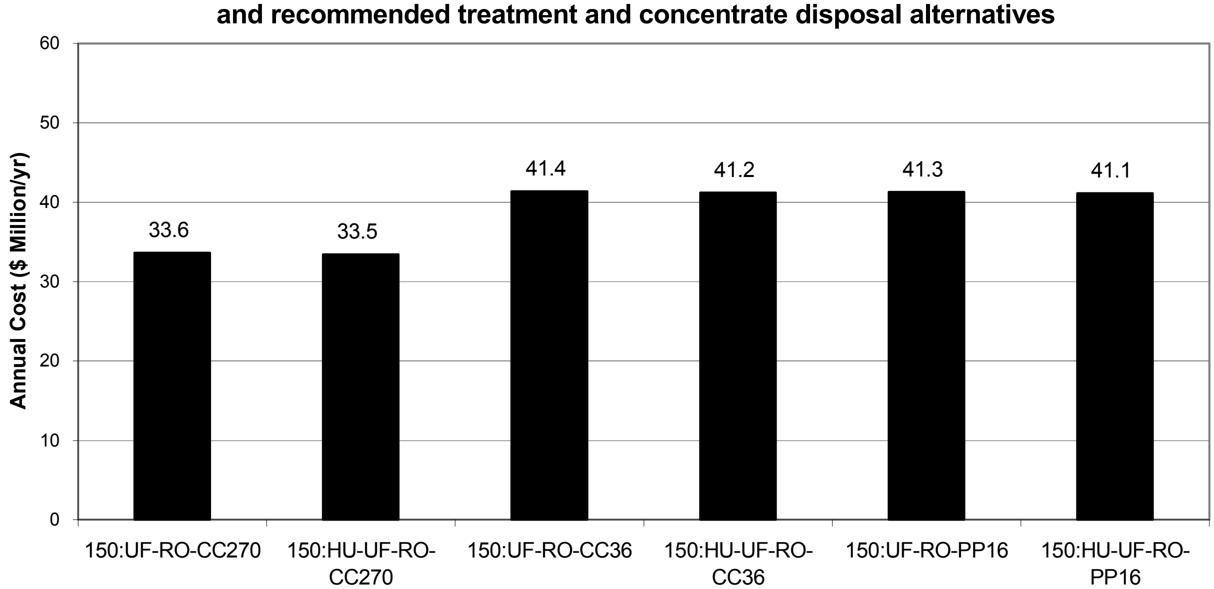
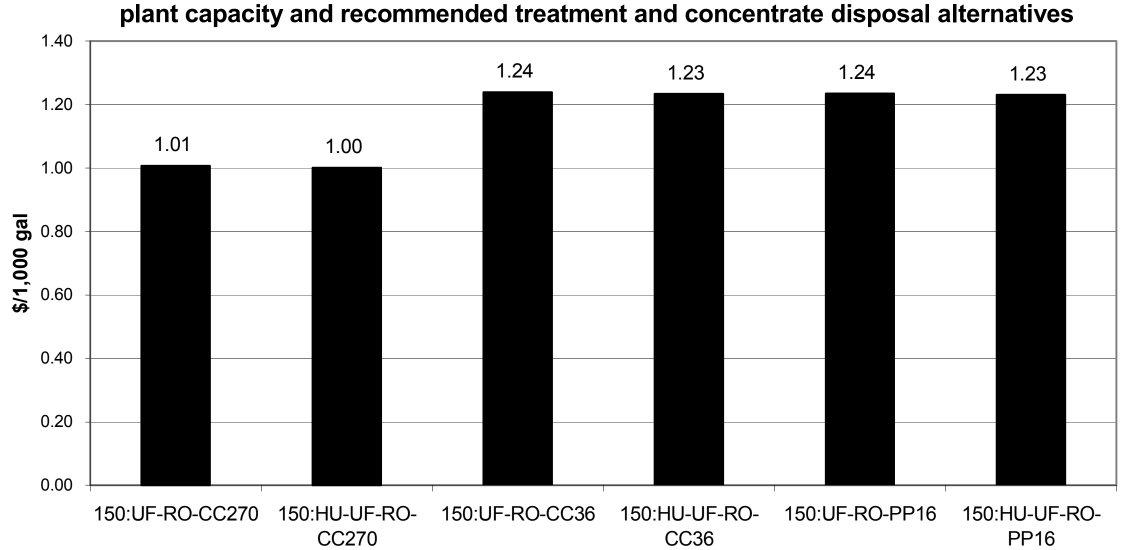


Figure 11 presents the cost to upgrade to desalting (including concentrate disposal) per thousand gallons of water by dividing the estimated upgrade costs shown in figure 10 by the annual production of desalted water of 33,400,000 thousand gallons. For example, for desalting with alternative 150:UF-RO-CC270 with an upgrade cost of $33.6 million per year, the unit cost to include desalting is $1.01 per thousand gallons. The estimated costs to include desalting by the recommended alternatives range from a low of $1.00 per thousand gallons to a high of $1.24 per thousand gallons.

In terms of costs per ton of removed salts, the estimated costs to include desalting by the recommended alternatives range from a low of $308 per ton to a high of $380 per ton (see Appendix E, Revision 1, table 10b).

Figure 11. --Costs per thousand gallons to upgrade HUWTF for the recommended plant capacity and recommended treatment and concentrate disposal alternatives



Summary of costs to upgrade to desalting for all alternatives

Table 5 summarizes the costs of desalting and concentrate disposal for the 48 combinations of treatment, plant size, and concentrate disposal alternatives. Table 6 summarizes the costs to upgrade the present HUWTF to include desalting and concentrate disposal.

Figures 12 and 13 summarize the upgrade costs for the 48 alternatives. The cost bars of the six recommended combinations of alternatives are shown in bold on figures 12b and 13b.

