Development of a Knowledge Base on Desalination Concentrate and Salt Management

Revised Draft Final Report

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ACRONYMS

AMTA	American Membrane Technology Association
ASR	aquifer storage recovery
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
AZ	Arizona
BC	brine concentrator
BOD	biological oxygen demand
BWRO	brackish water reverse osmosis
CA	California
CF	concentration factor
CFD	computational fluid dynamics
CHIWAWA	Consortium for High Technology and Investment in Water and Wastewater
CM	concentrate management
CO	Colorado
CO_2e	carbon dioxide equivalent
CWA	Clean Water Act
DO	dissolved oxygen
DWI	deep well injection
ED	electrodialysis
EDR	electrodialysis reversal
EPOC	emerging pollutants of concern
ERD	energy recovery device
FDEP	Florida Department of Environmental Protection
FDER	Florida Department of Environmental Regulation
FL	Florida
FO	forward osmosis
ft	feet
g/L	gram per liter
GHG	greenhouse gases
GWI	Global Water Intelligence
HR	high recovery
KS	Kansas
LA	land application
LC50	50 percent lethal concentration
MD	membrane distillation
MED	multi-effect desalination
MF	microfiltration
mgd	million gallons per day
mg/L	milligram per liter
MSF	multi-stage flash
MT	million tons
NCED	National Center of Excellence for Desalination
NF	nanofiltration
NOEC	no observable effect concentration
NORM	naturally occurring radioactive material
NPDES	National Pollutant Discharge Elimination System

NRC	National Resource Council
NSF	National Sanitation Foundation
NWRI	National Water Research Institute
O&M	operating and maintenance
OSW	Office of Saline Water
OWRT	Office or Water Research and Technology
PAC	project advisory committee
PDFB	percent difference from balance
POTW	publically owned treatment works
ppt	part per thousand
PVC	poly vinyl chloride
R	recovery
RFP	request for proposal
RO	reverse osmosis
SAR	sodium adsorption ratio
SARI	Santa Ana River Interceptor
SJRWMD	Saint Johns River Water Management District
SOC	synthetic organic compounds
SWRO	seawater reverse osmosis
U.S.	United States
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
TMDL	total maximum daily loads
TOC	total organic carbon
TSD	Technical Support Document
TSS	total suspended solids
TX	Texas
UF	ultrafiltration
UIC	Underground Injection Control
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USDW	underground source of drinking water
USEPA	U.S. Environmental Protection Agency
WAIV	wind aided intensive evaporation
WET	whole effluent toxicity
WLA	waste load allocation
WQ	water quality
WRF	Water Research Foundation
WRRF	WateReuse Research Foundation
WTP	water treatment plant
WWTP	wastewater treatment plant
ZID	zone of initial dilution
ZLD	zero liquid discharge

FORWARD

ACKNOWLEDGEMENTS

This project was funded by the WateReuse Research Foundation in conjunction with the U.S. Bureau of Reclamation and the California Department of Water Resources.

The project had two subcontractors, CH2M HILL, Inc. and Geo-Processors Pty. Limited. The author thanks the co-PI, Jim Jordahl of CH2M HILL, for helpful consideration and review of many ideas, thoughts, and early drafted sections throughout the course of the project, and for extensive review of the draft report. Dr. Jordahl was also responsible for writing Chapter 16 on Beneficial Use of Concentrate and for organizing and executing the workshop held at the July 2009 American Membrane Technology Association (AMTA) Conference and Exposition in Austin, TX. The author also thanks CH2M HILL and Geo-Processors for providing background material for the report. Geo-Processors' help in addressing issues and practices of non-municipal desalination and salt recovery were particularly helpful.

Over 150 utilities provided in-kind participation in the project in the form of taking part in the municipal membrane desalination plant survey. Several utilities also committed in-kind support at the time of the project proposal. These included:
- Eastern Municipal Water District (CA)
- City of Abilene (KS)
- City of Chandler (AZ)
- PUB Singapore
- Sweetwater Authority (CA)
- Tampa Bay Water (FL)
- Metro Water District - Tucson (AZ)
- City of Vero Beach (FL)
- City of Goodyear (AZ)
- El Paso Water Utilities (TX)
- City of Chesapeake (VA)
- Collier County Water Sewer District (FL)
- City of Marco Island (FL)
- City of Palm Coast (FL)
- Sarasota County Utilities (FL)
- City of Scottsdale (AZ)
- West Basin Municipal Water District (CA)

The Project Advisory Committee (listed below) was helpful in reviewing progress reports and the draft final report and offering constructive suggestions. Finally, the author thanks the WateReuse Research Foundation Project Manager, Julie Minton, for continuous helpful understanding and guidance.

Project Advisory Committee
- Samer Adham (Conoco Phillips)
- John Balliew (El Paso Water Utilities)
- Andy Hui (Metropolitan Water District of Southern California)
- Scott Irvine (Bureau of Reclamation)
- Robert McConnell (Tampa Bay Water)

NATIONAL ACADEMY OF SCIENCES
NATIONAL ACADEMY OF ENGINEERING
INSTITUTE OF MEDICINE
NATIONAL RESEARCH COUNCIL

REPORT IN BRIEF

Management and Effects of Coal Bed Methane Produced Water in the Western United States

The extraction of methane (natural gas) trapped deep in some coal beds is a common practice, especially in Western States, but carries with it the issue of what to do with the water that must be pumped out to release the methane. This water must be managed through some combination of disposal, use, or storage, and often requires treatment to manage salts and other compounds. Currently, the majority of the water is disposed of at least cost, rather than being put to beneficial uses such as for irrigation or drinking water for livestock. This study investigates the critical environmental, economic, and regulatory issues associated with coal bed methane produced water, and finds that current management decisions are made within a complex regulatory framework that fails to fully consider opportunities for beneficial use.

Methane, an increasingly important energy source, is trapped in some coal beds by water, and sometimes can only be easily extracted by pumping the water to the surface (see Figure 1). Operations to extract methane from coal beds have expanded in the western United States during the past several decades, and in 2008 supplied nearly 10 percent of the total U.S. natural gas production, while producing some 42 billion gallons of water in five western states.

Deciding what to do with the water produced from coal bed methane operations, known as produced water, is a challenging task. The water varies greatly in both quality and quantity, depending on the geology of the coal basin from which it is extracted, and sometimes requires treatment before disposal or use. A complex regulatory framework underlies the management of produced water, with some states' laws considering the water a waste product of methane extraction, and others considering it a beneficial byproduct of the extraction process.

At present, the management of coal bed methane produced water is driven by consideration of the costs and complex regulations associated with treating and disposing of produced water, rather than by consideration of potential beneficial uses. Furthermore, there is no national consensus or national regulatory framework on management goals, objectives, or policies for coal bed methane produced water. At the request of Congress, the National Research Council convened a committee of experts to review critical

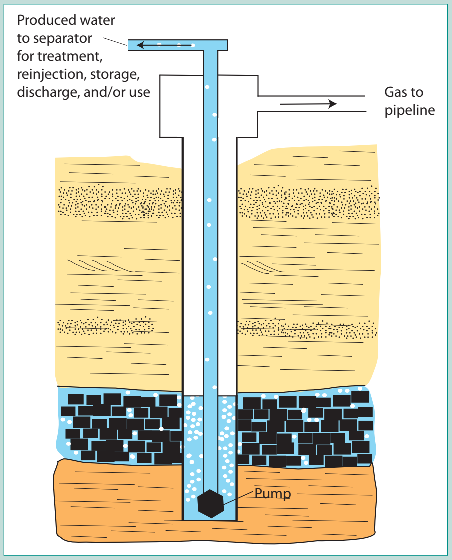


Figure 1. Illustration of a coal bed methane well. The black brick-like pattern represents a coal deposit lying between two shale or sandstone deposits. The blue shading represents water that is present in and around the coal deposit. Methane gas (white dots and white shading) is trapped on surfaces in the coal. A submersible pump near the bottom of the well-bore cavity pumps water from the coal deposit to reduce pressure enough to allow methane to flow freely up the well bore.

Source: Adapted from Rice and Nuccio, 2000.

