



Water Resources Research Center • College of Agriculture and Life Sciences • The University of Arizona

Desalination in Arizona

—a growing component of the state's future water supply portfolio



Desalination, the removal of salts from water, harvests fresh water from salty water. It is not the “silver bullet” that will supply the world, or Arizona, with fresh water, but rather a potentially important component of the water portfolio. “At its simplest, the technology might substantially reduce water scarcity by making the almost inexhaustible stock of seawater and the large quantities of brackish groundwater that appear to be available into new sources of fresh water supply,” as the National Research Council stated in *Desalination: A National Perspective*. However, disposal of waste salts, energy requirements, environmental impacts, infrastructure costs and regulatory uncertainty remain challenges to water managers.

The Need for Desalination

Less than three percent of the world's water is classified as fresh, and much of that is bound within glaciers and permanent snow, leaving less than one percent available for human use. Salinity—the content of total dissolved solids (TDS) in water—is present in varying concentrations within that one percent. Surface and groundwater, especially in arid regions, are often degraded by both natural and anthropogenic causes of salinity.

Salinity in water is measured as milligrams per liter (mg/L) or, equivalently, parts per million (ppm) TDS. It is a concentration of dissolved ions such as sodium, magnesium, calcium, chloride, sulfate, and bicarbonate and carbonate. Other dissolved minerals that derive from rock and soil weathering contribute to the TDS content, usually in minor amounts. In addition, dissolved organic matter, viruses and some bacteria are included in the TDS count. Brackish waters have a TDS concentration between that of fresh water and seawater, generally 1,000–30,000 mg/L. In contrast, ocean water has a TDS of 33,000 to 37,000 mg/L. The World Health Organization has established a recommended human health standard for drinking water at 500 mg/L TDS and the Environmental Protection Agency (EPA) has set this as the non-regulatory, “Secondary MCL” (Maximum Contaminant Level) as a drinking water quality goal. The EPA has not established a regulatory Primary MCL for TDS. As a matter of practice, the Phoenix Water Department deems water with a TDS content of 1,200 mg/L unsuitable for human consumption because it may cause adverse health effects such as diarrhea. Typically, the Lower Colorado River contains 700–900 mg/L TDS, which is above the

Executive Publisher: Sharon Megdal
Authors: Susanna Eden, Tim W. Glass,
Valerie Herman
Layout: Nancy Bannister



Arroyo, a single-issue newsletter, is published by the Water Resources Research Center, College of Agriculture and Life Sciences, University of Arizona, 350 N. Campbell Ave., Tucson, Arizona 85719; phone: 520-621-2526; email: wrrc@cals.arizona.edu; web site: <http://cals.arizona.edu/azwater>

EPA's secondary MCL, but below the level at which it is considered unsuitable to drink.

The water cycle links various water bodies—rivers, aquifers, lakes, and oceans—so that one water source can influence others. Surface waters evaporate through a natural process powered by the sun. Condensation produces rain and snow, replenishing the water supply through runoff and infiltration. Drought affects surface water salinity through increased evaporation, while groundwater receives less replenishment when precipitation dwindles. Additionally, reductions in precipitation create increasing demand on other water sources. For example, without adequate rainfall homeowners watering their landscape and farmers irrigating their crops require supplemental water. Desalination is therefore an important technology to have available during times of prolonged drought to extend existing water supplies.

Arizona uses more than 7.7 million acre feet (MAF) or 2.5 trillion gallons of water annually (6.9 billion gallons per day). An acre-foot (AF) is the amount of water that would cover one acre, one foot deep, or 325,851 U.S. gallons. This is the most common measurement used in the western United States when discussing large volumes of water. The state's rivers supply around 15 percent of Arizona's water needs or about 1.2 MAF per year. In addition, Arizona is allotted 2.8 MAF of water from the Colorado River annually that supplies approximately 41 percent of Arizona's water demand. Of this, 1.5 MAF is distributed through the Central Arizona Project (CAP) and the rest is used along the river, mostly for agriculture. Use of reclaimed water (wastewater treated to water quality standards for reuse) is increasing, but still meets only 3 percent of Arizona's water demand. Groundwater fills the remaining 40–41 percent of demand.

Very little of the water Arizonans use is actually consumed outright by humans. According to the U.S. Geological Survey (USGS), the average person uses between 80–100 gallons of water each day, most for bathing or showering and toilet flushing. This estimate does not include other “municipal” uses such as landscape irrigation. Given the population of Arizona, which the 2010 census pegs at 6,595,778, one might reason that municipal users consume somewhere in the vicinity of 1,800 acre-feet, or 600 million gallons per day (MGD), or close to 0.7 MAF on an annual basis. Census Bureau projections show the Arizona population increasing by 61 percent to over 10.7 million in 2030. Because of advances in water use efficiency and conservation, water demand does not necessarily increase in lock step with population increase; however, substantial population growth will lead to significant increases in water use.


According to the Arizona Department of Water Resources, municipal water use amounts to about 20 percent of the water used by Arizonans. Agricultural use of water has been declining since 1976 in Arizona, but it continues to be the largest user, accounting for approximately 75 percent or about 5.8 MAF per year. Industry consumes approximately 5 percent of the water used in Arizona.

*Cover photo: The Yuma Desalting Plant, which when built was the largest desalination facility in North America, sat idle for more than 15 years. Now water managers are investigating the feasibility of operating the plant to increase fresh water supplies for the Colorado River's Lower Basin States.
Photo by Tim W. Glass.*



WRRC 210 Summer Intern Gets Taste of Salty Water Issues

Tim W. Glass, one of the authors of this *Arroyo*, was the 2010 Montgomery & Associates Summer Writing Intern at the WRRC. A student in Journalism, Tim brought a fresh eye to the topic of desalination; he said that if he could understand the technical aspects of the subject, anybody could. A talented writer, his first love is photography and the WRRC took advantage of his photographic skills while he was here.

The first page photo of the Yuma Desalting Plant is his. 