Table 5.- Cost summary of treatment and concentrate disposal alternatives

Constant-production plant with aquifer storage and recovery (ASR) for 91.5 MGD average, 96.3 MGD peak capacity, and 95% plant factor

		Treatment configuration		Concentrate disposal alternative		Total	Annual costs (million $/yr)	
			Costs		Costs	Costs	Capital/O&M	Total
Capital costs	million $	MF/UF - RO	129.71	Pipeline to Puerto Penasco	156.21	285.92	22.28	37.24
O&M costs	milliion $/yr	Figure 1a	14.55	PP16	0.41	14.97	14.97	
Capital costs	million $	MF/UF - RO	129.71	CASI pipeline to Yuma	266.57	396.28	30.68	45.92
O&M costs	milliion $/yr	Figure 1a	14.55	CP16	0.69	15.24	15.24	
Capital costs	million $	MF/UF - RO	129.71	CASI canal to Yuma	160.51	290.22	22.60	38.43
O&M costs	milliion $/yr	Figure 1a	14.55	CC16	1.27	15.82	15.82	
Capital costs	million $	MF/UF - RO	129.71	CASI pipeline to Yuma	203.96	333.67	25.91	40.99
O&M costs	milliion $/yr	Figure 1a	14.55	CP36	0.52	15.08	15.08	
Capital costs	million $	MF/UF - RO	129.71	CASI canal to Yuma	119.56	249.27	19.49	34.99
O&M costs	milliion $/yr	Figure 1a	14.55	CC36	0.95	15.51	15.51	
Capital costs	million $	MF/UF - RO	129.71	CASI canal to Yuma	55.03	184.74	14.58	29.58
O&M costs	milliion $/yr	Figure 1a	14.55	CC270	0.44	15.00	15.00	
Capital costs	million $	MF/UF - (RO & GAC)	155.56	Pipeline to Puerto Penasco	145.21	300.77	23.51	39.38
O&M costs	milliion $/yr	Figure 2a (13% Blending)	15.49	PP16	0.38	15.87	15.87	
Capital costs	million $	MF/UF - (RO & GAC)	155.56	CASI pipeline to Yuma	245.29	400.85	31.13	47.26
O&M costs	milliion $/yr	Figure 2a (13% Blending)	15.49	CP16	0.65	16.14	16.14	
Capital costs	million $	MF/UF - (RO & GAC)	155.56	CASI canal to Yuma	153.02	308.57	24.10	40.79
O&M costs	milliion $/yr	Figure 2a (13% Blending)	15.49	CC16	1.20	16.69	16.69	
Capital costs	million $	MF/UF - (RO & GAC)	155.56	CASI pipeline to Yuma	178.37	333.93	26.03	41.98
O&M costs	milliion $/yr	Figure 2a (13% Blending)	15.49	CP36	0.46	15.94	15.94	
Capital costs	million $	MF/UF - (RO & GAC)	155.56	CASI canal to Yuma	105.89	261.45	20.52	36.84
O&M costs	milliion $/yr	Figure 2a (13% Blending)	15.49	CC36	0.84	16.33	16.33	
Capital costs	million $	MF/UF - (RO & GAC)	155.56	CASI canal to Yuma	47.83	203.39	16.10	31.97
O&M costs	milliion $/yr	Figure 2a (13% Blending)	15.49	CC270	0.39	15.87	15.87	
Capital costs	million $	HUWTF - MF/UF - RO	125.97	Pipeline to Puerto Penasco	156.21	282.18	21.98	36.75
O&M costs	milliion $/yr	Figure 3a	14.36	PP16	0.41	14.77	14.77	
Capital costs	million $	HUWTF - MF/UF - RO	125.97	CASI pipeline to Yuma	266.57	392.54	30.38	45.42
O&M costs	milliion $/yr	Figure 3a	14.36	CP16	0.69	15.05	15.05	
Capital costs	million $	HUWTF - MF/UF - RO	125.97	CASI canal to Yuma	160.51	286.48	22.30	37.93
O&M costs	milliion $/yr	Figure 3a	14.36	CC16	1.27	15.62	15.62	
Capital costs	million $	HUWTF - MF/UF - RO	125.97	CASI pipeline to Yuma	203.96	329.93	25.61	40.49
O&M costs	milliion $/yr	Figure 3a	14.36	CP36	0.52	14.88	14.88	
Capital costs	million $	HUWTF - MF/UF - RO	125.97	CASI canal to Yuma	119.56	245.53	19.19	34.50
O&M costs	milliion $/yr	Figure 3a	14.36	CC36	0.95	15.31	15.31	
Capital costs	million $	HUWTF - MF/UF - RO	125.97	CASI canal to Yuma	55.03	181.00	14.28	29.08
O&M costs	milliion $/yr	Figure 3a	14.36	CC270	0.44	14.80	14.80	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	151.86	Pipeline to Puerto Penasco	145.21	297.07	23.21	37.55
O&M costs	milliion $/yr	Figure 4a (13% Blending)	13.95	PP16	0.38	14.34	14.34	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	151.86	CASI pipeline to Yuma	245.29	397.15	30.83	45.43
O&M costs	milliion $/yr	Figure 4a (13% Blending)	13.95	CP16	0.65	14.60	14.60	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	151.86	CASI canal to Yuma	153.02	304.88	23.81	38.97
O&M costs	milliion $/yr	Figure 4a (13% Blending)	13.95	CC16	1.20	15.16	15.16	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	151.86	CASI pipeline to Yuma	178.37	330.24	25.74	40.15
O&M costs	milliion $/yr	Figure 4a (13% Blending)	13.95	CP36	0.46	14.41	14.41	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	151.86	CASI canal to Yuma	105.89	257.76	20.22	35.02
O&M costs	milliion $/yr	Figure 4a (13% Blending)	13.95	CC36	0.84	14.79	14.79	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	151.86	CASI canal to Yuma	47.83	199.70	15.80	30.14
O&M costs	milliion $/yr	Figure 4a (13% Blending)	13.95	CC270	0.39	14.34	14.34	

Table 5.- Cost summary of treatment and concentrate disposal alternatives, continued

Variable-production plant to meet peak-day 150-MGD capacity, 91.5-MGD average, and 61% plant factor