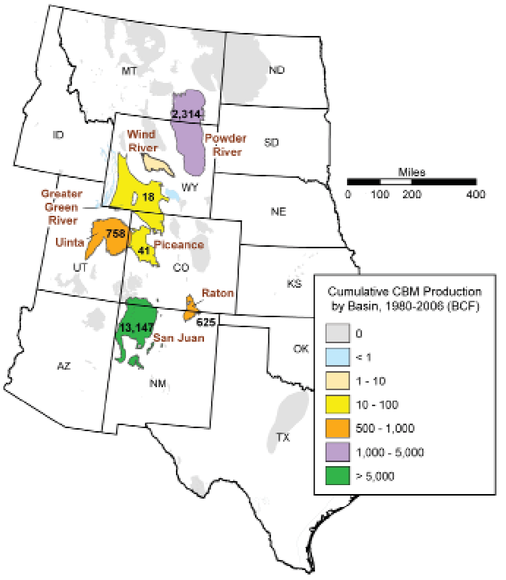


Figure 2. Map of western coal bed methane basins within the six states that are considered in this report.

Source: Adapted from EIA (2007).

environmental, economic, and regulatory issues associated with extracting and managing coal bed methane produced water in the western states of Colorado, Montana, New Mexico, Utah, North Dakota, and Wyoming (see Figure 2).

The Challenge of Coal Bed Methane Produced Water

Produced water from coal beds contains varying amounts of salts and, in some cases, metals, depending on the geology and hydrology of the coal beds and surrounding rocks. Both the quality of the produced water and the amount of water that must be removed to allow methane extraction influence the way in which produced water is managed. For example, the fairly shallow coal beds in the Powder River Basin of Wyoming and Montana yield large amounts of low-salt content water that can be treated to meet state regulations before being released into local rivers and streams for disposal, or put to beneficial uses such as irrigation (see Box 1). Some produced water from the Powder River Basin meets water quality standards for disposal or certain uses without any treatment at all. In contrast, the more deeply buried methane-containing coal beds of New Mexico, Utah, and Colorado yield smaller volumes of generally very saline water. Because it would be expensive to treat such relatively small quantities of this water to meet state regulations for surface disposal or use, and because suitable geologic formations are readily available, produced water extracted from coal bed wells outside of the Powder River Basin is usually reinjected deep into the ground for permanent disposal. Factors such as:

- availability of infrastructure,
- cost of treatment and transport of produced water,
- quality and quantity of produced water,
- age of the water in the coal bed and its connections to other groundwater (see Box 2), and
- states' legal consideration of produced water

mean that in certain areas it is easier to dispose of the water at least cost than to pursue beneficial uses, which may also require treatment.

Environmental Impacts

The short-term environmental effects of the extraction of water from coal beds and its eventual disposal, storage, or use are well-documented, localized, and relatively benign, based on environmental monitoring data that are currently available. However, because coal bed methane production is a relatively young industry, further monitoring and analysis of groundwater, surface water, soil, and ecological systems are needed to fully understand the potential for long-term environmental impacts.

To assess potential long-term, pervasive, or regional environmental problems associated with water extracted from coal beds, this report suggests a range of technologies and research approaches, to provide a scientific basis for and increase the consistency and sophistication of management of coal bed produced water, including:

- the use of better geochemical fingerprinting tools to estimate the age of produced water and to understand the existence and persistence of produced water in surface and groundwater systems (see Box 2);
- increasing the frequency of monitoring before and after production starts to better understand the potential impacts of coal bed methane produced water extraction and management on groundwater, surface water, soil, and ecological systems;
- research on the connections or links between coal bed waters and other groundwater aquifers—underground layers of water-bearing rock—and surface water;
- analysis of the effects of extracting nonrenewable "fossil" water from coal beds; and
- studies to evaluate the effects of produced water in indigenous aquatic biological species in the field.

Box 1. The Options for Coal Bed Methane Produced Water

Many options exist for the disposal, storage or beneficial use of coal bed produced water. The options employed vary among coal bed basins, among states sharing the same basin, and within basins in the same state (see Figure 3). A summary of these options includes:

Disposal by Reinjection—Produced water can be reinjected deep underground. This option is often used for the relatively small volumes of very saline water produced from coal bed basins in New Mexico (Raton and San Juan Basins), Colorado (San Juan and Piceance basins), and Utah (Uinta Basin), and generally requires no treatment.

Direct Disposal to Waterways—This management option often (but not always) involves treating water to meet federal and state water quality standards before discharge to streams and rivers. This option is the primary management approach used for produced water in the Colorado portion of the Raton Basin and is also used in the Powder River Basin.

Storage—Produced water can be stored in constructed ponds or impoundments. These structures include ponds specially designed to allow the water to evaporate, shallow pits that allow the water to seep into the ground beneath the impoundment, and ponds lined with impermeable materials to prevent leakage into groundwater. This option is the primary approach used in the Wyoming portion of the Powder River Basin.

Potential Use—Produced water could be put to various uses, including irrigation, drinking water for livestock, industrial applications, wetlands habitat enhancement, groundwater recharge or municipal or domestic purposes. Treatment may be necessary, depending upon initial water quality, to meet different regulatory standards. Currently, beneficial use applications are only employed for a small proportion of the total volume of coal bed produced water in the West.

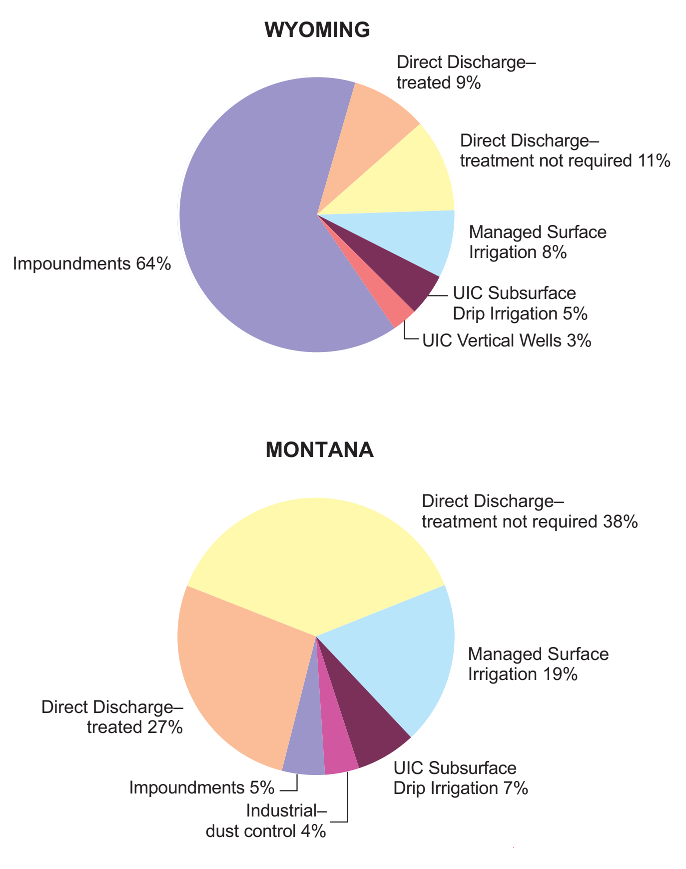


Figure 3. These charts illustrate variations in options for the disposal, storage, and use of coal bed methane produced water in Wyoming and Montana.

Source: Adapted from D. Fischer, Presentation to the committee, Denver, CO., March 30, 2009; A. Bobst, Montana Bureau of Mines and Geology, Personal communication, December 21, 2009; T. Reid, Montana Department of Environmental Quality, Personal communication, December 30, 2009; and J. Zupancic, BeneTerra, Inc., Personal communication, December 28, 2009.

Box 2. Fossil Water

Studies from the San Juan Basin that used geochemical techniques to "date" coal bed water indicated that the water is thousands to tens of millions years old. These findings suggest that old or "fossil" water in coal beds accumulates slowly, and once removed may not be replenished for many millions to tens of millions of years, making the water essentially a "nonrenewable" resource. However, scientists don't yet know if all coal beds store water of ancient origins—and more data are needed to determine the age of produced water from other coal bed basins.

Determining the age of coal bed water and its "renewability" can help in understanding the connections or linkages among coal bed waters, other groundwater aquifers, and surface water. Understanding these connections, in turn, is critical to understanding the consequences of the removal of coal bed waters for local groundwater and surface water systems and how produced water can be appropriately managed.

Regulatory Framework

Regulations for leasing and permitting coal bed methane operations on public lands are authorized through the Bureau of Land Management, and those for the protection of surface and groundwater resources are authorized by the U.S. Environmental Protection Agency. Although these federal agencies work in concert with state and tribal authorities to enforce national standards and regulations, the Environmental Protection Agency has delegated responsibility for many permitting and regulatory functions to a number of state agencies and tribes. As a result, many states and tribes oversee the management of produced water in their jurisdiction and have established, through appropriate legal processes, differing standards for the quality of produced water discharged to streams and rivers or used for irrigation or agriculture. In addition, differing state definitions of coal bed methane produced water as either a waste product or as a beneficial byproduct of methane extraction have contributed to differing state approaches to management of the produced water.

