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Inland Desalination: Challenges and Research Needs

Patrick V. Brady, Richard J. Kottenstette, Thomas M. Mayer, Mike M. Hightower

Sandia National Laboratories

Drought and population growth have both contributed to water scarcity in many inland areas of the United States, especially the Southwest. This has focused attention on inland desalination of subsurface brackish waters and wastewaters. Inland desalination will differ from seawater desalination because the byproduct brine (concentrate) produced during reverse osmosis treatment cannot be disposed of in the ocean. Moreover, inland brackish waters and wastewaters differ in composition from seawater, the former being dominated by calcium, carbonate and sulfate rather than sodium and chloride. Concentrate management for inland desalination will have to address basic salinity and sustainability issues, while smaller plant size and water pumping costs may lead to increased expenses for inland desalination plants.

Background

The demand for freshwater in many regions of the world has outstripped supply. More than 50 percent of countries in the world will likely face water stress or water shortages by 2025, and by 2050, as much as 75 percent of the world's population could face water scarcity (United Nations, 2003). Despite limited supplies, economic growth in the Southwest U.S. has increased the demand for water, which has led to unsustainable water management practices including ground water mining, subsidence, and reductions in surface and ground water quality and availability.

In the United States, the economic future of the arid Southwest will demand some combination of water conservation, recycling, and the creation of "new water." One source of "new water" is desalinated brackish surface and ground water. As shown in Figure 1, much of the United States, and particularly the Southwest, contains extensive brackish ground water resources. Because it underlies more easily-accessible and higher-quality fresh water resources, it has remained largely untapped. However, as fresh water supplies become more limited, desalination of these brackish water resources has become more common.

Desalination research and development efforts have greatly improved desalination performance and costs. By the late 1990s, there were more than 12,500 desalination plants in operation in the world, which generated more than six billion gallons of fresh water per day and accounted for approximately 1 percent of the world's daily production of drinking water. In the next 20 years, over $20 billion will be spent to develop new desalination facilities worldwide, which will double the volume of freshwater being generated through desalination (Martin-Lagardette, 2001). Many of the newer systems are being used inland for both brackish water desalination and water reuse. By 2002, about 500 desalination systems were in operation in about forty states in the U.S.

Desalination Trends and Needs in the Southwest

Desalination in the Southwest and other inland areas takes many forms including:

- **Enhancing domestic water supplies.** Many southwestern water districts are evaluating brackish groundwater desalination to supplement the limited freshwater supplies and to provide water for industrial and municipal use.

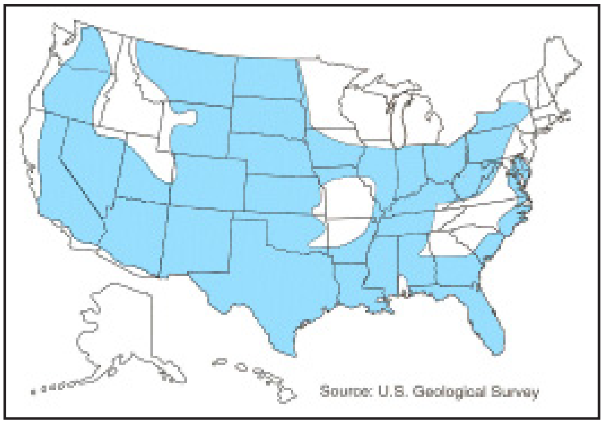

Figure 1. General Location of Saline Ground Water Resources in the United States (Krieger et al., 1957)

- **Fossil energy production.** Large volumes of saline or brackish water are commonly co-produced in oil and gas production (roughly ten times as much water is produced as oil in many fields). Oil companies in New Mexico (NM), Colorado (CO), and Texas (TX) are evaluating the treatment and desalination of oil and gas produced water for supplementing river flows during drought, rehabilitating rangeland, and cooling water for power plants.
- **Treatment of impaired surface water.** Many of the river systems in the Southwest suffer from salt buildup caused by surface runoff, irrigation practices, urban uses, and evaporation. Desalination of these impaired rivers will become increasingly important to meet more stringent water quality standards for domestic and ecological-based total maximum daily load (TMDL) requirements.
- **Industrial and domestic water pretreatment and reuse.** As water conservation and reuse become increasingly more important, desalination-based water and wastewater treatment technologies could meet water quality standards for water reuse.