		Treatment configuration		Concentrate disposal alternative		Total	Annual costs (million $/yr)	
			Costs		Costs	Costs	Capital/O&M	Total
Capital costs	million $	MF/UF - RO	183.46	Pipeline to Puerto Penasco	188.91	372.37	29.07	46.69
O&M costs	milliion $/yr	Figure 1b	17.12	PP16	0.50	17.62	17.62	
Capital costs	million $	MF/UF - RO	183.46	CASI pipeline to Yuma	333.88	517.35	40.10	58.09
O&M costs	milliion $/yr	Figure 1b	17.12	CP16	0.86	17.98	17.98	
Capital costs	million $	MF/UF - RO	183.46	CASI canal to Yuma	192.63	376.09	29.35	48.02
O&M costs	milliion $/yr	Figure 1b	17.12	CC16	1.54	18.66	18.66	
Capital costs	million $	MF/UF - RO	183.46	CASI pipeline to Yuma	313.69	497.15	38.57	56.49
O&M costs	milliion $/yr	Figure 1b	17.12	CP36	0.80	17.92	17.92	
Capital costs	million $	MF/UF - RO	183.46	CASI canal to Yuma	178.17	361.63	28.25	46.80
O&M costs	milliion $/yr	Figure 1b	17.12	CC36	1.43	18.55	18.55	
Capital costs	million $	MF/UF - RO	183.46	CASI canal to Yuma	85.90	269.37	21.23	39.04
O&M costs	milliion $/yr	Figure 1b	17.12	CC270	0.69	17.81	17.81	
Capital costs	million $	MF/UF - (RO & GAC)	208.10	Pipeline to Puerto Penasco	179.74	387.85	30.35	48.68
O&M costs	milliion $/yr	Figure 2b (15% Blending)	17.86	PP16	0.47	18.34	18.34	
Capital costs	million $	MF/UF - (RO & GAC)	208.10	CASI pipeline to Yuma	313.92	522.03	40.56	59.22
O&M costs	milliion $/yr	Figure 2b (15% Blending)	17.86	CP16	0.80	18.66	18.66	
Capital costs	million $	MF/UF - (RO & GAC)	208.10	CASI canal to Yuma	180.96	389.06	30.44	49.74
O&M costs	milliion $/yr	Figure 2b (15% Blending)	17.86	CC16	1.44	19.30	19.30	
Capital costs	million $	MF/UF - (RO & GAC)	208.10	CASI pipeline to Yuma	273.83	481.93	37.51	56.07
O&M costs	milliion $/yr	Figure 2b (15% Blending)	17.86	CP36	0.70	18.56	18.56	
Capital costs	million $	MF/UF - (RO & GAC)	208.10	CASI canal to Yuma	156.88	364.98	28.61	47.72
O&M costs	milliion $/yr	Figure 2b (15% Blending)	17.86	RO-CC36	1.26	19.12	19.12	
Capital costs	million $	MF/UF - (RO & GAC)	208.10	CASI canal to Yuma	74.69	282.79	22.35	40.81
O&M costs	milliion $/yr	Figure 2b (15% Blending)	17.86	CC270	0.60	18.46	18.46	
Capital costs	million $	HUWTF - MF/UF - RO	178.36	Pipeline to Puerto Penasco	188.91	367.28	28.66	46.22
O&M costs	milliion $/yr	Figure 3b	17.06	PP16	0.50	17.56	17.56	
Capital costs	million $	HUWTF - MF/UF - RO	178.36	CASI pipeline to Yuma	333.88	512.25	39.70	57.61
O&M costs	milliion $/yr	Figure 3b	17.06	CP16	0.86	17.92	17.92	
Capital costs	million $	HUWTF - MF/UF - RO	178.36	CASI canal to Yuma	192.63	370.99	28.95	47.54
O&M costs	milliion $/yr	Figure 3b	17.06	CC16	1.54	18.60	18.60	
Capital costs	million $	HUWTF - MF/UF - RO	178.36	CASI pipeline to Yuma	313.69	492.05	38.16	56.02
O&M costs	milliion $/yr	Figure 3b	17.06	CP36	0.80	17.86	17.86	
Capital costs	million $	HUWTF - MF/UF - RO	178.36	CASI canal to Yuma	178.17	356.53	27.85	46.33
O&M costs	milliion $/yr	Figure 3b	17.06	RO-CC36	1.43	18.49	18.49	
Capital costs	million $	HUWTF - MF/UF - RO	178.36	CASI canal to Yuma	85.90	264.27	20.82	38.57
O&M costs	milliion $/yr	Figure 3b	17.06	CC270	0.69	17.75	17.75	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	203.07	Pipeline to Puerto Penasco	179.74	382.81	29.94	46.88
O&M costs	milliion $/yr	Figure 4b (15% Blending)	16.46	PP16	0.47	16.94	16.94	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	203.07	CASI pipeline to Yuma	313.92	516.99	40.16	57.41
O&M costs	milliion $/yr	Figure 4b (15% Blending)	16.46	CP16	0.80	17.26	17.26	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	203.07	CASI canal to Yuma	180.96	384.03	30.04	47.94
O&M costs	milliion $/yr	Figure 4b (15% Blending)	16.46	CC16	1.44	17.90	17.90	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	203.07	CASI pipeline to Yuma	273.83	476.90	37.10	54.26
O&M costs	milliion $/yr	Figure 4b (15% Blending)	16.46	CP36	0.70	17.16	17.16	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	203.07	CASI canal to Yuma	156.88	359.95	28.20	45.92
O&M costs	milliion $/yr	Figure 4b (15% Blending)	16.46	RO-CC36	1.26	17.72	17.72	
Capital costs	million $	HUWTF - ([MF/UF-RO] & GAC)	203.07	CASI canal to Yuma	74.69	277.76	21.95	39.01
O&M costs	milliion $/yr	Figure 4b (15% Blending)	16.46	CC270	0.60	17.06	17.06	

Table 6.- Annual cost to upgrade HUWTF to include desalting and concentrate disposal

Constant-production plant with aquifer storage and recovery (ASR) for 91.5 MGD average, 96.3 MGD peak capacity, and 95% plant factor