Conclusion

At present, the management of coal bed methane produced water is driven by the costs of water management and regulations regarding the treatment and disposal of produced water, rather than by consideration of the potential beneficial uses of this resource. Continued research and monitoring to resolve gaps in knowledge of the chemistry and age of the water extracted from coal beds and effects of the water on the environment would permit development of more effective coal bed methane produced water management practices. More effective practices will help to ensure the stewardship of water resources, particularly in the arid West.

Figure 4. Ponds storing coal bed methane produced water in Wyoming. The green parcels are fields irrigated with coal bed methane produced water.

Source: J.W. Bauder

Committee on Management and Effects of Coal Bed Methane Development and Produced Water in the Western United States: William Fisher, (*Chair*), University of Texas, Austin; **James W. Bauder**, Montana State University; **William H. Clements,** Colorado State University; **Inez Hua,** Purdue University; **Ann S. Maest,** Stratus Consulting, Boulder, Colorado; **Arthur W. Ray,** Wiley Environmental Strategies, Columbia, Maryland; **W.C. "Rusty" Riese,** BP America, Inc.; **Donald J. Siegel,** Syracuse University; **Geoffrey Thyne,** University of Wyoming, Laramie; **Elizabeth A. Eide** (*Study Director*), **National Research Council.**

The National Academies appointed the above committee of experts to address the specific task requested by Congress. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

EXPERT CONSENSUS REPORT

For more information, contact the Board on Earth Sciences and Resources at (202) 334-2744 or visit http://nationalacademies.org/besr. Copies of *Management and Effects of Coal Bed Methane Produced Water in the Western United States* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.

Realising the Potential for CSG Water Injection to Aquifers in the Surat and SOUTHERN Bowen Basins

[1]Andrew Moser, [2]Kathryn Harris

[1]Klohn Crippen Berger Ltd, Australia (seconded to Origin Energy), [2]Origin Energy, Australia

Introduction

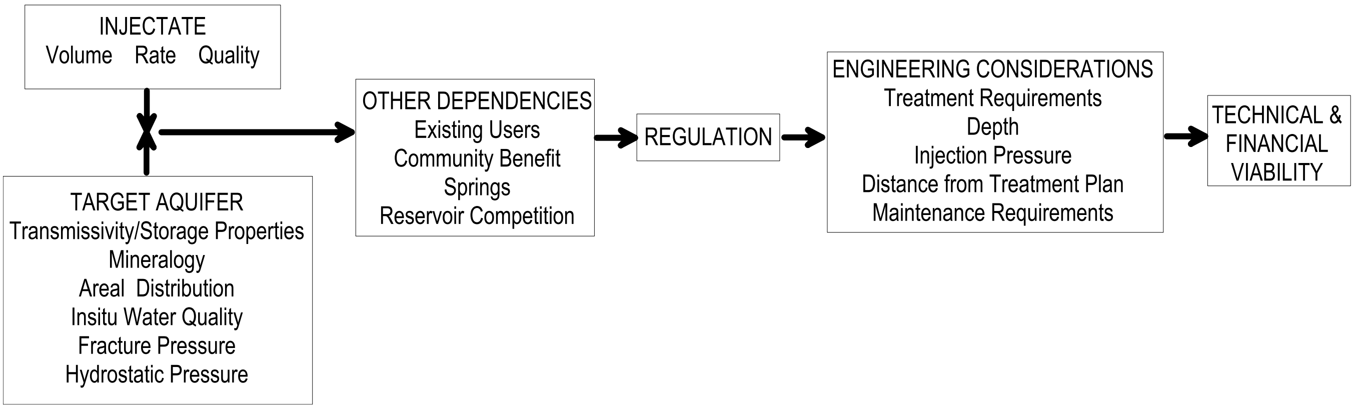
Coal seam gas (CSG) extraction requires the depressurisation of the host coals, with the subsequent production of associated water. In Queensland's Surat and southern Bowen Basins, the coals are hosted within generally low permeability strata, but form part of the Great Artesian Basin (GAB) sequences which include some extensive aquifers and aquitards.

To maximise the value and management options for CSG associated water, operators are generally proposing to treat the majority of produced water by reverse osmosis (RO). Greater than 90% of RO output is very fresh water (permeate), with the remainder being highly concentrated brine. Management options for the permeate include provision of supply for aquaculture, mineral processing, dust suppression, industrial and manufacturing, irrigation and livestock water, or surface water (watercourse) augmentation. However, the State Government has communicated a preference for injection of associated water or treated associated water streams to aquifers in a manner which will maintain or improve insitu groundwater quality.

Assessment of the potential of aquifer injection as a large-scale management option for CSG associated water is in an intensive but early stage, and must be progressed rapidly if injection is to meet industry development timelines. The following describes the hydrogeological, regulatory and engineering constraints within which solutions are being progressed.

Injection Assessment Framework

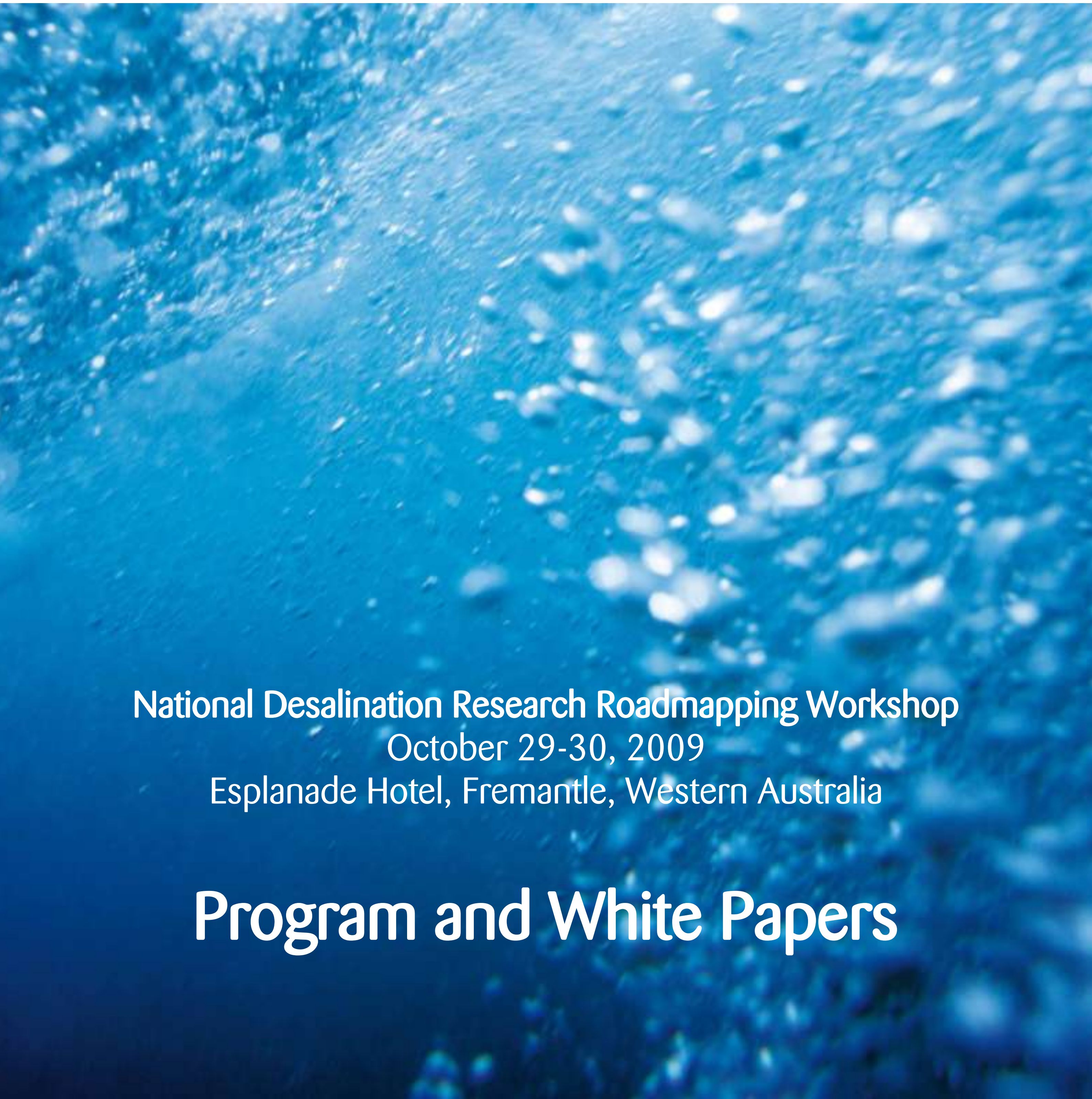
Data requirements for the assessment of aquifer injection are reasonably well understood. Investigation logically begins with the identification of aquifers with appropriate storage and transmission characteristics in the area of interest, then progresses to evaluation of the mineralogical and hydrochemical compatibility of the injectate and insitu groundwater quality and mineralogy. While treatment can overcome some compatibility issues, the history of injection indicates that appropriate consideration up-front is essential for the long-term viability of a scheme.