Cities such as El Paso, Las Vegas, Phoenix, and Tucson are all considering desalination plant options to supplement or improve water supplies in their area, while cities such as Scottsdale, AZ, and Ft. Stockton, TX are currently operating desalination facilities. A mid-sized city like Alamogordo, NM, which has a population around 30,000, is planning to construct an approximately 10 million gallon per day desalination plant to supplement its fresh surface and groundwater resources. This reflects the fact that desalination of locally available brackish water in many water-poor regions of the U.S. is becoming cost competitive with transporting fresh water from greater distances.

To lower the overall cost of desalination, significant investment in research and development of new desalination technologies must be implemented in the coming decades. The Desalination and Water Purification Technology Roadmap developed by the U.S. Bureau of Reclamation and Sandia National Laboratories is currently being updated to help identify future desalination research objectives and goals for the U.S. between 2008 and 2020 (U.S. Bureau of Reclamation 2003). In addition, the Tularosa Basin National Desalination Research Facility has recently been constructed outside of Alamogordo, NM (Sandia National Laboratories 2002). Its purpose is to pilot test new and promising inland desalination technologies. In the discussion below, we highlight a few of the research efforts for inland desalination that are presently being conducted at Sandia in line with the Roadmap.

Inland Desalination Concerns

There are at least three major concerns for inland desalination. These include variable and site-specific water composition, concentrate disposal (since it is impossible to put saline concentrate into a large reservoir like the ocean), and inefficient economies of scale (since most inland plants will not be as large as their seawater counterparts).

Chemical Composition

The chemical composition of inland brackish waters set sharp constraints on the level and cost of water recovery. They also point to where technological advances are needed. Table 1 compares the compositions of several brackish inland waters to seawater. It should be noted that most inland salt waters are enriched in calcium and depleted in sodium relative to seawater (Powder River Basin coal bed methane water is an exception and will be described later). Silica levels are often higher in inland waters. Bicarbonate levels are broadly similar reflecting equilibrium with dissolved carbon dioxide and possibly calcium carbonate salts. Unlike seawater, the dominant anion in inland waters tends to be sulfate as opposed to chloride.

Table 1. Compositions of Seawater and Inland Brackish Sources – (mg/L)

Composition	Seawater Reference	Groundwater Tularosa Basin, NM	Groundwater Las Vegas, NV	Groundwater Hueco Bolson, TX	Wastewater Plant Stream Rio Rancho, NM
Na	10800	114	755	116	150
K	390	2	72	7	25
Ca	410	420	576	136	36
Mg	1300	163	296	33	51
Cl	19400	170	954	202	142
NO_3	NR	10	31	NR	79
PO_4	NR	0	NR	NR	20
SO_4	2710	1370	2290	294	110
HCO_3	143	270	210	190	110
SiO_2	2.1	22	77	31	32
TDS	**35300**	**2630**	**5270**	**1200**	**640**
Composition	**Groundwater Brighton, CO**	**Colorado River Yuma, AZ**	**Agricultural Drain Yuma, AZ**	**Coal Bed Methane Water Powder River, WY**	**Oil & Gas Prod. Water Eddy Co., NM**
Na	127	121	609	300	3430
K	4	5	8	8.4	NR
Ca	112	80	157	32	600
Mg	26	30	70	16	171
Cl	100	109	596	13	4460
NO_3	15	0.3	3.8	NR	NR
PO_4	NR	< 0.25	< 1.0	NR	NR
SO_4	210	276	828	2.4	2660
HCO_3	310	179	392	950*	488
SiO_2	NR	9.1	14.8	11	NR
TDS	**880**	**730**	**2630**	**850**	**11900**