The first page photo of the Yuma Desalting Plant



MONTGOMERY & ASSOCIATES

Water Resource Consultants

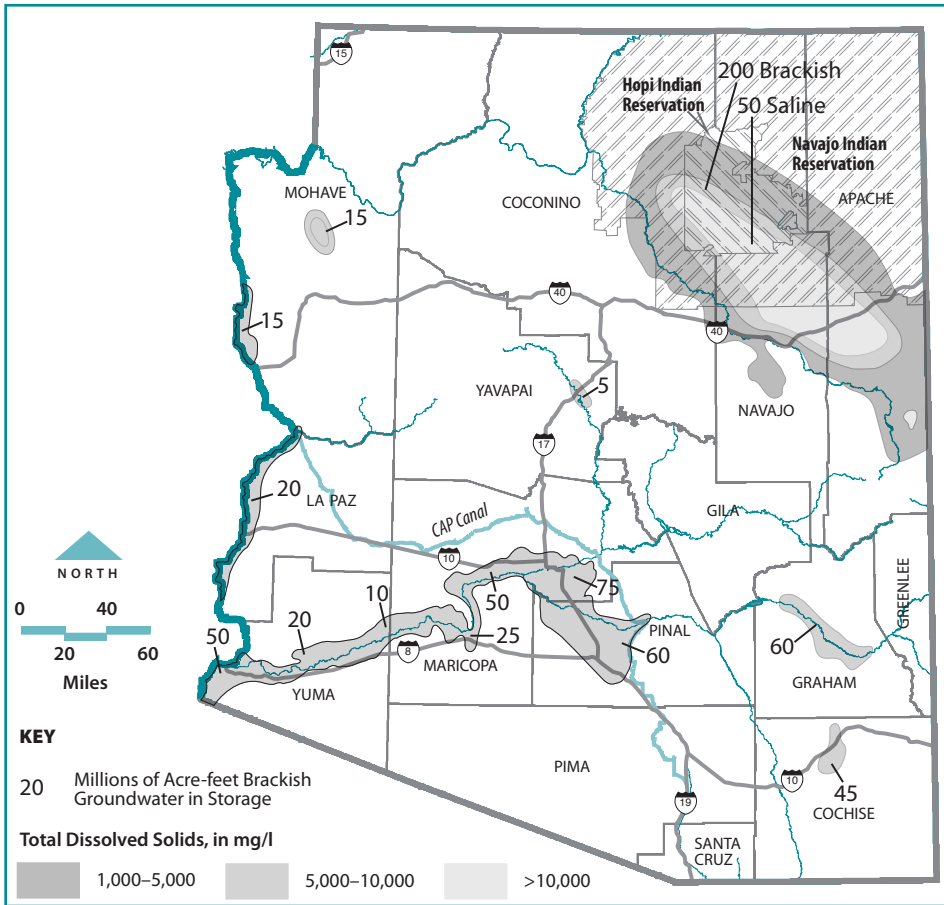
Electrical power production requires 20 to 1,000 gallons of water per megawatt hour (gal/MWh) depending on the method of generation, among other factors, with the typical coal-fired thermal plant requiring about 500 gal/MWh. Power companies have worked to reduce their use of fresh water; however, 30 percent of the water used by power plants in Arizona comes from freshwater sources.

What Water Would Be Desalinated?

Global Water Intelligence estimated in 2010 that 69 percent of active desalination plants worldwide used brackish water and river sources and 23 percent used treated wastewater (or produced ultra-pure water for industrial uses from drinking water). The remaining 8 percent of the plants treated seawater. In Arizona there are four main sources of salty water: water delivered by the Central Arizona Project (CAP), brackish surface water, brackish groundwater, and treated wastewater, all of which may require desalination in the future. Although it lacks direct access to an ocean, seawater desalination also may be in Arizona's future.

According to the website of the City of Phoenix, the Salt River contains 580 mg/L TDS and concentrations along the Gila can be several times higher than this because of agricultural return flows. In addition, Colorado River water delivered through the CAP canal to central and south central Arizona, though an essential part of the Arizona water supply portfolio, is also a major contributor to the salt load in Arizona. Although the basin states are doing a better job of preventing increases in salinity through runoff control and by retiring agricultural land, salinity is still a concern. Along with water, the CAP delivers 1.3 million tons of salt per year to Central Arizona and 250,000 to 300,000 tons per year to Southern Arizona.

Salinity can be an economic issue for all water using sectors. High salinity levels affect agricultural crop yields through salt stress, potentially destroying the plant's tissue and root system. High salinity also limits the types of crops that may be cultivated, eliminating salt-intolerant crops. Salinity poses problems for water infrastructure by decreasing the lifespan of delivery systems, industrial equipment and household appliances. The effects on most industrial users are similar to those of residential users, but costs can increase significantly for industries that must purify water to high standards, such as semiconductor fabricators. “About nine million tons of salt per year are carried by the Colorado River and cause an estimated



Source: Montgomery and Associates.

Sources of brackish groundwater in Arizona have been identified along the Colorado, Salt, and Gila rivers, associated with agricultural drainage, and elsewhere, associated with geological salt formations.

\$300 million in damage annually in Southwestern states,” according to the Bureau of Reclamation. The Central Arizona Salinity Study (CASS) Phase I found that an increase of 100 mg/L TDS equates to \$30 million of additional costs in the Phoenix Metropolitan area. These costs are an important reason researchers are continuing to explore and develop desalination technology.

Local and imported sources of water with high TDS are increasing the salinity of groundwater in some areas and also raising salinity of reclaimed water in Arizona. In 2007, participants at a workshop hosted by the Bureau of Reclamation and the Arizona Water Institute predicted that recharging aquifers with Colorado River water and reclaimed water adds salts that would increase groundwater salinity over time if salt loading problems are not addressed. On the other hand, in some areas with a heritage of many decades of agricultural land use and associated flood irrigation, recharging aquifers with reclaimed water actually reduces groundwater salinity.

Saline groundwater is a virtually untapped water resource, in part, because accurate inventories of brackish water sources are only beginning to appear. Development of this resource faces other impediments, too. Desalination facilities are optimally located near wells tapping the saline supply, but this leaves the problem of delivering the water where it is needed. As with any desalination facility, disposal of the concen-

trated waste brines is a vexing issue that must be addressed. In addition, like most groundwater, brackish groundwater resources are finite, and the economics of building expensive infrastructure with a limited expected usefulness have to be carefully weighed.

Desalination can be used to improve the quality of treated wastewater intended for reuse. The same technology that removes salts also removes residual microbial and pathogenic organisms. These capabilities provide another reason research and development of desalination technology benefits water managers seeking to extend and augment existing sources of water supply.

Finally, there is seawater, which may seem too far removed from Arizona to be a useable source of water supply. Even so, proposals are being considered for desalting plants in Mexico and California that could supply water directly to Arizona or be exchanged for other water. The consulting firm Bouchard and Associates, Inc. conducted an initial feasibility study for the U.S. Trade and Development Agency to site a desalination facility in Puerto Penasco, Mexico, to supply local demand. In parallel, the consulting firm HDR investigated the feasibility of cooperative, binational development of desalination at the same location. Partners in that study included CAP, the Salt River Project, the Arizona Department of Water Resources and their Mexican counterparts.

Brackish Groundwater Supplies in Arizona

A study by the water resources consulting firm Montgomery & Associates found that an estimated 600 million acre-feet (MAF of brackish) water is obtainable in Arizona. Brackish groundwater supplies in Arizona are typically associated with agricultural regions, but saline groundwater is also due to bedded salt in sedimentary formations in the northeastern part of the state and large salt bodies contained within sediments in some of Arizona’s desert groundwater basins. Other contributors include agricultural runoff of fertilizer and wastewater recycling (reuse of reclaimed water). Both of these activities occur extensively throughout Arizona, the Southwest and other arid regions around the world. This untapped supply may become more attractive as demand continues to strain existing water resources.