There are several other dependencies which need to be considered in the Surat and southern Bowen basins. Landowners tend to target shallow aquifers while larger users (power stations, feedlots etc) prefer higher reliability Hutton and Precipice Sandstone supplies. Certain groundwater resources are significantly depleted in some regions due to historical use, while southern areas are marginally artesian. Potential impacts or benefits to existing users are therefore a significant consideration. The possibility of springs impacts must be also be considered, as injection to highly confined aquifers can influence pressure heads at significant distances from the injection point. The Surat basin is also host to less frequently encountered reservoir competition such as injection by adjacent tenure holders, proposed geosequestration, and historical conventional oil and gas production, all of which impose potential constraints.

Over the past year, the Queensland government has engaged with industry in a period of intensive legislative development to meet the challenges of potential CSG groundwater management issues. While the primary management instrument for injection will be a project's Environmental Authority, the policies and guidelines applying to assessment, construction and operation of injection facilities have remained at the (advanced) draft stage while amendments to legislation have been developed. These amendments have been developed to include injection schemes in regulations applying to the augmentation of urban water supplies with ‘recycled water’. Until the controlling legislation is enacted and subordinate policies and guidelines are finalised (and probably for some time after while the new regulations are ‘field tested’), investment in injection assessment retains some degree of risk and uncertainty. Irrespective of the passage of these regulations, the implications of the policies-of-the-day must be considered in the feasibility of any injection project.

National Centre of
Excellence in Desalination



National Desalination Research Roadmapping Workshop
October 29-30, 2009
Esplanade Hotel, Fremantle, Western Australia

Program and White Papers

Australian Government

Department of the Environment,
Water, Heritage and the Arts

Murdoch
UNIVERSITY

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Workshop Information

Program

Speakers and program subject to change

Thursday October 29, The Orion Room, Esplanade Hotel, Fremantle

8:30	**Opening remarks:** Setting the vision and framework Prof. David Doepel, Interim CEO, NCED
8:45	**What's a roadmap and why do you need one?** Lessons from the US Dr Thomas E. Hinkebein, former Desalination Research Roadmap Program Manager, Sandia National Laboratories
9:30	**Summary presentation and forum:** Australian water needs Mr Joe Flynn, CEO, Water Industry Alliance
10:00	**Break for morning tea**
10:30	**White paper presentation and forum:** What's so special about water? Prof. Richard Pashley, Founding Chief Investigator, NCED
11:00	**White paper presentation and forum:** Reducing the carbon footprint: It's more than just the energy A/Prof. Greg Leslie, Deputy Director, UNESCO Centre for Membrane Science and Technology, UNSW
11:30	**White paper presentation and forum:** Directly using renewable energy for large-scale desalination Mr Kenneth Moore, Regional Technology Leader – Desalination, CH2M HILL
12:00	**White paper presentation and forum:** Inland desalination brine management Dr Aharon Arakel, President and Chief Technologist, Geo-Processors
12:30	**Lunch address:** Desalination technology – what's hot, what's not Mr David Furukawa, former President and Director of the International Desalination Association
2:00	**Technology forecasting:** Rolling up our sleeves Mr Tom Hinkebein, former Desalination Research Roadmap Program Manager, Sandia National Laboratories
2:30	**Improvement opportunities workshop** Facilitated by industry leaders, this session will workshop improvement opportunities, strategies, and benefits for six areas: pretreatment, membrane based desalting, non-membrane based desalting, brine management, social and environmental challenges, and research infrastructure needs
5:00	**Session concludes**
5:30	**Sundowner**, Mussel Bar, 42 Mews Road, Fishing Boat Harbour (3 min walk south)

Friday October 30, The Orion Room, Esplanade Hotel, Fremantle

8:30	**Summary**: Identified improvement opportunities Industry leader facilitators
10:10	**Break for morning tea**
10:40	**Voting for improvement opportunities:** Putting your money where your mouth is Prof. David Doepel, Interim CEO, NCED
11:20	**Wrap up:** What have we learned? Prof. David Doepel, Interim CEO, NCED
11:45	**Session concludes**

Speakers

David Doepel is the Interim CEO of the National Centre of Excellence in Desalination and the Director of the Institute for Resource Technology at Murdoch University. In his role on behalf of the Centre, Mr Doepel is leading the establishment phase including the development of the National Desalination Research Roadmap. Previously, he served as a Principal Policy Adviser to the Hon. Alan Carpenter, Premier of Western Australia. Prior to that engagement he was the Regional Director for the Americas, based in Los Angeles, for the Western Australian Trade and Investment Office. In that role he was responsible for the WA Government's strategic marketing efforts on behalf of industry in the Americas. In both positions Mr Doepel was a powerful advocate for Western Australian technology, creativity and innovation. Mr Doepel holds degrees from Murdoch University, the Melbourne College of Divinity and Boston University.

Thomas E. Hinkebein received his Ph.D. in Chemical Engineering from the University of Washington, Seattle in 1976 followed by a distinguished thirty-year career at Sandia National Laboratories. During his last 10 years at Sandia, Dr Hinkebein was the Water Treatment Lead for the Advanced Water Treatment program at Sandia and became manager of the Geochemistry Department where he oversaw all water treatment activities at Sandia. He also managed several lab directed research and development programs which explored novel concepts in desalination. Additionally, Dr Hinkebein was responsible for coordinating the development of a technology roadmap for future research in desalination technology. This National Roadmap was developed in conjunction with the Bureau of Reclamation for all regions in the US. Dr Hinkebein also contributed to the Energy and Water Nexus Roadmapping effort. The roadmapping concepts developed at Sandia have gained international acceptance and have been applied in North Africa, the Arab States, and Israel and now Australia. Since retiring from Sandia Laboratories, Dr Hinkebein formed a consulting company, Hinkebein and Associates. His company specializes in underground storage of materials in salt, and in desalination roadmapping. Dr Hinkebein is the author of over 100 technical papers.

Joe Flynn has an international infrastructure background at the Managing Director and GM level having led water and electricity utilities, and run companies for some of Australia's largest infrastructure service businesses including Leighton and Tenix. He has chaired government-industry economic development initiatives and is currently the CEO of the Water Industry Alliance, over 240 companies who collectively have accumulated more than $2.4 billion in exports of South Australian water related services and technologies.

Richard Pashley is Founding Chief Investigator of the National Centre of Excellence in Desalination, and has an internationally-recognised and distinguished career that spans academia and industry, drawing on his extensive understanding of the physical chemistry of water and salt solutions. Professor Pashley is a leader in surface forces and developed the main technique (Colloid Probe – Atomic Force Microscopy) used to measure forces between colloidal materials in water and aqueous solutions. He also discovered the long range hydrophobic interaction which led to the discovery of the effect of de-gassing on emulsion stability. This more recent discovery led to the award of an ARC Professorial Fellowship (2004-2008). He has high level experience of academic leadership in university administration and extensive experience in commercialisation.

Greg Leslie is employed at the University of New South Wales as an Associate Professor in the School of Chemical Sciences and Engineering and is Deputy Director of the UNESCO Centre for Membrane Science and Technology. Prior to joining UNSW, he was CH2M Hill's Technology Leader for membrane systems and water reuse in the Asia Pacific Region. In this capacity he was involved in a variety of water treatment and reuse projects in Australia, New Zealand, Singapore and the United States, including the role of lead process designer for CH2M Hill on the Singapore NEWater projects at Bedok, Kranji and Seletar.

Kenneth Moore has been in the water industry for 10 years. His primary focus has been the use of membranes for potable water treatment, desalination and reuse. He is currently CH2M HILL's Regional Technology Leader for Desalination in Australia. Mr Moore spent the first half of his career commissioning ultrafiltration membrane plants before transitioning into research and product development. Four years ago, he relocated to Perth with a UF supplier, to provide technical support to the growing number of water reuse and MBR projects in Australia. Since then, he's joined CH2M HILL based in Melbourne as a membrane and water treatment technology specialist focusing on reuse and desalination projects.