*Alkalinity reported on this sample (primarily HCO_3^-), NR = Not Reported

Each water source has been considered for treatment to drinking water quality. The brackish groundwater from Tularosa, NM is a Ca-SO_4 type water whose chemistry reflects interaction with subsurface gypsum deposits. Las Vegas, NV brackish groundwater is a Na-SO_4 type water that formed through interaction with gypsum and Ca-rich clays – in parallel with evaporative concentration. Waters in the Hueco Bolson of Texas are a dilute version of the Tularosa Basin, NM waters. In Yuma, AZ, the water of the Colorado River and an agricultural drain contain concentrated water high in Na, Cl and SO_4. Produced waters from oil and gas operations also possess a wide range of compositions. Typically, there is organic carbon and sulfur – sulfide or sulfate depending upon the oxidation state of the fluid. Some coal bed methane waters are so dilute as to be potable – the only hazard being their high Na/Ca ratio which leads to soil deterioration that reduces use for irrigation. Wastewater has been subjected to direct use by humans and can potentially contain pharmaceutically active compounds – in addition to bacterial and viral contaminants, and the simple salts (especially nitrate) that are concentrated through general use of water.

Concentrate Disposal

The preferred method of desalination for all new installations is reverse osmosis (RO), a membrane process that extracts fresh water from salty water, thus leaving a more concentrated waste stream, or concentrate. A critical question for inland desalination is: "What to do with the concentrate?" Currently, concentrate from inland RO plants is discharged to surface water, sewers, deep wells, land application, and/or evaporation ponds/salt processing. With the exception of deep well injection, each disposal path increases the salt load of surface soils and waters, thus decreasing the ambient or down-stream value of each through decreased soil fertility and/or decreased water quality. Evaporation ponds often require large land areas and are only appropriate in arid climates with low land values. Expensive liners are required to prevent salt seepage contamination of adjacent waters. Sewer disposal sends the salt accumulation problem downstream. Deep well injection is not allowed in many states, but those states that allow it require permits, monitoring wells, and completions in deep, contained aquifers to ensure that freshwater supplies are not contaminated. Typically, the state regulations that are applied to injection of relatively inert desalination residuals were originally designed to cover the disposal of more hazardous oilfield or industrial wastes.

Research at the University of Texas-El Paso (UTEP), Sandia National Laboratories, and the Texas Bureau of Economic Geology have considered manipulating the sequence by which evaporation occurs in evaporation ponds to selectively precipitate out low permeability minerals that might "self seal" ponds. Minerals that have been considered include calcite and sepiolite – a magnesium silicate clay mineral. A self-sealing, self-healing evaporation pond, if sufficiently impermeable, might not require a liner and may be much cheaper than at present.

The City of El Paso, Los Alamos National Laboratories, and Sandia are examining the geochemical reactions that occur when RO brines are injected into deep subsurface formations so that sustainable deep well injection practice might be assured. Critical unknowns being investigated include the subsurface stability and transport of Ca-complexing anti-scalants and the compatibility of the injected brine with the underground aquifer fluids.

An emerging technology for concentrate minimization is based on zero liquid discharge (ZLD). University of South Carolina and Sandia are working on a combined reverse osmosis-electrodialysis treatment to recover saleable salts from RO concentrate, which produces a solid product. Other ZLD approaches use multiple effect evaporation, crystallizers and enhanced evaporation machinery to reduce concentrate volume (Bostjancic 1996).