The source of high salt content in some Arizona groundwater varies, but is usually related to Arizona’s arid to semi-arid climate. Relatively low precipitation in much of the state leads to inadequate dilution of salts and increased TDS in those supplies. High evapotranspiration rates extract moisture from vegetation and soils, which concentrates the dissolved solids that are left behind. Without adequate precipitation or irrigation with high quality water to carry the


Search on for Water Softener Alternatives

Many alternatives to standard home water softeners have been proposed and built, but none has so far gained widespread acceptance. Many people object to the taste of water with dissolved salt concentration greater than about 500 mg/L, but the most common reason people use home water softeners is to remove hardness. Water with a high level of dissolved salts is likely to be hard water, although the hardness will depend on the specific water chemistry. Hardness can be caused by calcium and magnesium ions and may include ions of sulfate or chloride. For the homeowner, the main problem with hard water is its tendency to form scale in hot water heaters and other appliances that heat water, reducing their efficiency (increasing power use) and shortening

their working life. Hard water ions also react with soap to form insoluble soap scum, which does not rinse off. Stiff and scratchy towels, sheets and clothes, and potentially, irritated skin and brittle hair are the result.

Standard ion-exchange water softeners replace the hardness ions with sodium chloride (table salt) or potassium chloride (a salt substitute). Because home desalination is not an economically feasible alternative for most households, except for drinking water, other methods are needed to substitute for conventional ion-exchange water softeners.

Arizona State University researchers recently carried out a test of a few of these alternatives that had reported good results: template assisted crystallization (TAC), electrically

induced precipitation, electromagnetic technology, and capacitive deionization (CD). The tested devices use different methods to prevent scale formation on heating elements representative of the insides of hot water heaters. Of the methods tested, TAC and CD performed best with 96.4 and 83.3 percent scale reduction over the untreated water. TAC adds chemicals to the water to start the formation of tiny crystals that remain in the water rather than precipitate or form scale. In CD, hard water ions are sequestered on special sheets of paired electrodes when an electrical current is applied. Although promising, both of these technologies have disadvantages that further research will have to overcome before they are likely to be widely adopted. 

salts downward, they are drawn towards the soil surface. This is particularly problematic in agricultural, turf, and landscape irrigation contexts. Large volumes of water are used to flush salts from the root zone to protect plants, but the practice not only can adversely affect the underlying aquifer, but offset gains from otherwise good water conservation practices. Buckeye, Yuma, and the Wellton-Mohawk Irrigation District are examples of areas where high groundwater salinity has resulted largely from agricultural practices.

Water used by the industrial and municipal sectors also concentrates salinity. Industrial activities such as mining contribute by adding metals or simply concentrating naturally occurring constituents in the waste stream. The largest wastewater treatment plant in Arizona, the 91st Avenue Waste Water Treatment Plant in Phoenix, produces treated wastewater with a TDS of nearly 900 mg/L because of the initial high salt content of the Phoenix area's water supply and the added salt from water softeners and other sources. Residential ion-exchange water softeners, which replace hard water ions of calcium, magnesium and iron with soft water ions of sodium chloride, add salinity to wastewater when the brine is flushed from the system into local sewers. In 2007, participants in a workshop hosted by the Bureau of Reclamation and the Arizona Water Institute on brackish water desalination in the arid West suggested that the use of residential regenerative ion exchange water softeners be discouraged. According to Reclamation's Tom Poulson, one quarter of salts added to municipal waste streams in the Phoenix area can be attributed to the use of water softeners, commonly found in newer residential developments. Other technologies may be substituted to achieve the same benefit to households in the future.

Who Does Desalination?

Desalination plants have operated successfully in Arizona for decades. The town of Buckeye, Arizona, began operating a desalination plant to treat its municipal water in 1962. It was the first desalination plant in the United States used to produce a municipal water supply. The plant operated at 0.65 MGD capacity using electrodialysis technol-

ogy. It operated until 1988 when a replacement was constructed with updated technology. The new plant was built next to the 1962 plant and treated 0.9 MGD until it was closed as no longer uneconomical.

The communities of Buckeye, Goodyear and Scottsdale, along with Glendale, Mesa, Phoenix, Tempe, Chandler, Peoria, Surprise, Gilbert, and Tucson, partnered with others in the CASS Phase II study on brackish groundwater. The study provided salient information about 30 community RO and ED facilities desalinating brackish groundwater, as well as systems at a prison and a bottling plant.

Goodyear began operating an RO plant to treat its groundwater in 2004. According to Jerry Postema, the City's Deputy Director of Environmental Services, the plant produces 1.0–7.0 MGD of drinking water with blending, depending on the time of year. Blending the desalinated water with brackish groundwater enables the municipality to meet quality targets, provide the quantity demanded, and reduce the corrosiveness of the product water. The plant discharges brine concentrate directly to the sewer system for the Goodyear 157th Avenue Water Reclamation Facility, but the City is considering brine wetlands as a possible concentrate management solution. Currently, a wetlands research project is underway utilizing brine from this facility. The project monitors water quality for metal and nitrate reductions. The brine contains 7,000–8,000 mg/L TDS, but provides water for halophytes that can tolerate high salt concentrations. Time will tell whether the vegetation and other organisms will thrive in this environment and the wetlands improve water quality to a level safe for discharge into the Gila River.

At the other end of the Salt River Valley, Scottsdale has been operating a 20 MGD RO plant since 1999 as part of their Advanced Water Treatment Plant. Concentrate produced by the plant, with an average salinity of 15,000–20,000 mg/L TDS, is discharged via sanitary sewer to the regional 91st Avenue Wastewater Treatment Plant operated by the City of Phoenix. According to Art Nuñez, Scottsdale water treatment director, alternatives to this method of concentrate management have been considered, but no cost effective options have been found.

Yuma Desalting Plant

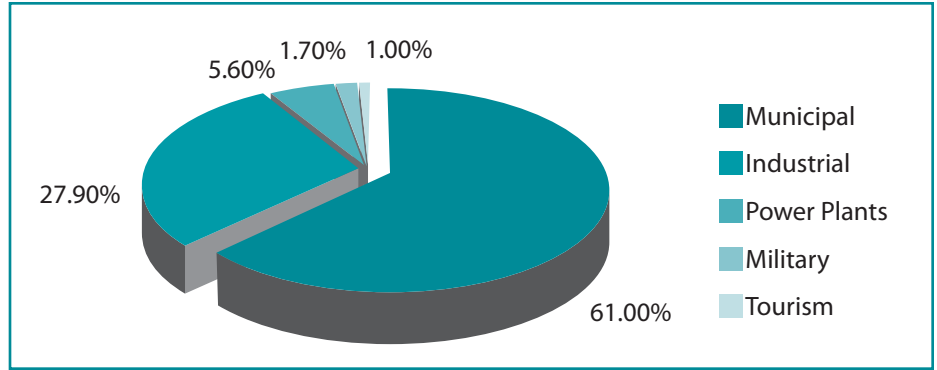
One of the largest RO plants in the United States is located here in Arizona: the Yuma Desalting Plant (YDP) operated by the Bureau of Reclamation. It was built to improve the quality of the Colorado River water flowing into Mexico as a way for the United States to comply with treaty obligations. Completed in 1992, the plant has been dormant for most of its existence because the quantity and quality of the river water flowing across the border have met the treaty requirements. The plant was originally designed to treat saline agricultural drainage water from the Wellton-Mohawk Irrigation District before it was discharged into the Colorado. Instead, the drainage water was diverted through a bypass canal that crosses the international boundary and discharges directly to the Colorado River Delta area about 50 miles south of the border in Mexico. An extended drought and rising water demand in the lower Colorado Basin states has reawakened an interest in using the Yuma Desalting Plant as a part of the solution to increasing water supplies.