Aharon Arakel is an authority on land and water salinisation issues and is at the forefront of technology development that includes innovative salt recovery processes for salinity management and saline wastewater minimisation. Dr Arakel has spent some 30 years in practical experience with a wide range of scientific research, university teaching, academic and industry research centre, research management, and technology development and commercialisation, and is now President and Chief Technologist of Geo-Processors, Inc. Dr Arakel is a pioneer of zero liquid discharge (ZLD) processes that involve the recovery of values from saline and alkaline waste streams, including reject brine from desalination processes. He has actively participated in collaborative research projects in the US and elsewhere on various technical aspects of ZLD processes for the management of saline and alkaline effluents. He was until recently a member of the Management Committee of the Specialist Group on Membrane Technology of the International Water Association.

David Furukawa has more than 40 years of desalination technology experience in both public and private sectors. He is Chairman of the Research Advisory Board, National Water Research Institute; Vice-moderator of the Research Advisory Council, Middle East Desalination Research Centre; Past-President and Director of the International Desalination Association and American Desalting Association (now AMTA), and life member of AWWA. He has more than 60 publications and is patented in the field. His company, Separation Consultants, Inc., provides technical, management and strategic business consultancy

Venue

The Orion Room, Esplanade Hotel
54 Marine Terrace (cnr Essex Street), Fremantle WA 6160
Phone: (08) 9432 4000
esplanadehotelfremantle.com.au

In the heart of cosmopolitan Fremantle is the Esplanade Hotel. The hotel offers guests a myriad of leisure activities such as two heated tropical swimming pools, three outdoor spas, sauna and fitness centre. The uniqueness of its heritage and colonial architecture blends with the character of Fremantle's historical Port and Fishing Boat Harbour.

Transport

Fremantle is 25 km from the Perth domestic airport terminal. A taxi will take around 45 minutes. Bus services are available, see Transperth or Google Maps.

Valet parking is available at the hotel for $25/day. Closest ticket parking is at the 197-bay Esplanade Car Park on Marine Terrace or the 455-bay Collie Street Car Park.

Registration

Please direct any questions about the workshop to:

Ashleigh Ninnes
Phone: (08) 9360 2367
Fax: (08) 9360 6686
Email: A.Ninnes@murdoch.edu.au

About Fremantle



Renowned as WA's premier tourist destination, Fremantle is rich in history, culture and tradition. Fremantle boasts some of the finest shopping, dining, recreational and leisure facilities in Western Australia. Located in a beautiful port city, where the Swan River meets the Indian Ocean, Fremantle enjoys a Mediterranean climate. The city features the largest collection of heritage listed buildings in Western Australia and is internationally recognised as the world's best preserved example of 19th century port streetscape.

Western Australian Maritime Museum. The Western Australian Maritime Museum has unique architecture and exhibits over three locations. Join a complimentary introductory tour, and experience all that encompasses WA's maritime history. Explore inside a real submarine, and hear about Fremantle's Historical wartime history. Built by convicts, see Australia's oldest shipwrecks.

Fremantle Prison. The Fremantle Prison is the largest convict built structure in Western Australia. With thick limestone walls, solitary cells and gallows it is a monument to a system of punishment that occurred up until recent times. The Prison offers a range of themed tours with experienced guides. Day tours depart every 30 minutes from 10am. By night you can experience a spooky Torchlight Tour. Or, for a more extreme spin on the heritage site, explore the labyrinth of tunnels 20 meters beneath the Prison by foot and by boat. This new tour is very popular, bookings are essential.

The Mussel Bar (Sundowner, Thursday October 29). The Mussel Bar sits directly over the water in Fremantle's famous Fishing Boat Harbour and is one of this historic port city's finest seafood restaurants. With the freshest seafood and local produce, creative cuisine, extensive wine list, friendly professional service and fabulous location over the water the Mussel Bar is the perfect venue for all occasions. 42 Mews Road, Fishing Boat Harbour, Fremantle.

White Papers

The Unusual Properties of Water and Salt Solutions and their Potential Application in Desalination

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Summary

Some of the fundamental physical properties of liquid water and salt solutions still present significant theoretical challenges. A better understanding of these unusual properties might assist in the development of a range of novel and improved desalination processes.

Background

Recent studies on water and dilute electrolyte solutions have demonstrated that the so-called 'inert' atmospheric gases, oxygen and nitrogen, have a significant influence on the fundamental properties of water, even at their relatively low level of solubility. For example, the almost complete removal of these dissolved gases enhances the dispersion of fine oil droplets in water, simply by shaking, without the need for added surfactants. Even more importantly, the almost complete de-gassing of liquid water significantly increases the suction pressure required to cavitate water and also, surprisingly, enhances its natural electrical conductivity. These recent discoveries, together with the (still) un-explained effect of added salt on preventing air bubble coalescence in water, have recently been applied in the development of several novel ideas, for each of the three desalination methods.

Although RO filtration has become the most popular method in recent years, it has many disadvantages which add to its cost. Thus, large volumes of concentrated salt, typically at twice sea salt levels, has to be returned to the sea, as only about half of the feed actually passes as clean water through the membranes. This also means that membranes are easily fouled and they are expensive to make. The sea water has to be pre-cleaned to protect the membranes, adding to the cost. Also, the high osmotic pressure of sea water (of about 30 atm) means that sophisticated and expensive liquid pumping is required at pressures of around 65 atm (Water Corporation, Perth). High pressure liquid pumping can be made relatively efficient and this has been achieved recently by the use of mechanical pressure recovery devices. The best-practice commercial energy cost for the desalination of sea water is about 2.5 kWh/m^3 or 9 MJ/m^3.

The minimum work required to desalinate sea water can be calculated from the work done by applying a pressure infinitesimally higher than the osmotic pressure and so obtain the reversible work done, at constant temperature, to move a semi-permeable membrane an infinitesimal distance, so desalinating a very small volume of solution. This gives a minimum work required of about 3 MJ/m^3 of pure water. Commercial RO systems are less efficient, typically in the range of 10-20 MJ/m^3. Also as the salt accumulates the osmotic pressure required also increases. Membrane methods also have higher capital costs, require pre-treatment of the salty feed water and are also limited in salt concentration (both in the feed and the waste water). Electrodialysis (ED) has fewer disadvantages than RO but still requires fairly sophisticated equipment and specialized membranes. It also relies on electrical work to separate the ions into fairly expensive ion-exchange membranes.

These various factors demonstrate clearly why the relatively simple process of evaporation is attractive. This is the method by which clouds are formed, producing drinking water in rain because in the vapour state salt is almost completely excluded. The interface between water and air (or vapour) offers a natural barrier to the transport of salt. This transfer does not require a membrane and does not require the use of the very high pressures needed with membranes. This interface offers the most simple exchange process for pure water and ought to offer the best commercial process, when suitably harnessed. An innovative approach to this process is one of the main aims of this work.

The most common current commercial form of this type of thermal/evaporative process is called multi-stage flash distillation. In this process salt water is heated close to its boiling point, usually in an environment of reduced pressure to lower the boiling point. The water boils and the vapour is condensed and collected. Only a small proportion of the water boils off at each stage of the process and so a series of 'multi-stages' are required. No membrane is needed but substantial energy costs are required to vaporise significant volumes. The latent heat of vaporization of water is about 2.3 GJ/m^3 at 100°C and about 2.5 GJ/m^3 at room temperature.

These values are not altered much by the addition of salt. Although these values seem high, almost all of this thermal energy is, in practice, recycled on condensation of the water vapour, and used to heat the salt water feed, which substantially reduces the overall energy costs. Evaporation methods can also reduce the energy cost in other ways, for example using ambient or solar heat to pre-heat the sea water. Commercial thermal/evaporative units have energy costs typically in the range 20–200 MJ/m^3 but these are still commercially viable because of significantly lower capital costs and equipment replacement costs. These plants are often built close to industrial sites which produce heat as waste, to reduce energy costs still further.

In the following sections three desalination processes are considered with respect to the development of potential innovations based on applying some of the unusual properties of water.

Desalination process 1: Reverse osmosis

Water cavitation

Water cavitates much more readily, under suction pressure, when it is saturated with dissolved air and is exposed to hydrophobic groups. It is actually very difficult to cavitate pure water in a clean, smooth vessel. If we make the reasonable assumption that a phase change occurs when a spherical cavity of 1 nm radius is created in water, then we can easily estimate the suction pressure required. The total energy (E_T) of a cavity of radius (r) is given by the sum of the negative work done by the suction pressure ($\Delta P < 0$) on the cavity volume and the surface tension work done on creating the surface of the cavity. Thus, the total cavity energy is given by:

$$E_T = \frac{4}{3}\pi r^3(\Delta P) + 4\pi r^2 \gamma \qquad [1]$$

If we make the assumption that 1 nm is the critical radius of cavity formation, i.e. when $dE_T/dr = 0$, then it follows that we can estimate the critical suction pressure:

$$\Delta P = -\frac{2\gamma}{r_c} \qquad [2]$$

This for pure water gives a critical suction pressure of about -1,460 atm. The highest experimental measurements reach a value of -1,200 atm (see Figure 1).