	Capital costs		O&M costs					Annual costs	Upgrade costs	
Treatment alternatives	Capital costs of desalting & concentrate disposal	Amortized Capital Costs of desalting & concentrate disposal	CAP water delivery	HUWTF O&M	Sum of CAP water delivery & HUWTF O&M	Desalting, & concentrate disposal	CAP water delivery, partial HUWTF, desalting, & concentrate disposal	Amortized capital & O&M	Additional O&M costs to upgrade to desalting	Amortized capital & additional O&M
	million $/yr	million $/yr	million $/yr	million $/yr	million $/yr	million $/yr	million $/yr	million $/yr	million $/yr	million $/yr
HUWTF, existing	0	0	5.54	8.05	13.59	0	13.59	13.59	0.00	0
96:UF-RO-PP16	285.92	22.28	6.53	1.64	8.17	14.97	23.14	45.42	9.55	31.82
96:UF-RO-CP16	396.28	30.68	6.53	1.64	8.17	15.24	23.42	54.09	9.82	40.50
96:UF-RO-CC16	290.22	22.60	6.53	1.64	8.17	15.82	24.00	46.60	10.40	33.01
96:UF-RO-CP36	333.67	25.91	6.53	1.64	8.17	15.08	23.25	49.16	9.66	35.57
96:UF-RO-CC36	249.27	19.49	6.53	1.64	8.17	15.51	23.68	43.17	10.09	29.57
96:UF-RO-CC270	184.74	14.58	6.53	1.64	8.17	15.00	23.17	37.75	9.58	24.16
96:UF-RO&GAC-PP16	300.77	23.51	6.40	1.62	8.02	15.87	23.89	47.40	10.30	33.81
96:UF-RO&GAC-CP16	400.85	31.13	6.40	1.62	8.02	16.14	24.16	55.28	10.56	41.69
96:UF-RO&GAC-CC16	308.57	24.10	6.40	1.62	8.02	16.69	24.71	48.82	11.12	35.22
96:UF-RO&GAC-CP-36	333.93	26.03	6.40	1.62	8.02	15.94	23.97	50.00	10.37	36.41
96:UF-RO&GAC-CC36	261.45	20.52	6.40	1.62	8.02	16.33	24.35	44.87	10.76	31.27
96:UF-RO&GAC-CC270	203.39	16.10	6.40	1.62	8.02	15.87	23.89	39.99	10.30	26.40
96:HU-UF-RO-PP16	282.18	21.98	6.53	1.95	8.48	14.77	23.25	45.23	9.66	31.63
96:HU-UF-RO-CP16	392.54	30.38	6.53	1.95	8.48	15.05	23.53	53.90	9.93	40.31
96:HU-UF-RO-CC16	286.48	22.30	6.53	1.95	8.48	15.62	24.10	46.41	10.51	32.82
96:HU-UF-RO-CP-36	329.93	25.61	6.53	1.95	8.48	14.88	23.36	48.97	9.77	35.38
96:HU-UF-RO-CC36	245.53	19.19	6.53	1.95	8.48	15.31	23.79	42.98	10.20	29.38
96:HU-UF-RO-CC270	181.00	14.28	6.53	1.95	8.48	14.80	23.28	37.56	9.69	23.97
96:HU-UF-RO&GAC-PP16	297.07	23.21	6.40	1.92	8.32	14.34	22.66	45.87	9.07	32.28
96:HU-UF-RO&GAC-CP16	397.15	30.83	6.40	1.92	8.32	14.60	22.93	53.76	9.33	40.16
96:HU-UF-RO&GAC-CC16	304.88	23.81	6.40	1.92	8.32	15.16	23.48	47.29	9.89	33.70
96:HU-UF-RO&GAC-CP-36	330.24	25.74	6.40	1.92	8.32	14.41	22.73	48.47	9.14	34.88
96:HU-UF-RO&GAC-CC36	257.76	20.22	6.40	1.92	8.32	14.79	23.12	43.34	9.52	29.75
96:HU-UF-RO&GAC-CC270	199.70	15.80	6.40	1.92	8.32	14.34	22.66	38.47	9.07	24.87

Table 6.- Annual cost to upgrade HUWTF to include desalting and concentrate disposal, cont.

Variable-production plant to meet peak-day 150-MGD capacity, 91.5-MGD average, and 61% plant factor

	Capital costs		O&M costs					Annual costs	Upgrade costs	
Treatment alternatives	Capital costs of desalting & concentrate disposal	Amortized Capital Costs of desalting & concentrate disposal	CAP water delivery	HUWTF O&M	Sum of CAP water delivery & HUWTF O&M	Desalting, & concentrate disposal	CAP water delivery, partial HUWTF, desalting, & concentrate disposal	Amortized capital & O&M	Additional O&M costs to upgrade to desalting	Amortized capital & additional O&M
150:UF-RO-PP16	372.37	29.07	6.53	1.64	8.17	17.62	25.79	54.87	12.20	41.27
150:UF-RO-CP16	517.35	40.10	6.53	1.64	8.17	17.98	26.15	66.26	12.56	52.67
150:UF-RO-CC16	376.09	29.35	6.53	1.64	8.17	18.66	26.84	56.19	13.24	42.60
150:UF-RO-CP36	497.15	38.57	6.53	1.64	8.17	17.92	26.10	64.66	12.50	51.07
150:UF-RO-CC36	361.63	28.25	6.53	1.64	8.17	18.55	26.72	54.98	13.13	41.38
150:UF-RO-CC270	269.37	21.23	6.53	1.64	8.17	17.81	25.98	47.22	12.39	33.62
150:UF-RO&GAC-PP16	387.85	30.35	6.40	1.62	8.02	18.34	26.36	56.71	12.77	43.11
150:UF-RO&GAC-CP16	522.03	40.56	6.40	1.62	8.02	18.66	26.68	67.24	13.09	53.65
150:UF-RO&GAC-CC16	389.06	30.44	6.40	1.62	8.02	19.30	27.33	57.77	13.73	44.17
150:UF-RO&GAC-CP-36	481.93	37.51	6.40	1.62	8.02	18.56	26.58	64.09	12.99	50.50
150:UF-RO&GAC-CC36	364.98	28.61	6.40	1.62	8.02	19.12	27.14	55.75	13.55	42.15
150:UF-RO&GAC-CC270	282.79	22.35	6.40	1.62	8.02	18.46	26.48	48.84	12.89	35.24
150:HU-UF-RO-PP16	367.28	28.66	6.53	1.95	8.48	17.56	26.04	54.70	12.45	41.11
150:HU-UF-RO-CP16	512.25	39.70	6.53	1.95	8.48	17.92	26.40	66.09	12.81	52.50
150:HU-UF-RO-CC16	370.99	28.95	6.53	1.95	8.48	18.60	27.08	56.03	13.49	42.43
150:HU-UF-RO-CP-36	492.05	38.16	6.53	1.95	8.48	17.86	26.34	64.50	12.75	50.91
150:HU-UF-RO-CC36	356.53	27.85	6.53	1.95	8.48	18.49	26.97	54.81	13.37	41.22
150:HU-UF-RO-CC270	264.27	20.82	6.53	1.95	8.48	17.75	26.23	47.05	12.63	33.46
150:HU-UF-RO&GAC-PP16	382.81	29.94	6.40	1.92	8.32	16.94	25.26	55.20	11.67	41.61
150:HU-UF-RO&GAC-CP16	516.99	40.16	6.40	1.92	8.32	17.26	25.58	65.74	11.99	52.15
150:HU-UF-RO&GAC-CC16	384.03	30.04	6.40	1.92	8.32	17.90	26.23	56.26	12.63	42.67
150:HU-UF-RO&GAC-CP-36	476.90	37.10	6.40	1.92	8.32	17.16	25.48	62.59	11.89	49.00
150:HU-UF-RO&GAC-CC36	359.95	28.20	6.40	1.92	8.32	17.72	26.04	54.24	12.45	40.65
150:HU-UF-RO&GAC-CC270	277.76	21.95	6.40	1.92	8.32	17.06	25.38	47.33	11.79	33.74