In 2007 the YDP was restarted for a test run. The Bureau of Reclamation conducted a three-month test to determine how well the then 14-year-old plant would operate after being inactive for so long. Reclamation also was interested in exploring the economic feasibility of running the plant. The YDP ran at 10 percent capacity for three months. Membranes used for a short while in 1993 and new membranes stored since then were used in the test run. The system was originally designed to produce water at 150–300 mg/L TDS. The 2007 test showed that the combined used and new membranes

could produce water with an average salt concentration of 252 mg/L TDS, well within acceptable standards.

Based on these favorable results, Reclamation and a group of water providers developed a plan for a longer, higher-capacity pilot test. The year-long pilot test began in May 2010 and ran at 30 percent capacity until March 31, 2011. Reclamation reported that by December 31, 2010 they had treated 20,931 acre-feet of agricultural drainage water from the Wellton-Mohawk Irrigation District and added it to the Colorado River for delivery to Mexico.

One of the main sticking points in developing the YDP pilot test was the potential negative effect of cutting off flow to the Ciénega de Santa Clara, the wetlands in Mexico supported, not by a spring as the Spanish name “ciénega” implies, but by the discharge from the bypass canal. For this reason, monitoring by a scientific team from the University of Arizona was included as part of the agreement establishing the pilot test program. If the plant were to operate at full capacity, it would eliminate 100,000 acre-feet per year of flow to the wetlands. Environmental groups fear the diversion will have adverse impacts on the animal and plant communities that have flourished since the Wellton-Mohawk Irrigation District’s drainage water was diverted to the area. In addition to the program of monitoring by the the University of Arizona that was agreed to, environmental interests, Reclamation and its collaborators negotiated a groundbreaking agreement to provide an alternate water supply to the Ciénega in the event the YDP operates again after the pilot test.



Adapted from American Membrane Technology Association (AMTA).

Worldwide, of the 12,000 desalination plants larger than 11 billion gallons per day, by far the largest portion serve the municipal sector.



Photo: Tim W. Glass.

Surface discharge of concentrate from the YDP destined for the Ciénega de Santa Clara in Mexico.

Puerto Peñasco

Governments on both sides of the Arizona-Mexico border have been investigating the feasibility of developing a binational desalination plant in the growing resort town of Puerto Peñasco (Rocky Point), Mexico, on the upper Sea of Cortez. The 2008 feasibility study by W. L. Bouchard and Associates investigated a proposed desalination plant that would draw seawater from the Sea of Cortez and process it for Mexican use in the initial phase. Preliminary plans called for an 11.4 MGD plant to be constructed by 2011, with an increase in production to 45.6 MGD by 2020. The Phoenix Business

Continued on page 8.

How Does Desalination Work?

There are two primary ways to accomplish desalination: distillation and membrane processes. The two use different mechanisms to separate salt molecules from water molecules. Distillation uses heat to cause water to vaporize. Because the salt does not vaporize or bind to the vaporizing water molecules, the water vapor leaves the salt behind. When the vapor condenses back into liquid water, it is no longer salty. Membrane processes force the water molecules through a membrane that is more permeable to water than to salt molecules. This leaves a large volume of purified water (permeate) on one side of the membrane, and a smaller volume of briny water (concentrate) on the other side of the membrane. Which technology is used depends on the weighing of many factors, including the nature of the source water, the cost and availability of energy, environmental concerns including management of the concentrate, and financial considerations such as the trade-off between the cost of the initial infrastructure and projected operating costs.

Distillation

The process of distillation has been known at least since Aristotle observed the natural water cycle. Water is vaporized by the heat of the sun and after cooling, returns to earth as rain. Aristotle also observed the practices of mariners who boiled seawater in a brass vessel and hung large sponges from the mouth of the vessel to absorb what evaporated thus creating water for drinking.

Scientists began seriously exploring distillation to produce potable water in the late 1800's. In 1870, the first American patent was granted for solar distillation. In 1872, a Swedish engineer designed and built in Chile the first large-scale solar distillation plant. The plant operated for nearly 40 years, desalinating effluent from a saltpeter mine to produce drinking water for the miners and their families.

Thermal Distillation is the most commonly used method for commercial scale desalination around the world, although it makes up only 43 percent of the world's total desalination capacity. The basic distillation plant consists of a heat source, a chamber in which the feed water is heated, a source of cooling and a surface on which the vapor

condenses, a chamber to collect the condensate, and a means of disposing of the salt [see schematic]. Modern commercial distillation plants are considerably more sophisticated and use several different technological innovations to improve distillation efficiency.

One method for improving efficiency is to carry out the distillation in successive stages within the same plant. Because the boiling point of water decreases as the air pressure decreases, water that has been heated to boiling once can be brought back to the boiling point, without introducing more heat, when the pressure is decreased. The water can be boiled again and again as it moves from one chamber to the next, when the pressure in each successive chamber is lower than the one before. This is the principle behind the two main distillation processes in common use: *Multi-Stage Flash (MSF) Distillation* and *Multi-Effect Distillation (MED)*. MSF is the method commonly used in Saudi Arabia and other countries in the Middle East. MED is an older technology that had fallen out of favor, but improvements have brought it back with newer facilities in the Caribbean and Canary Islands. The difference between these two processes is mainly in the mechanism used for evaporation and heat transfer. A third type of distillation process, Vapor Compression Distillation (VC) also uses pressure to control the boiling point of water, but within a single stage. VC plants typically have a much smaller footprint than the other two, with a smaller output and simpler operation. They are popular desalination plants in places, such as seaside resorts, where freshwater supplies may be limited and demand is well-defined and relatively small.

The buildup of scale and corrosion are the major maintenance problems for distillation facilities. Keeping the water temperature as low as possible and using chemical additives can reduce these problems.

Membrane Processes

Membrane processes include reverse osmosis, nanofiltration, ultrafiltration, microfiltration, and electrodialysis. In 2010, there were more than 1,400 desalination plants operating in the United States with a total contracted capacity of almost 2,500 MGD;

of this capacity, 97 percent was derived from membrane processes.