Economies of Scale

Many coastal desalination plants treat large volumes of water, often 50 million gallons per day or greater, at relatively low costs by co-locating them with coastal power plants to take advantage of common intake and outfall structures and less expensive power. These strategies enable coastal facilities, such as the Tampa Bay Desalination Facility, to maintain desalination costs as low as $2.50 per 1000 gallons of water produced. Similar facilities in inland areas may cost twice as much to operate because of smaller plant sizes, higher concentrate disposal costs, higher well-water pumping costs, and higher energy costs (U.S. Bureau of Reclamation 2002).

Desalination efficiency is also an obstacle in inland areas. Today, desalination systems have recovery efficiencies of 60 to 85 percent for brackish water desalination. Although most inland RO input streams contain relatively high levels of calcium, bicarbonate and sulfate, the upper limit of RO extraction is often defined by precipitate scaling of the membranes by silica. Many inland waters contain 20-30 mg/L dissolved silica. Recovery efficiencies like that cited above concentrate the silica to above 120 mg/L whereupon silica scales form, preventing further water extraction (anti-scalants are effective for calcium carbonate and sulfate salts, but not for silica). The current recovery limit means that roughly a fifth of the brackish resource is not used and instead must be disposed of. Much higher recovery efficiencies could be attained by developing new ways to quickly and effectively lower silica from 100 mg/L to 20-30 mg/L. This would halve concentrate disposal volumes, extend the supply of brackish resources, and potentially reduce overall desalination costs. Sandia and various university partners are researching cost-effective treatment technologies to reduce silica scaling by desaturating RO interstage streams.

Future Prospects

The development of fundamentally new approaches to desalination to supplant the established desalination technologies in the coming decades is unlikely. This is a factor of both the basic thermodynamics of desalination, as well as the significant advances made in desalination technology over the last 50 years (Miller 2003). In order to minimize concentrate volume, energy consumption, and the overall costs of desalinated water, significant improvements in current technologies will have to take place. Fortunately, there is the potential for significant improvements in membrane technologies, as well as advances in engineering designs and construction materials that can bring other desalination technologies within the reach of current needs.

Thermal Desalination

Thermal phase change methods (primarily distillation processes) will always be limited by the high heat of vaporization of water. Heat recovery and recycling engineering has been advanced to a very high degree, and it is likely that advances in this area will be incremental. Low temperature thermal processes that can efficiently use low grade solar, geothermal, or industrial waste heat sources have the most potential for adoption. However, such processes are currently capital intensive, and may with RO for widespread application. Small capacity distributed systems using cheap, reliable, low cost materials will likely find widespread application in remote areas and other situations where cheap land and low grade energy are abundant, but access to an installed infrastructure is lacking.

Membrane Processes

Reverse osmosis and to a lesser degree, electrodialysis are likely to remain the dominant desalination technologies for the foreseeable future. This is primarily a reflection of the progress that has been made in membrane materials and in reducing the required energy expenditure. Any competing technology will have to do significantly better in order to as the preferred water treatment option. There is the potential for improvements of the efficiency of membrane processes through novel nanostructured materials that take advantage of unique thermodynamics and transport properties of water in confined spaces. Projects currently underway at Sandia are exploring membrane structures with nm-scale channels engineered to selectively pass water or salt ions with greatly increased efficiency. Synthetic structures that mimic the function of biological systems in transporting water across cell walls have the potential to increase RO membrane efficiency by more than an order of magnitude. To take full advantage of the promise of these super-efficient membranes, we will need to develop better methods of preventing membrane fouling, as well as better designs for membrane modules that efficiently transport water to the membrane surface, and waste salts away from it.

Hybrid Systems

Hybrid systems that take advantage of the complementary efficiencies of different desalination processes may also provide a significant improvement in water recovery, energy use, and concentrate minimization. We mentioned the example of a hybrid RO-electrodialysis system above. Other approaches employ low temperature distillation processes driven by waste heat sources to reduce the volume of RO concentrate and increase fresh water recovery.