Figure 12a. --Annual costs to upgrade HUWTF to include 96-MGD desalting capacity for all alternatives. Average daily production is 91.5 MGD

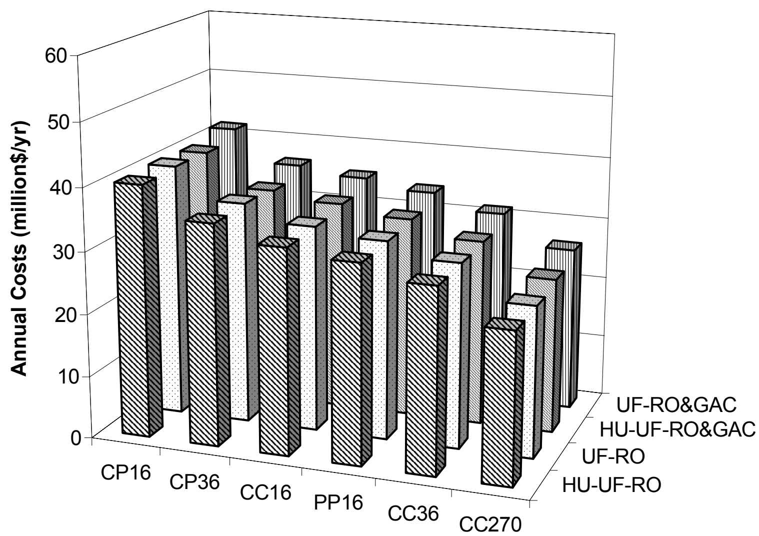


Figure 12b. --Annual costs to upgrade HUWTF to include 150-MGD desalting capacity for all alternatives. Average daily production is 91.5 MGD.

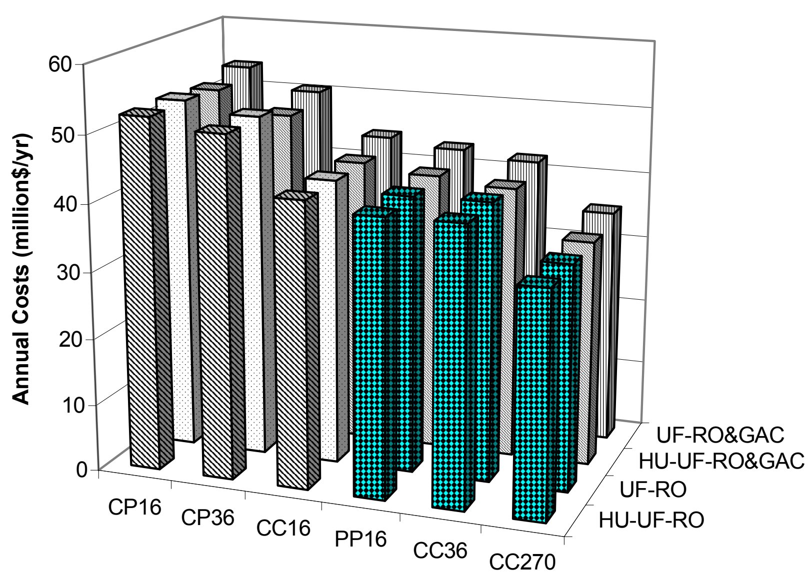


Figure 13a. --Costs per thousand gallons to upgrade HUWTF to include 96-MGD desalting capacity for all alternatives