Reverse Osmosis

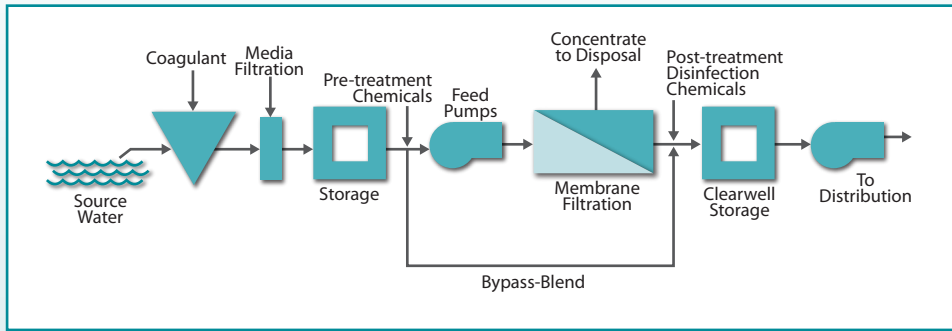
Reverse Osmosis (RO) has been used since the 1960s and is the most widely adopted technology for desalination in the United States. Osmosis is the natural process that allows a liquid, with two differing concentrations of dissolved impurities separated by a semi-permeable membrane, to pass through the membrane from the side with the higher concentration to that with the lower concentration, until the concentration of dissolved impurities is equal on both sides of the membrane. Fresh water will naturally move by osmosis through a semi-permeable membrane toward the saltier water. Reverse osmosis applies pressure to force water through a membrane in the opposite direction. Salty water is pushed toward the freshwater side of the membrane. The water molecules can move through the membrane more readily than the dissolved salts, thus leaving behind the salt molecules. Reverse osmosis membranes, can remove pesticides, viruses, and bacteria in addition to removing salts.

Depending on the feed water chemistry, pressure requirements are 50–400 pounds per square inch (psi), in order to reverse the natural osmotic effect. Energy consumption to sustain the high pressure varies with feed water quality and the system used, but generally is in the range of 3.7–8.6 MWh/acre-foot (megawatt-hours of power used per acre-foot of water produced) for seawater and 0.6–3.7 MWh/acre-foot for brackish water.

Like distillation, recovery rates for RO can be increased using multiple stages, or "trains" and by using hybrid technologies. One or more pretreatment processes always precede RO desalination. These processes can reduce scaling that clogs RO membranes, forcing pumps to work at higher pressures and reducing fresh water recovery efficiency. For this reason, much of the current research related to RO is being conducted in the area of membrane fouling.

Filtration

Nanofiltration (NF), *Ultrafiltration (UF)*, and *Microfiltration (MF)* are processes commonly employed for pretreatment in



Adapted from the American Water Works Association.

Typical reverse osmosis process treatment train.

a desalination treatment train, with the choice among them depending on source water quality, finished water requirements, infrastructure cost, and operational factors. Membrane filtration is used primarily to remove viruses and organic molecules from water and is effective in removing many odor, and color causing agents. NF also removes large-molecule salts (e.g., calcium, magnesium and sulfate). Nanofiltration membranes have pore sizes around 0.001 micrometers diameter. The pore sizes of ultrafiltration membranes are larger, in the range of 0.01 to 0.1 micrometers; while microfiltration uses membranes with still larger pore sizes, from 0.1 to 3 micrometers. Membranes can be designed for specific water chemistries. Because the filtration membranes are more permeable than that used for reverse osmosis, filtration systems operate at lower pressure than RO processes. Filtration does not remove all the materials that RO does, but its lower energy requirement makes it ideal for use upstream from an RO train to pretreat feed water. By removing constituents that would scale the RO membranes, filtration extends their useful life.

Because of the effectiveness of these filtration membranes in removing pathogens, the U.S. EPA grants disinfection credits for fecal viruses, *Giardia* and *Cryptosporidium* if they are employed in a drinking water treatment train. With these membranes operating at pressures as low as 1–30 psi, energy costs are significantly lower than RO, making them viable water treatment options if the removal of salts is not the end goal.

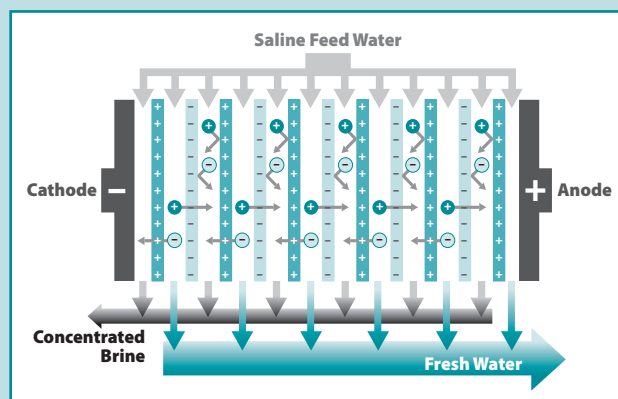
Electrodialysis

Electrodialysis (ED) also uses membranes to separate salts from feed water, but instead of pressure to push water molecules through the membranes, ED uses electrodes to pull

the salts through the membranes. Because most salts are ionic, that is, they have a positive or negative electric charge, they are attracted to electrodes with the opposite charge. An electro dialysis cell consists of a membrane that allows only negative ions to pass through and a parallel membrane that allows only positive ions through. These membranes are called “ion-selective” membranes. Salts in the feed water moving along the outside of each membrane are pulled by the electrodes into the stream of brine moving between the two membranes. Several hundred pairs of these cells are stacked in the typical ED plant. Energy demand for ED is comparable to RO, approximately 0.6 MWh/acre-foot for water with salt concentrations up to 3,500 mg/L TDS, but it is more energy intensive than RO when the salinity is higher.

Membrane Distillation

Membrane Distillation is a process that combines distillation and membrane separation. This desalination approach uses a membrane that will allow water vapor to pass through but not liquid water. A higher vapor pressure is created on one side of the membrane usually by warming the water. The water



Schematic by Nancy Bannister.

Process of electro dialysis.

vapor is driven from the side of the membrane with a high vapor pressure to the side with a low vapor pressure. MD needs only a small temperature differential to operate and thus can utilize the waste heat from industrial and power generation processes. However, it has not been widely used because of the relatively low price of energy and is probably best suited for use in small-scale applications where low-grade thermal energy is available.

Other Technologies

Forward Osmosis (FO) relies on the natural osmotic process to move water across a permeable membrane. In FO, water molecules from the feed water move through the membrane toward a “draw solution” with a higher solute concentration than the feed water. Fresh water that accumulates in the draw solution then must be separated from the draw solution itself. The key to FO, and its principal research challenge, is choosing a draw solution that can be easily separated from the water and recycled for reuse. No commercial FO project has been developed to date, but the process holds promise because of its extremely low power requirements, less than 0.3 MWh/acre-foot.

Freezing is another process that separates solids from the water, in this case by allowing pure water ice crystals to form. Solids are washed from the ice crystals and collected in a brine solution. Desalination by freezing offers advantages over distillation in terms of energy used, because feed water is always closer to freezing temperature than to boiling, and because scaling is not a problem. Commercial approaches to freezing have not yet been found. The challenge of this method is how to wash the solids from the crystals without re-dissolving the salts.