Water Reuse

Finally, wastewater recovery and reuse represents the most sustainable, efficient, and in many cases, the lowest cost alternative for making limited resources go further. This is true since the wastewater has a low inherent salinity and has a low osmotic pressure to overcome in RO operations. Currently, a pilot plant is being operated by Montgomery Watson Harza for Sandia in Rio Rancho, New Mexico to look into membrane bioreactor primary treatment of wastewater followed by reverse osmosis polishing. These technologies for removing organic and biological contamination, as well as dissolved salts, will allow for the substantial recycling of water and will reduce strain on our limited resources in the face of increasing demand.

Conclusion

Water scarcity and population growth will be important factors that will drive the U.S. towards increased water conservation and the increased use of desalination. The most readily available source of water for desalination is the appropriate and safe use of recycled or "reuse" water. Other sources of brackish waters suitable for desalination are found throughout the inland part of the country. Desalination of these sources will require new efforts to lower the costs of desalination by reducing the energy required for purification, as well as finding a cost-effective and environmentally acceptable way of treating the concentrated salt byproduct.

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Author Bio and Contact Information

Patrick Brady is a Distinguished Member of the Technical staff in the Geochemistry Department at Sandia National Laboratories. He is currently the Program Manager for the Sandia desalination program. He has responsibility for the Desalination and Water Purification Roadmap implementation as well as the long range R&D and Jumpstart efforts at Sandia. His research interests are natural attenuation of soil contaminants, mineral surface chemistry, geochemical kinetics, arsenic removal and water treatment. He is also an Adjunct Professor of Environmental Engineering at New Mexico Institute of Mining and Technology. Patrick holds M.S. and Ph. D. degrees from Northwestern University. Patrick V. Brady, Sandia National Laboratories, PO Box 5800, MS 0754, Albuquerque, NM 87185. (505) 844-7146. pvbrady@sandia.gov.

Richard Kottenstette is a technical staff member in the Geochemistry Department at Sandia National Laboratories. He is an analytical chemist with over 25 years experience in fossil fuel, environmental and homeland security research. His current position is project leader for the Sandia desalination - Jumpstart Project. This new effort, aimed at selecting and developing emerging desalination technologies, will work closely with the Tularosa Basin National Desalination Research Facility in Alamogordo New Mexico. Richard J. Kottenstette, Sandia National Laboratories, PO Box 5800, MS 0754, Albuquerque, NM 87185. (505) 845-3270. rkotten@sandia.gov.

Thomas M. Mayer is a technical staff member in the Geochemistry Department at Sandia National Laboratories, and is responsible for initiating and managing long range R&D programs in water treatment technologies, including desalination and arsenic remediation. In this role, he has started a number of research programs at Sandia and collaborating universities and companies on advanced membrane materials, biofilm characterization and control, and modeling of advanced membrane modules. Prior to this effort, he has 25 years R&D experience in materials and process development for microelectronics, micro-electro-mechanical systems, and nanostructure fabrication. He holds a Ph.D. in chemistry from Pennsylvania State University. Thomas M. Mayer, Sandia National Laboratories, PO Box 5800, MS 0754, Albuquerque, NM 87185. (505) 844-0770. tmmayer@sandia.gov.

Michael M. Hightower is a Distinguished Member of the Technical staff in the Energy Security Center at Sandia National Laboratories. He is a civil and environmental engineer with more than 25 years experience with research and development projects including security and protection of critical infrastructures. Currently, Mike supports research and development projects addressing water and energy resource sustainability, and water and energy infrastructure security and protection. These efforts include developing new water treatment and water monitoring technologies, developing models and techniques to improve water resource use and management, desalination and produced water treatment, impact of water availability on energy security and reliability, and water, electric power, and natural gas infrastructure security and protection. Mike holds a B.S and M.S. in civil engineering from New Mexico State University. Mike Hightower, PO Box 5800, MS 0755, Albuquerque, NM 87185. (505) 844-5499. mmhight@sandia.gov.

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