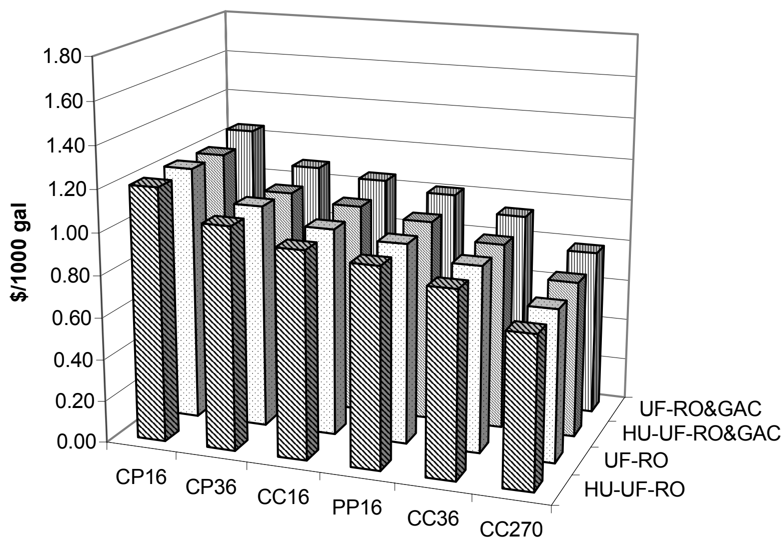
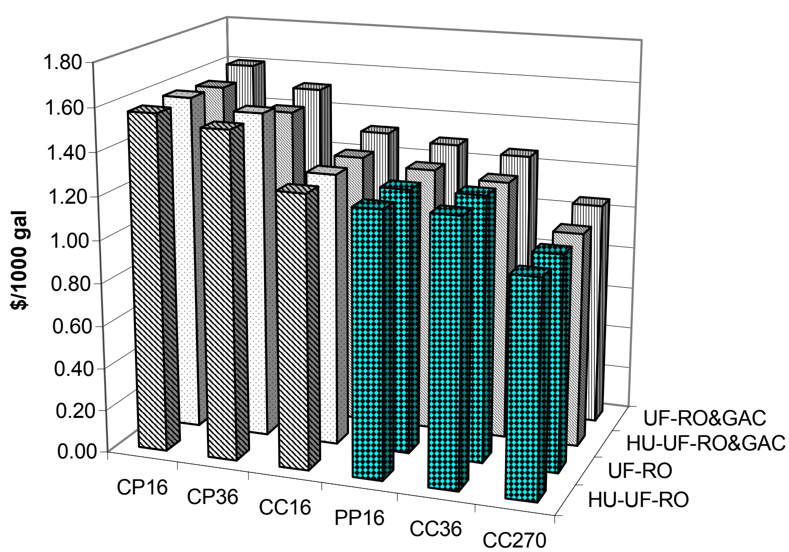


Figure 13b. --Costs per thousand gallons to upgrade HUWTF to include 150-MGD desalting capacity for all alternatives



From the 48 alternatives, the authors selected:

1. Treatment. RO without GAC because GAC in parallel to RO results in no cost savings and produces lower-quality water.

2. Treatment. Both MF/UF-RO and HU-MF/UF-RO because of MF/UF effectiveness in maintaining low RO fouling during pilot tests and the similar costs of the two treatment alternatives.

3. Plant size. 150-MGD plant size because of limited information on the effectiveness of the 96-MGD plant size ASR in maintaining the high quality of RO product water during aquifer storage.

4. Concentrate disposal.
CC270 as the lowest cost alternative and one that offers a regional solution to the required disposal of brackish waste waters from central Arizona.

   CC36 for joint discharge of 16 MGD from Tucson and 20 MGD from SROG in Phoenix.

   PP16 for direct discharge to the Gulf of California if no partners are available to share CASI costs to Yuma.

The six recommended combinations of alternatives are:

150:UF-RO-CC270	150:HU-UF-RO-CC270
150:UF-RO-CC36	150:HU-UF-RO-CC36
150:UF-RO-PP16	150:HU-UF-RO-PP16

For the recommended alternatives, installation of 150-MGD capacity MF/UF and RO treatment processes at the HUWTF has an estimated capital cost of approximately $178 to 183 million (refer to table 5) for an installed cost of $1.19 to 1.22 per gpd capacity. Concentrate disposal has an estimated capital cost of $86 to 189 million, depending on which of the three recommended alternatives is selected. The estimated total capital costs range from $264 to 372 million, of which concentrate disposal capital costs represent 32 percent with the high-volume CASI canal (CC270) and 51 percent with the non-partnered pipeline to Puerto Penasco (PP16).

For the recommended alternatives, operation and maintenance of 150-MGD capacity MF/UF and RO treatment processes has an estimated cost of $17.1 million per year (refer to table 5). Operation and maintenance for concentrate disposal has much lower estimated costs of $0.5 to 1.4 million per year.

Compared to the present design of the HUWTF, water treatment operating and maintenance costs increase by $12.2 to $13.4 million per year (refer to table 6). Compared to the present HUWTF, the combination of amortized capital costs and operating and maintenance costs results in additional annual costs of $33 to $41 million per year to upgrade to desalting (refer to table 6 and figure 10).

For the annual production of 33.4 billion gallons of desalted water, the cost to upgrade to include desalting with the recommended alternatives ranges from $1.00 to $1.24 per thousand gallons (refer to figure 11). In terms of tons of salt removed, desalting and concentrate disposal removes 108,600 tons of salt per year at a cost ranging from $308 to $380 per ton (see appendix E, revision 1, table 10).

Because of the absence of cost savings, increased complexity, and lower quality treatment associated with GAC, the authors do not recommend using GAC as a parallel treatment to RO.

Water Quality with Recommended Treatment Alternatives

For the recommended MF/UF and RO treatment alternatives, Table 7 lists the design values for TDS, hardness, and TOC for the CAP canal, Hayden Udall WTF product, RO product, and finished RO product stabilized for corrosion control and compares these with the WCPA's maximum levels for these constituents.

The average annual finished RO product water with post-treatment stabilization for corrosion control has expected concentrations of 95 to 137 mg/L TDS, 44 to 86 mg/L hardness, and 0.14 mg/L TOC. In August when the lowest rejection occurs with the warmest water, the finished RO product water has expected concentrations of 108 to 166 mg/L TDS, 48 to 104 mg/L hardness, and 0.14 mg/L TOC. These concentrations meet the WCPA criteria for TDS and TOC and, with caustic replacing some of the lime, if needed, also meet the WCPA criteria for hardness.