In *Dewvaporation* a film of saline water passes near a heat exchanger and the water evaporates. The humidified air passes along the condensing side of the heat exchange surface and the condensate is collected. The condensation releases heat, which is passed through the heat transfer surface to the evaporation side. This process requires very large surface areas and thus is suited only to specialized applications. 🏗️

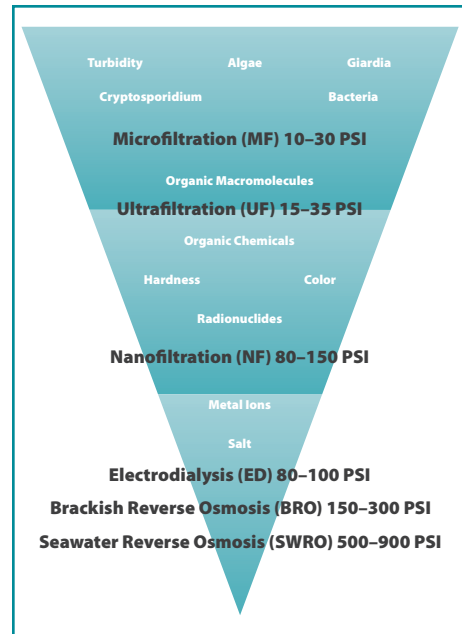
Journal quoted Bouchard as saying, “If [the plant is] not in construction in the next two to three years, I suspect they’re going to have a water crisis that’s pretty severe.” Sources of investment for the estimated cost of \$120 million are local, State and Federal governments. Initially the project received priority support from the Mexican government; however, political uncertainty in the region has raised questions about the ability of the government to successfully maintain the plant as a priority. Local residents and developers are hopeful, but the projected first-phase completion date of February 2011 was not met.

The planned final capacity of this plant would exceed the local Mexican water demand. This would leave excess water that could be transported to southern Arizona or exchanged. The parallel study by the consulting firm HDR included estimation of the costs associated with a pipeline to carry product water to Imperial Dam on the Colorado River near Yuma. New construction in California would connect it to the Imperial Dam forebay, assuming the project received permits from California. Arizona could then take additional water from the Colorado River via the CAP or other infrastructure. Talks continue among the interested parties, but any actions appear far off.

Desalination Challenges and Potential Solutions

Efficiency Losses

Each approach to desalination has specific challenges, generally related to scaling or fouling of operating parts and the resulting reduction in efficiency. Fouling is caused by organic constituents in the feed water, while scaling is caused by inorganic constituents. Because RO technology has been favored in the United States for desalination, research has focused on ways to reduce membrane fouling and thereby increase efficiency. Feed water pretreatment and coupling of RO systems to ion exchange processes or nanofiltration are some of the ways researchers are attempting to reduce RO membrane fouling. Other approaches include membrane improvements and mechanical or chemical ways to inhibit scaling. For example, a team at the University of California, Los Angeles, has reported on developing a membrane that resists clogging and can be tailored to specific water sources. The new membrane uses chemical chains that move constantly in the feed water, brushing away solids that would foul the membrane surface. Researchers from the University of Arizona and elsewhere are demonstrating potential efficiency improvements using a vibratory shear-enhanced process (VSEP®), which vibrates the membrane, thus agitating the surface boundary layer and preventing particles from attaching to the membrane. Fouling can be addressed by other pretreatment technologies



Adapted from American Membrane Technology Association (AMTA).

Membrane separation processes depend on pressure to force water through membranes that exclude salts and other undesirable constituents in the feed water. The less permeable the membrane, the more constituents are excluded and the more pressure is needed.

that reduce the organic load in feed water, such as biologic filtration. These also have been receiving research attention.

Challenges facing thermal distillation methods include reducing energy costs and preventing scaling. Scaling problems also can be addressed through feed water pretreatment, as well as by operating at lower temperatures and pressures. Capturing and reusing heat is another approach that is the subject of research to improve thermal efficiency. Most new plants use some form of heat capture and reuse, but more efficiency gains are possible.

Brine or ‘Concentrate’ Management

Brine management continues to be the single largest challenge facing engineers, regardless of how desalination is approached. According to the journal *Desalination*, there simply are no cost-effective solutions to concentrate management for inland desalination plants. Nationally, the most common method of concentrate management has been discharge into surface waters. Sewer discharge is the next most common method, followed by deep well injection. Evaporation, reuse and land discharge together are employed for only about 15 percent of the concentrate produced nationally.

Not surprisingly, in landlocked Arizona, concentrate management also is the main challenge facing desalination. Experts have estimated that by the year 2020, desalination facilities in the greater Phoenix area will produce 7.8 MGD of brine that will require management. Also not surprisingly, all of the brine management approaches mentioned above present significant limitations. Evaporation ponds have been Arizona’s disposal method of choice for decades, but the cost of this method increases significantly as the volume of brine and cost of land increases. However, improved methods of brine management are being explored.

Brine may be disposed of through deep injection wells. These wells are regulated by EPA as “ClassV” injection wells and must be sufficiently isolated from fresh water aquifers that the concentrate will not contaminate potable groundwater. The Kay Bailey Hutchinson Desalination Facility in El Paso, TX pumps their concentrate 22 miles to injection wells drilled thousands of feet deep in dolomite rock. In Arizona, there are limited sites suitable for deep well injection. All aquifers in Arizona are designated by default as drinking water aquifers, so a permit for deep well injection would require a demonstration that the isolated aquifer contained only water unsuitable for drinking. On the Colorado Plateau and in the Phoenix basin, there are large deposits of salt that may be appropriate for deep well injection because aquifers associated with them are already high in TDS. In general, locating deep well injection near Phoenix is unlikely because of the lack of suitable locations, although the

Phase II Concentrate Management section of the CASS identified a potential site: the Luke Salt Body seventeen miles northwest of Phoenix, with 15–30 cubic miles of halite (NaCl). Morton Salt Company mines salt there, leaving behind caverns that Amerigas uses to compress and store natural gas. These caverns provide the right conditions for regulatory approval and thus could be used for storage of brine concentrate; however, toxic ions in the concentrate, such as selenium, might compromise future production of salt from the salt body, at least for human consumption.

Brine minimization is a necessary consideration. Brine from an RO desalination process may be further treated using secondary RO, electrodialysis, and/or thermal concentration to minimize the volume of waste brine and thus reduce the cost and environmental impact of disposal. Carried to maximum effect, this results in zero liquid discharge or ZLD.

Research is ongoing to capture useful salts and precious metals from the brine. The brine may be manipulated to precipitate or crystallize out valuable compounds such as calcium carbonate, used in concrete production, and calcium sulfate, used in gypsum wallboard production. Slurry or dried salts may be sold to manufacture these products. The term zero discharge desalination (ZDD) has been used to differentiate this process, which results in salable salts, from ZLD. The cost effectiveness of ZDD depends on location, other market factors, and further advancements in separation technologies.



Photo: Valerie Herman.

Reverse Osmosis Membrane Stacks tower over visitors to the Kay Bailey Hutchison Desalination Facility in El Paso, Texas.

If industrial markets will not support the use of recovered chemicals, the dry material must be disposed of in lined landfills in a more ZLD-like scenario.