In most practical situations contaminants and real, rough surfaces facilitate the nucleation of cavities in water at much lower suction pressures than this. The presence of dissolved gases and hydrophobic groups also substantially reduce the cavitation pressure. For example, experimental cavitation pressures are typically about -1 atm for distilled water, saturated with air, and -200 atm for 99.98% de-gassed water (see Figure 2). Thus it is clear that the de-gassing of water and salt solutions strongly inhibits cavitation.

Figure 1. Theoretical calculation of the energy (in kT units) required to form a spherical cavity of radius r in pure water under ideal, de-gassed conditions, in the absence of nucleation sites, with an applied suction pressure of -1200 atm. [Compare this with the cavitation pressure of gassed water of -1 atm.]

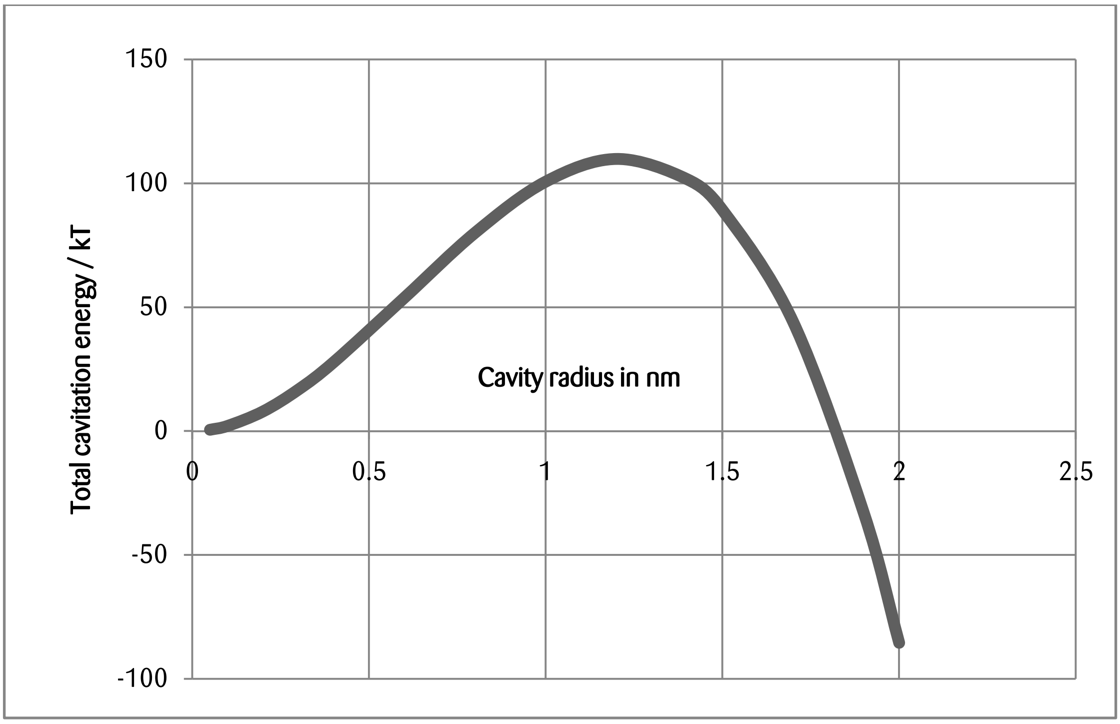
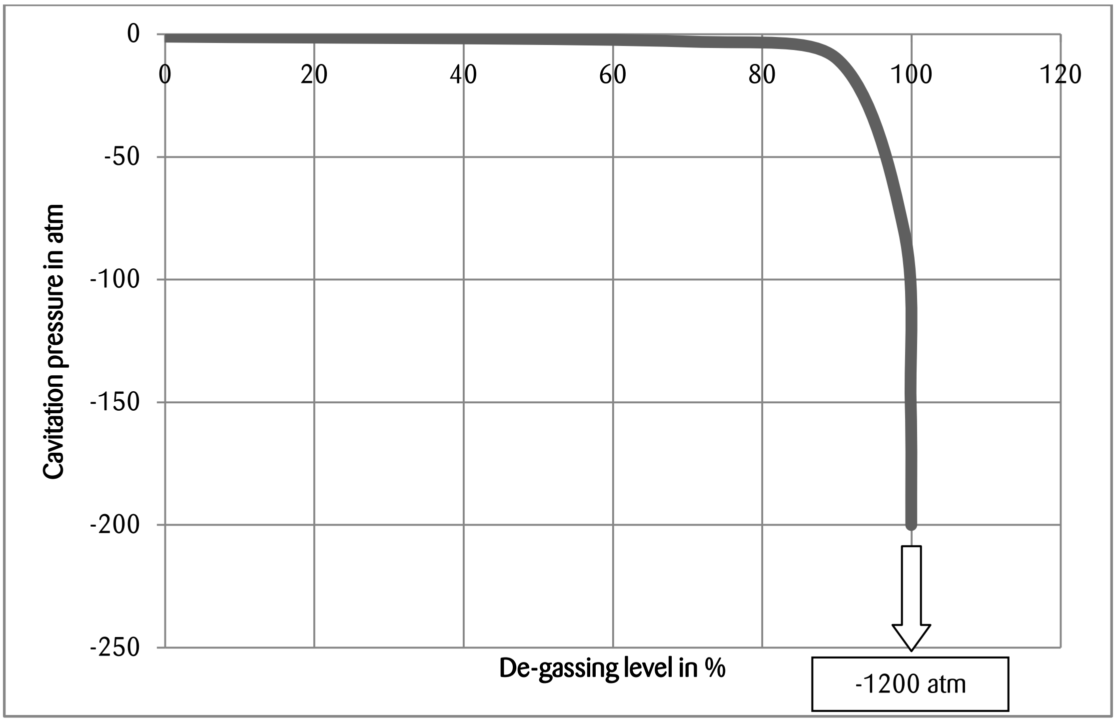


Figure 2. The effect of de-gassing on the cavitation suction pressure for water.



The high pressure differential established across the thin surface skin layer of an RO membrane, during the reverse osmosis process, could give rise to cavitation within the porous polymer network. This cavitation would have the effect of substantially reducing product flow. The polymers used in modern composite RO membranes contain hydrophobic moieties, such as saturated and unsaturated hydrocarbon rings. These groups can form nano-size surface regions of hydrophobicity within the polymer matrix of the membrane, which could nucleate cavities in water. In addition, it is likely that different RO membranes have different levels of hydrophobicity.

Desalination process 2: Electrodialysis
The electrical conductivity of de-gassed water

The Grotthus mechanism (1805) for the electrical conductivity in pure water is based on the principle that water molecules in pure water conduct electricity by a sequential process of bond breakage and reformation to carry the charge of the extra protons (always bonded to hydronium ions) and hydroxyl ions. A simple schematic diagram of this process is shown in Figure 3. Traditionally, dissolved nitrogen and oxygen gases have been considered to be inert. In fact, nitrogen purging is used to displace dissolved carbon dioxide, which would otherwise dominate the electrical conductivity of pure water. However, we have recently discovered that these 'inert' dissolved atmospheric gases significantly reduce the flow of electricity in water, perhaps by forming closed clusters, which reduce the number of conducting chains of water molecules.

We have discovered that the almost complete de-gassing of water substantially increases its electrical conductivity. This situation is summarized in Figure 4. These remarkable results lead us to ask whether the use of de-gassed salt solution could increase the overall efficiency of the electrodialysis (ED) process by increasing the electrical conductivity of the ion depletion layers set up within the ED process. It is likely that any effect will be more significant using dilute electrolyte solutions.

Figure 3. Schematic diagram of the Grotthus mechanism for electrical conductivity in pure water and a proposed model for the effect of dissolved nitrogen gas molecules.