Table 7.—Water quality criteria levels

Stream	TDS mg/L	Hardness mg-$CACO_3$/L	TOC mg/L
WPCA maximum level	210	84	0.4
CAP	697	328	3.5
Hayden Udall WTF product	697	328	2.1
RO product			
Annual average at 22.4 °C[1] (72 °F[2])	56	5.4	0.14
January at 14.4 °C (58 °F)	47	7.4	0.14
August at 30.8 °C (87 °F)	69	6.9	0.14
Finished RO product with post-treatment[3]			
Annual average at 22.4 °C[1] (72 °F[2])	95 - 137	44 - 86	0.14
August at 30.8 °C (87 °F)	108 - 166	48 - 104	0.14

[1] °C = degrees Celsius.
[2] °F = degrees Fahrenheit.
[3] Post treatment to control corrosion in the water distribution system achieved by adding low-turbidity lime and carbon dioxide. Caustic soda can replace some of the lime to reduce the added hardness if needed to meet the WPCA maximum level of 84 mg/L hardness.

Conclusions

To determine the cost and viability of NF or RO membrane treatment of CAP water, this study developed the following information.

1. Membrane type

Polyamide reverse osmosis membrane elements operating at pressures of 90 to 140 pounds per square inch gauge (psig) pressure are selected for the preliminary conceptual design. PA NF "softening" membrane elements (with sodium chloride salt rejections of 80 percent or less) have insufficient salt rejection to produce the target 210 mg/L TDS. Cellulose acetate (CA) membrane elements were not selected primarily because they require operation at pH 5.5, and the required acid (if sulfuric acid) increases the supersaturation and potential scaling of barium sulfate by about 40 percent.

A downside to using PA membranes compared to CA membranes is that free chlorine disinfection cannot be used, because PA membranes can suffer significant losses in salt rejection in the presence of free chlorine. Although PA membranes operated successfully without degradation in short-term pilot tests in this study, in short-term pilot tests at Reclamation's WQIC, and for several years with chloramine disinfection at wastewater reuse plants, generally PA membranes operate with no disinfectant and rely on periodic cleanings to control biofouling. The selected treatment alternatives incorporate PA membranes with an estimated 3-year replacement frequency, no disinfection, and nine RO cleanings per year.

NF remains a potential alternative in stage 1 of a three-stage NF/RO plant. CA remains a potential alternative if, in future tests, PA elements exhibit high fouling rates or high cleaning frequencies, if CA operation at high recovery can be achieved at the higher barium sulfate supersaturation levels associated with sulfuric acid addition, or if hydrochloric acid is used.

2. Maximum product water recovery

Pilot tests with MF/UF - RO operated at RO recoveries as high as 90 percent with no observed scaling or performance decline in the tail elements. Because the design CAP water TDS is higher than that of the pilot test feedwater, the authors selected an 85-percent RO water recovery for this conceptual design.

3. Selection of microfiltration or ultrafiltration pretreatment to reverse osmosis

Pilot tests with Hayden Udall PP modeled to represent the Hayden Udall WTF provided marginally adequate pretreatment for RO stage 1 in pilot test activity 4. Observed RO pilot plant stage 2 performance declines are attributed to scaling by aluminum hydroxide from the alum coagulant. Although the direct filtration provided by the HUWTF (or conventional treatment if the HUWTF is modified with sedimentation basins), possibly may be modified to provide low-fouling and low-scaling waters to the RO process, pilot tests with the Hayden Udall PP did not achieve this goal.

Because pilot tests with MF and UF pretreatment successfully maintained RO performance in pilot test activities 5 and 7, MF or UF pretreatment was selected.

4. Concentrate disposal quantity, composition, recommended alternatives, and costs

At 85-percent RO water recovery, a desalting plant producing an average of 91.5 MGD of desalted water requires a feed flow of 107.6 MGD and a concentrate flow of 16.1 MGD. Operating with a CAP TDS of 700 mg/L and producing RO product water with a TDS of 56 mg/L, the concentrate TDS is 4,400 mg/L.

Concentrate disposal presents a serious challenge to the operation of an RO plant at an inland site, such as Tucson. Nevertheless, the study identified several viable alternatives. The recommended alternatives discharge to the Gulf of California, obtaining beneficial uses of the brackish water en route.

Based on the criteria of effectiveness, implementability, and cost, the work group selected and the authors recommend the use of a proposed Central

Arizona Salinity Interceptor to collect and transport brackish waters by gravity from the Tucson and Phoenix areas to Yuma. CASI offers a regional solution to projected needs throughout central Arizona for the discharge of brackish residual waters from desalting plants, water reuse plants, and urban and agricultural irrigation.

At Yuma the brackish water has several potential beneficial uses, including serving as an additional brackish water supply to the Santa Clara wetland, further desalting at the Yuma Desalting Plant, restoration of the Salton Sea, and/or restoration of the Colorado Delta.

The Central Arizona Water Conservation District could operate CASI in a manner similar to the Santa Ana Watershed Protection Authority's operation of the SARI pipeline in Orange County, California.

In the possible absence of partners to build and operate CASI, the authors recommend considering a shorter route to transport the concentrate by pipeline to the Gulf of California at a discharge site east of Puerto Penasco, where the brackish water is expected to have several potential beneficial uses.

These concentrate disposal alternatives have estimated capital costs of $86 to $189 million, depending on which of route to the Gulf of California is selected and the number of partners to share in the CASI route through Yuma.

Of the estimated total capital costs of $264 to 372 million for desalting and concentrate disposal, concentrate disposal capital costs represent 32 percent with the high-volume CASI canal (CC270) and 51 percent with the non-partnered pipeline to Puerto Penasco (PP16).

Operation and maintenance for concentrate disposal has estimated costs of $0.5 to 1.4 million per year.

Concentrate disposal alternative selection and costs will depend on the participation, agreement, and/or approval from local, state, tribal, U.S., and Mexico governments.

5. Costs of RO treatment including concentrate disposal

For the recommended alternatives, installation of 150-MGD capacity MF/UF and RO treatment processes at the HUWTF has an estimated capital cost of approximately $178 to 183 million for an installed cost of $1.19 to $1.22 per gpd capacity. Installation of concentrate disposal has an estimated capital cost of $86 to $189 million, depending on which of the three recommended alternatives is selected. The estimated total capital costs range from $264 to 372 million, of which concentrate disposal capital costs represent 32 percent with the high-volume CASI canal (CC270) and 51 percent with the non-partnered pipeline to Puerto Penasco (PP16).