Another possible solution to the issue of briny waste from desalination is to discharge it into wetlands and riparian areas. Where

The National Brackish Groundwater Desalination Facility


The Bureau of Reclamation's National Brackish Groundwater Desalination Facility in Alamogordo, New Mexico, is available for use by universities, companies, and other entities interested in studying a range of technologies. The forty-acre facility is supplied by brackish water for research purposes from four on-site wells. Brine concentrate from the tests can be sent to three evaporation ponds, the agricultural research area, or to the city sewer system.

The facility has been open for only three years and has not yet been utilized to its maximum potential. Projects planned for the facility include a study of Zero Discharge Desalination (ZDD), a process designed to significantly reduce the amount of concentrate requiring management, at the same time producing valuable minerals, and an electrodialysis (ED) system that operates using stacks of ion selective membranes to reduce the electricity requirement for separating product water from concentrate. Good research opportunities also exist in renewable energy operations and agriculture. Ala-

mogordo will soon begin building a municipal desalination plant directly across from the facility, utilizing effective and efficient technologies arising out of research performed at the facility.

The four on-site water supply wells, which tap two separate aquifers, are a unique part of the facility and contribute to its exceptional research capacity. Well #1 yields 120 gallons per minute from a depth of 1,400 feet below the surface. This is the least saline supply, producing water with a TDS content of about 1,200 mg/L. Thirty feet away, Well #2 produces 80 gallons per minute from 200 feet below the surface, with a TDS content of nearly 6,400 mg/L. Well #3 and 4 produce a range of TDS levels between 3,000 and 4,000 mg/L at the same rate and depth as Well #2. During a research project, the water is pumped into three tanks which can accommodate any order for a specific TDS level by mixing and manipulating these or other supplies. A chemical injection room can further alter the chemistry of the feed water, which can be distributed to six research bays, three inte-

rior and three exterior. The facility can prepare the agricultural site for application of concentrate on salt tolerant plant species, although this will require the construction of a drainage system to maintain the water quality of underlying aquifers.

The Expeditionary Unit Water Purification (EUWP), also housed at the facility, can be mobilized to respond to water shortages in emergencies. Developed in partnership with the Bureau of Reclamation, the Office of Naval Research, National Science Foundation, the Environmental Protection Agency, and others, the EUWP is transportable by aircraft and can be online producing potable water from practically any source within two hours. It was used to desalinate seawater for potable use following Hurricane Katrina. With the ability to produce 100,000 gallons per day, the EUWP produced 1.3 million gallons of potable water for the Biloxi Regional Medical Center, the only hospital in operation serving the residents of Biloxi immediately after Katrina. 

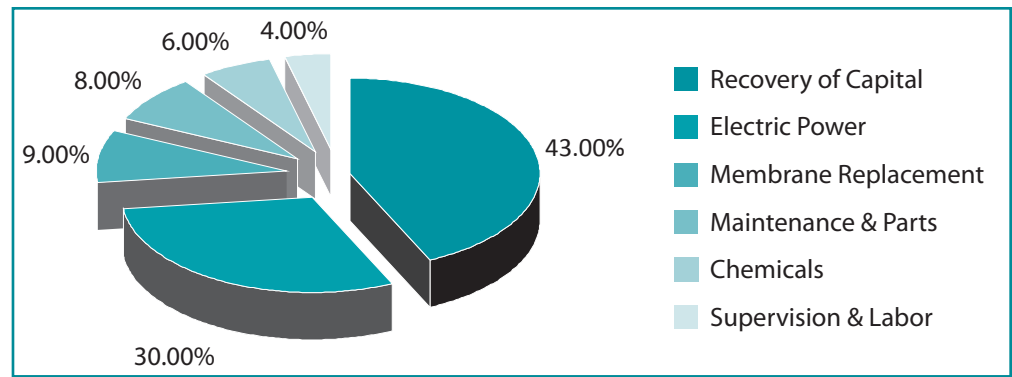
appropriate, these wetlands can provide a lower cost brine management solution for communities and potentially revitalize struggling ecosystems. If designed correctly, natural microbial processes and phytostabilization can reduce metals and nitrates to an acceptable level for surface water quality permitting. Concern exists because of the potential for salinity to build up over time, allowing salts to reach concentrations that are toxic to plant and animal life, unless the wetlands are flushed intermittently. Care must be taken, however, to avoid concentration spikes during flushing that would be detrimental to downstream ecosystems.

In the Tucson area, an appraisal of the economic feasibility of performing RO at the Hayden Udall Water Treatment Facility considered the possibility of releasing the concentrate into a canal. Canal options were considered that included transport of the concentrate from Tucson to the Gulf of California, discharging east of Puerto Peñasco. An alternative was a regional canal to carry concentrate from the Tucson and Phoenix areas, as well as areas in between, to the Bureau of Reclamation's Yuma Desalting Plant. Ideally, construction of such a canal would provide a permanent, long-term solution to concerns about brine disposal in areas where most Arizonans reside. Beyond considerations of cost, however, shipping out the brine also results in the loss of up to 15 percent of the original water supply.

Options studied for brine transport by canal included surface release to enrich the Santa Clara wetlands or the Salton Sea and reuse by agriculture or aquaculture. Since the Salton Sea's salinity is approaching 40,000 mg/L, transport of brine to that inland water would easily accommodate flows of brine with a salt concentration in the range of 4,000–8,000 mg/L. An influx of this water would temporarily dilute that inland water body and refresh the struggling ecosystem in that area, but it would also add to the salt load and ultimately increase its salinity through evaporation.

Regulatory Issues

Utilities planning to construct and operate a desalination plant must first obtain permits from the State and often from local county or municipal government agencies. Concentrate discharged into streams is regulated under the Clean Water Act through a National Pollution Discharge Elimination System (NPDES) permit (administered by the Arizona Department of Environmental Quality in Arizona and called an Arizona Pollutant Discharge Elimination System or AZPDES permit). Nationally, discharges generally are not permitted to raise the salinity of the receiving stream by more than 10 percent. Injected concentrate must comply with the Safe Drinking Water Act's Underground Injection Control (UIC) program administered by EPA. In Arizona a plant with any discharge that could affect aquifers would require an Aquifer Protection Permit (APP). The Arizona Department of Environmental Quality



Adapted from AMTA.

A typical cost breakdown of capital repayment and operating costs for desalinated water shows electric power as a larger percentage of operating costs than all the other categories combined; however, this breakdown does not include waste disposal.

(ADEQ), which issues APPs, historically has not looked favorably on deep well injection for concentrate disposal, but is now willing to review applications.

In addition, the utility is responsible for ensuring compliance with the Resource Conservation and Recovery Act (RCRA) if it is determined that there may be hazardous byproducts within the concentrate stream. The Solid Waste Disposal Act applies to zero discharge plants that dispose of dry salts from the brine. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Hazardous Materials Transportation Act, and the Toxic Substances Control Act may be applicable, depending on the specific site and the concentrate management options available. If the source water is wastewater, a Reclaimed Water Reuse Permit will have to be obtained from ADEQ if the treated water is intended for reuse or an Aquifer Protection Permit if the treated water is intended for aquifer recharge. If the product water will be used for drinking, the utility will have to comply with the Safe Drinking Water Act as well.