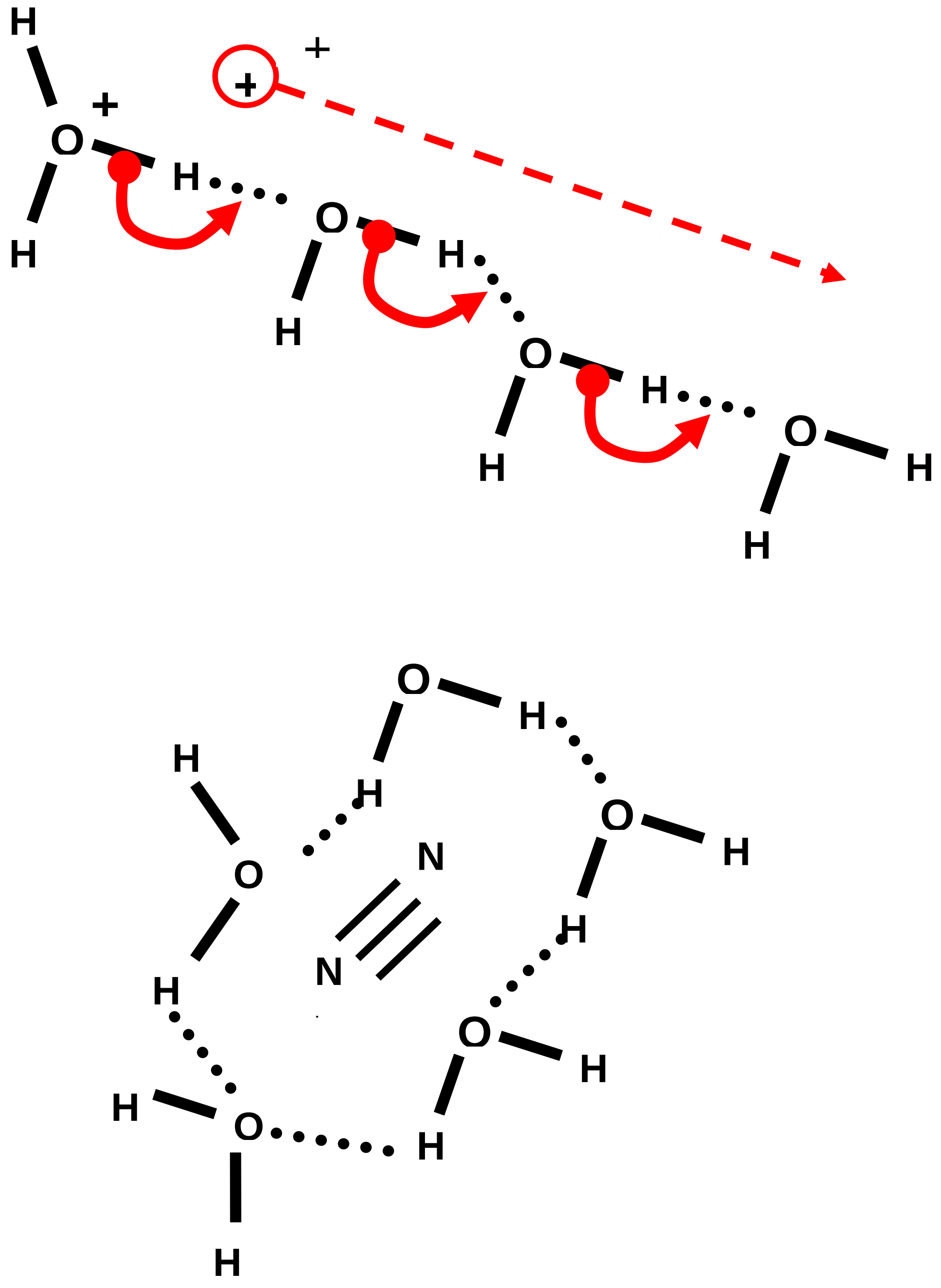


Figure 4. Schematic diagram to describe the recently discovered effects of de-gassing on the electrical conductivity of pure water.

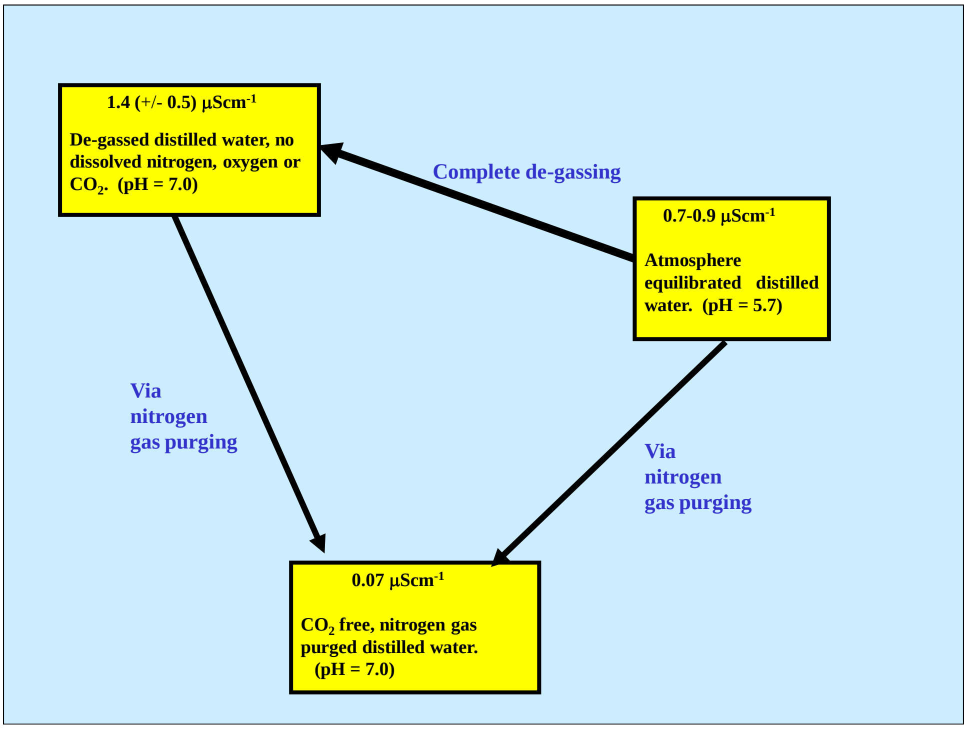
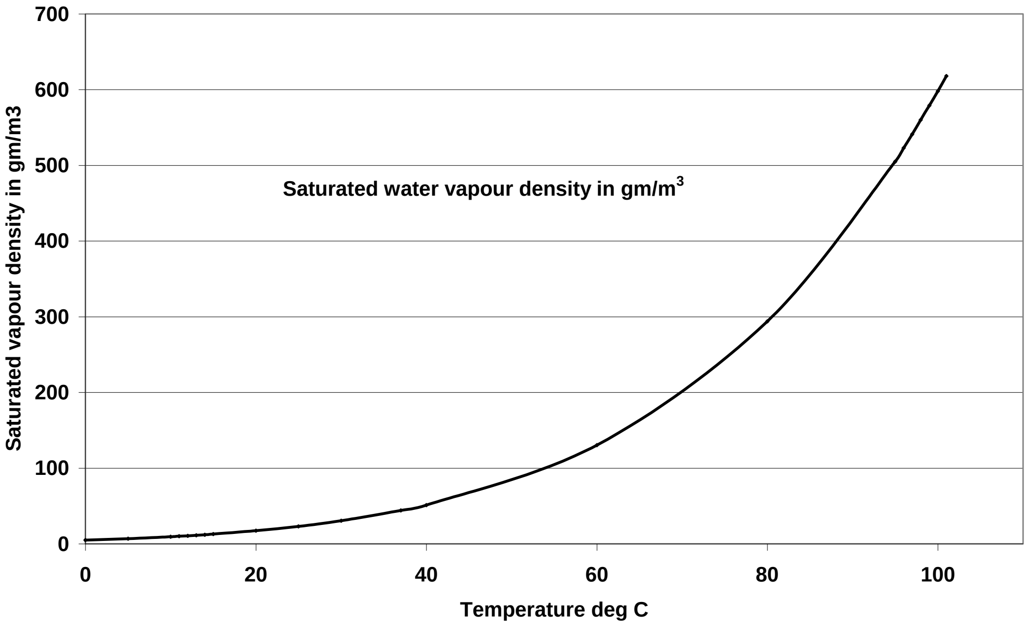


Figure 5. The amount of water vapour carried within an air bubble, at saturation, depends only on temperature and is given in the following graph.



Desalination process 3: Thermal
The ability of salt water to inhibit bubble coalescence.

The water vapour content of an air bubble in equilibrium with an aqueous solution is determined entirely by the temperature, and does not depend on whether the water is at its boiling point (see Figure 5). For example, the vapour pressure of water in an air bubble immersed in water at 70˚C is exactly the same as that in a boiling bubble created in water boiling under a reduced pressure, at the same temperature. The boiling process is difficult to control. However, an efficient transfer to the vapour phase can be produced without boiling.