Operation and maintenance of 150-MGD capacity MF/UF and RO treatment processes has an estimated cost of $17.1 million per year (refer to table 5). Operation and maintenance for concentrate disposal has much lower estimated costs of $0.5 to $1.4 million per year

Compared to the present design of the HUWTF, water treatment operating and maintenance costs increase by $12.2 to $13.4 million per year. Compared to the present HUWTF, the combination of amortized capital costs and operating and maintenance costs results in additional annual costs of $33 to $41 million per year to upgrade to desalting and concentrate disposal.

For the annual production of 33.4 billion gallons of desalted water, the cost to upgrade to include desalting with the recommended alternatives ranges from $1.00 to $1.24 per thousand gallons. In terms of tons of salt removed, desalting and concentrate disposal removes 108,600 tons of salt per year at a cost ranging from $308 to $380 per ton.

The study evaluated treatment by granular activated carbon (GAC) in parallel to RO, but estimated that the GAC process would not result in lower costs, and would add complexity and produce lower-quality water.

6. What additional pilot plant, regulatory, and cost issues need to be addressed in the next evaluation stage of this water treatment option?

Cost sharing of RO treatment

Explore cost sharing of RO treatment with WWTP and WWTP effluent owners, who benefit by having lower TDS wastewater. For the 62 percent of the treated water that reaches the WWTP, an RO plant lowers the wastewater TDS from 950 mg/L for direct-delivered CAP water to about 350 mg/L with RO-treated CAP water.

RO pretreatment design

Because two recent studies have concluded that slowsand filtration holds promise as an effective and low-cost pretreatment for RO treatment of CAP water, consider SSF-RO treatment alternatives 8 and 9 (refer to table 2).

Because the existing CAVSRP may also adequately filter CAP water for RO treatment if the recovered water is delivered to the RO plant in a closed pipeline, evaluate the effectiveness and costs of table 2 treatment alternatives 6 and 6a: CAVSRP - RO.

Because the emerging technology of MF/UF continues to improve rapidly, continue to review the costs of the two recommended treatment alternatives (refer to table 2 numbers 7 and 10): HUWTF - MF/UF - RO and MF/UF - RO. In pilot tests, evaluate the effectiveness of MF/UF improvements offering significant cost reductions.

Because the RO industry continues to advance RO membrane technologies, continue to review improvements such as "low-fouling" PA membranes for possible operation with the existing HUWTF for table 2 treatment alternative 3: HUWTF - RO. In pilot tests, evaluate effects of operational changes to the HUWTF and the use of low-fouling PA membranes with the goal of obtaining reliable low-fouling and non-scaling operation with this treatment alternative.

RO design

In pilot studies on surface water from the CAP or Colorado River:

a. Evaluate RO cleaning frequencies.

b. Evaluate the effects of antiscalants on RO fouling, RO recovery, and barium sulfate crystallization (see d. below). Because antiscalants are the third highest operation and maintenance cost item (after electricity and membrane replacement), it may be advisable to include the lower cost, generic sodium hexametaphosphate antiscalant in the evaluation.

c. Evaluate stabilization of RO product water to avoid pipe corrosion.

d. Evaluate the need for stabilization of RO concentrate to avoid scaling of concentrate disposal pipelines or canals. If stabilization is needed, test a pilot-scale barium sulfate crystallizer to remove supersaturated barite.

e. Evaluate operating at as high as 90-percent recovery because increasing recovery from 85 percent to 90 percent increases water use by 5 percent and decreases the concentrate disposal volume by one third. Include an evaluation of the effect the higher concentrate TDS (about 6,000 mg/L at 90-percent recovery) would have on concentrate disposal alternatives.

Concentrate disposal

The greatest uncertainties with respect to implementability and cost are related to concentrate disposal.

a. For the recommended Central Arizona Salinity Interceptor to Yuma,

- Review the rate of accumulation of salt and brackish water in Central Arizona and estimate the required discharge of brackish water to achieve salt balance so that salt outflows equal salt inflows.

- Because almost all present brackish water discharges in Central Arizona eventually reach groundwater, estimate the predicted groundwater salinities, groundwater rise rates, and dates when the groundwater levels will surface and thereby waterlog and salinize Central Arizona soils.

- To avoid surfacing groundwater, participate in a regional evaluation of the reuse and disposal of brackish water "concentrates" from desalting plants, water reuse plants, and agricultural and urban irrigation in Central Arizona.

The Central Arizona Salinity Study (CASS) began a regional evaluation to address the above three actions in October 2001. For information on CASS, see <http://cass.bcportals.com/public/default.cfm>. If the regional evaluation concurs with the recommendation of this study to construct and operate CASI, then proceed with the following actions:

- Work with Reclamation and the International Boundary and Water Commission (IBWC) to explore an international agreement for concentrate discharge to the Santa Clara wetland or Gulf of California using the existing bypass canal.

- Explore and evaluate additional beneficial uses of brackish water in the Yuma area, including further desalting at the Yuma Desalting Plant, restoration of the Salton Sea, and/or restoration of the Colorado Delta. Because selenium levels in the concentrated Colorado River water may present toxicity concerns for beneficial ecological uses, evaluate selenium toxicities for these ecologies.

- Refine the CASI cost estimates

- To share CASI construction and operating costs, evaluate potential partnerships with brackish water users in the Yuma area. Develop preliminary fee structures for delivered brackish water.

- Explore possibilities for power generation for the 2400-foot elevation drop.

- Determine if CASI return flows can be subtracted, on a full or partial basis, from CAP diversions in calculating CAP consumptive use. This would enable increased CAP diversions with the same consumptive use allotment.

b. For the alternate route to the Gulf of California with a discharge site east of Puerto Penasco,

    - Meet with the Tohono O'Odham Nation to explore obtaining a pipeline right-of-way.

    - Work with Sonora and Mexico Government agencies through the IBWC to evaluate beneficial uses for the brackish concentrate, select a discharge site, and address pipeline/canal right-of-way issues in Mexico.

    - Refine the cost estimates, including a more detailed analysis of costs with a canal for part of the route.

- Evaluate opportunities to obtain cost-sharing from end users for beneficial uses of concentrate water.
- Explore possibilities for power generation for the 2400-foot elevation drop.

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