Groundwater management laws may also place requirements and restrictions on the development of desalination capacity. Outside of an Active Management Area (AMA), groundwater may be pumped (and treated) if it is put to reasonable use, after filing a Notice of Intent to Drill with the Arizona Department of Water Resources. Within an AMA, the permit requirements of the groundwater management code are stricter. However, development of brackish groundwater may be more likely inside of AMAs, despite the more stringent regulations on groundwater extraction, because water demand is greater there. Developing brackish groundwater within AMAs will depend mainly on the costs and availability of other water supplies in comparison with desalination.

Desalination Costs

Building a desalination facility is a major undertaking that requires huge capital inputs and years of planning and construction before ribbon-cutting. The source of the water, distribution system needs, concentrate discharge options, and an electrical supply are important considerations when selecting a plant location and design. Identifying the desired end use for the product water is necessary as well. A fundamental question to ask is what is the target quality of the output given the quality of the input water?

	May	June	July	Aug	Total
Consumption					
Ammonia (tons)	12.1	11.0	12.1	11.6	46.8
Antiscalant (tons)	11.9	5.3	5.7	6.1	29.0
Chlorine (tons)	22.0	39.7	31.9	39.5	133.1
Ferric Sulfate (tons)	85.7	97.0	105.0	110.0	397.7
Lime (tons)	1,253.0	1,100.3	1,149.0	1,241.0	4,743.3
Sodium Bisulfite (tons)	19.5	15.4	15.4	19.6	69.9
Sulfuric Acid (tons)	206.0	175.8	182.0	208.0	771.8

Source: Bureau of Reclamation.

Two main cost categories are associated with a desalination system: capital, and operation and maintenance (O&M). As with any large infrastructure projects, capital investment paid back with interest is one of the largest expenses of a desalination project. Capital expenses are further divided into construction and incidentals. Construction includes equipment, pipelines, facilities, and other physical aspects of the site design. The design of a project is different for every water source to be desalinated, but some general assumptions can be made. These include the need for conveyance infrastructure from the supply to the plant, from the plant to the distribution system for delivery to customers, and for concentrate disposal. Incidentals may include, but are not limited to, permits, environmental impact statements, engineering, administration, and legal costs, as well as financial services.

Operation and maintenance costs are the ongoing expenses incurred at the plant. This can be separated into subcategories of fixed and variable costs. Fixed costs include labor and expected membrane replacement. Variable costs are related to the volume of water desalted at the site, including energy, chemicals, and concentrate disposal. Energy and disposal, along with capital repayment, are the three main expenditures of most desalination facilities.

Membranes are the central physical element of reverse osmosis. Although they are actually one of the lower costs associated with a desalination facility, according to a sensitivity analysis performed by the National Research Council, they account for approximately three to five percent of operating costs. Membrane components are becoming less expensive as the number of desalination plants being planned and constructed is increasing. Moreover, membrane lifespans can be extended with proper storage, pretreatment, and operating pressure protocols. Membranes currently have a useful life of approximately five years depending on conditions of use.

If deep well injection is used for concentrate disposal, the permitting costs and the infrastructure needed to move brine from desalting plants to the injection location add significantly to costs. Each injection well typically costs between \$2 million and \$4 million and at least two are required per site to avoid operation disruptions when maintenance is required. If the hydrogeological conditions are appropriate for this method, these wells are usually drilled 3,000 feet deep or more in order to isolate the concentrate from any overlying drinking water aquifers. Furthermore, limited well life spans are the norm because the receiving aquifer can only accept a finite amount of concentrate.

Chemicals and associated costs depend on feed water constituents as well as the volume and required water quality of the finished

water. The Yuma Desalting Plant pilot test illustrates the variety of chemicals and magnitude of expenditures needed for successful production of desalinated water. The monthly weights of treatment chemicals consumed, shown at left, were relatively stable throughout the beginning phases of the pilot program. By December 2010, chemical costs had reached over \$2.5 million. The pilot test ran at 30 percent capacity, so chemical use and costs will be correspondingly higher to run at higher capacities.

Energy Use

Energy requirements for desalination are large. Reliance upon fossil fuel powered plants creates additional disincentives to build desalting plants. A San Diego study found that for producing the same amount of product water, brackish water desalination uses four times the energy of pumping groundwater and twice the energy of importing Colorado River water. On the other hand, renewable energy does have a place in powering desalting operations. For example, a 38 MGD desalting plant in Perth, Australia, powered by the Emu Downs Wind Farm, uses only one third of the 80 megawatts per day output of the wind farm to operate. For small scale systems, solar photovoltaic panels and wind power have proven effective, presenting opportunities that would benefit rural areas not located on the power grid. Co-location with a nuclear or coal-fired power plant is also an option to reduce desalination energy costs if waste heat from the plant can be captured for the desalination.

Reverse osmosis, the most commonly used desalination technology in Arizona to date, is less energy intensive than thermal distillation techniques and more appropriate for brackish water and reclaimed water. At the Yuma Desalting Plant, 13,678 MWh of electricity produced 12,171 acre feet of water from May 3 through August 31, 2010. The power cost for this site averaged \$35.30 per MWh, resulting in a water production cost of \$31.41 per acre foot. This electricity cost is about half that of the \$70 per MWh estimated by the National Research Council.

Looking Forward

Desalination of salty or reclaimed water supplies for augmentation of potable supplies represents significant investment that should be made only if we as a society are comfortable with how we are using our existing supplies. Developing and delivering new sources of water using membrane or distillation processes will cost an order of magnitude more than the cost of existing resources. In Arizona, there is room to move toward water use behaviors, utility infrastructure and built environments that enable more efficient use of water. It seems likely that a “new norm” of water use behavior will develop before water providers and their rate-payers are willing to pay ten times more than they are for existing water supplies. In some locales, however, it will make economic sense to desalinate available saltwater resources and put them to use because the alternative is securing remote sources and paying to import them.

When it makes economic sense to develop desalination capacity in Arizona, several challenges will have to be met. Securing desal-



Water Resources Research Center
College of Agriculture and Life Sciences
The University of Arizona
350 N. Campbell Ave.
Tucson, AZ 85721

Address Service Requested

NON-PROFIT ORG.
US POSTAGE
PAID
TUCSON, ARIZONA
PERMIT NO.190



ination project funding, streamlining the permitting process, and finding acceptable brine disposal strategies are three major hurdles for Arizona. Funding for water projects is limited in economic downturns; however, private investments and public-private partnerships may help to attract support for future desalination facilities. Building a dialog among researchers, engineers, and municipalities will ensure that the latest, most appropriate technology is

implemented for new projects. In addition, regulators and the public can gain increased confidence that the technical challenges are being met when they are involved in the dialog. Public support and legislative support such as was enjoyed by the Kay Bailey Hutchison facility, named for the Texas Senator, ensures that desalination remains a viable option for providing potable water supplies for the future. 🏡

Thanks to UA Water Sustainability Program

The UA Water Sustainability Program provided funding for the printing and mailing of this *Arroyo*. We are grateful for WSP support.