Unfortunately, the energy costs for vaporizing water is very high. The latent heat of vaporization of water at 70°C is about 2.3 GJ/m^3. In commercial thermal or evaporation processes, almost all of this heat has to be captured during condensation and re-used to pre-heat the feed solution. In order to capture and re-use thermal waste heat, it is important to have a well controlled process. This possibility is afforded by the unusual behaviour of sea water, in preventing air bubble coalescence, which can be used as the basis for an improved process for the desalination of sea water, based on the efficiency of vapour transfer in a continuous, fine bubble column in an evaporative process below the boiling point. This method employs the very high surface area of the air/water interface afforded, naturally, by gas bubbling in salt water, such as sea water, to improve the efficiency of evaporation and transportation of water saturated vapour, to produce drinking water from sea water. This phenomenon is illustrated in Figure 6.

Flash distillation essentially uses only the surface of the liquid as the main water vapour transfer barrier and the boiling process itself is an irregular process, hard to control. In comparison, a high density of small air bubbles flowing continuously through the salt solution, held below the boiling point, will collect vapour throughout the entire body of the salt solution in a regular, uniform process, until the saturation point at that temperature and pressure. If the sea water is heated close to its boiling point (at normal or reduced pressure), then the air bubbles entering the base of a column will become completely filled with water vapour, which can then be transported regularly into a condenser and collected. There is no need to let the water boil in this process. The amount of water vapour in an air bubble immersed and equilibrated with water close to its boiling point is almost identical to that in a bubble created by boiling.

Figure 6. Nitrogen bubbles formed in a water column at a frit: in pure water (left photo) and in salt solution at 0.2M NaCl (right photo), for the same flow rate.

There is yet another unusual property of water which has direct application in the bubble column method. This stems from the observations that fairly large (> 1-2 mm) air bubbles in water, which are used in the bubble column method, become non-spherical and oscillate both in shape and in trajectory as they rise under gravity. This has the dual effect of limiting their rise rate and enhancing the rate at which water vapour equilibrates within the bubbles. It is remarkable that water vapour saturation within these bubbles is attained in a few tenths of a second because of these oscillations and the circulatory fluid flow induced inside the bubbles due to the shear forces generated at the surface of the bubbles.

A bubble column, non-boiling process has several potential advantages over other desalination processes. For example, a bubble column will have low capital and capital operating costs. Unlike membrane RO systems, it does not require extensive pre-filtration of the sea water feed. The bubble column actually affords a self-cleaning, flotation system. The system could be operated at lower temperatures, using sustainable energy sources, such as from solar heating and wind turbines. In addition, the bubble column could be readily used with hot, waste industrial flue gases, especially for coastal plants.

Concluding remarks

In addition to the unusual properties of water discussed here, there are other properties of water and salt solutions which also require further study. Such studies may also lead to the development of novel improvements in desalination processes.

About the author

Richard Pashley is Founding Chief Investigator of the National Centre of Excellence in Desalination, and has an internationally-recognised and distinguished career that spans academia and industry, drawing on his extensive understanding of the physical chemistry of water and salt solutions. Professor Pashley is a leader in surface forces and developed the main technique (Colloid Probe – Atomic Force Microscopy) used to measure forces between colloidal materials in water and aqueous solutions. He also discovered the long range hydrophobic interaction which led to the discovery of the effect of de-gassing on emulsion stability. This more recent discovery led to the award of an ARC Professorial Fellowship (2004-2008). He has high level experience of academic leadership in university administration and extensive experience in commercialisation.

Energy Issues in Desalination

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Executive Summary

Energy requirements are an important consideration in any alternative water supply option, particularly for desalination which is perceived as energy intensive.

The efficient production of potable water by desalination of seawater is a global objective. Many countries including Singapore, China, Korea, Japan, the Arabian Gulf States, the United States and members of the European Union have active R&D programmes involving government, industry and academic institutions. The research is focused on reducing the energy requirements for seawater desalination from the current benchmark of 3.5 kWh/m^3 to the theoretical minimum of 0.8 kWh/m^3 Options for reducing the energy requirements include alternative desalination processes (such as forward osmosis) and the development of new generation membrane materials for reverse osmosis systems. Some promising technologies, such as the nano-composite particle membranes and carbon nano-tube membranes are still in the developmental stage. Consequently, many R&D programmes include projects to improve the efficiency of established desalination processes such as distillation and reverse osmosis.

The management of energy consumption and the attendant greenhouse gas emissions are a significant factor in the development of desalination processes. The operation and maintenance costs for reverse osmosis based desalination processes are very sensitive to movements in the price of electricity. For example, in a two pass reverse osmosis system utilizing a medium efficiency energy recovery plant (4.0 kWh/m^3) designed to produce fresh water with less than 150 mg/L TDS and less than 0.1 mg/L of boron, the water production costs would increase by 170% (\$0.34/m^3 to \$0.91/m^3) as the power costs increase from \$0.05/kWh to \$0.2/kWh. Consequently, it is very important that water utilities investing in desalination develop effective strategies to manage the impact of increased power costs on the cost of producing and supplying potable water produced by desalination.

The operation and maintenance costs of desalination schemes will also be impacted by the introduction of a price for carbon. Consequently, offsetting the carbon emissions associated with desalination is an important part of managing potential increases in the cost of water as a result of the introduction of an emissions trading scheme or equivalent system that puts a price on carbon. For example, a desalination facility with a power consumption of 4.6 kWh/m^3 that sources electricity produced by black coal will emit between 4.7 to 6.0 kg CO_2/m^3 depending on the location of the plant. The introduction of an emissions trading scheme where carbon is priced at $50 per tonne of CO_2 will add approximately 16% to the operation and maintenance cost of the facility.

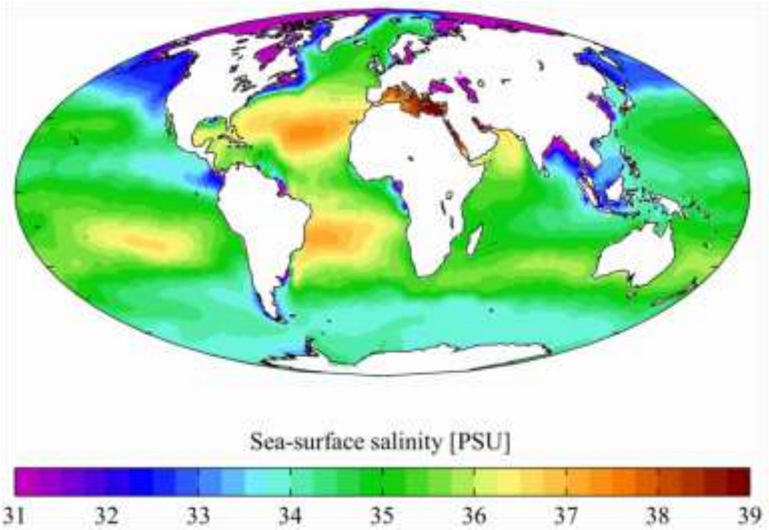
How much energy is required to remove salt from water?

Salt content in seawater

The treatment objective of a desalination process is to reduce the Total Dissolved Solids (TDS) content of the raw water such that the product water can be blended with the existing potable water supply without any detectable change in the taste or aggressiveness of the water towards the storage, conveyance, appurtenances and fixtures or fittings.

The salt concentration of the world's oceans ranges from 31,000 to 46,000 mg/L depending on location; in areas closer to the shoreline, this figure will vary due to the evaporation and dilution phenomena (Figure 1)[1]. The highest salinity levels are recorded around the Mediterranean and Red Sea, where relatively high temperatures increase the rate of evaporation, while near the North Pole the salinity is lower due to the low evaporation rate and the occurrence of ice melting. The World Health Organization recommends that the dissolved solids concentration, or salinity, of drinking water should be less than 500 mg/LIn Australian applications, additional treatment is required to reduce TDS to less than 100 mg/L, to match the TDS level of the drinking water supply.

Figure 1: Sea Surface Salinity, g/L[1]



Ideal energy requirements

The mixing process between salt and water occurs spontaneously, during which entropy is generated and exergy is destroyed. Therefore, the separation of the mixed constituents is not possible without supplying some energy. This energy is called the ideal separation work. It is a measure of the work required to overcome the entropy generated by mixing. Though desalination processes may have different technologies and configurations, the minimum power requirement is the same regardless of the process used, because the minimum separation work depends only on the properties of the incoming saline water and outgoing product water and waste brine.

Determination of minimum separation work

The minimum work required for all desalination processes may be calculated using the second law of thermodynamics. However, in the case of reverse osmosis process, the minimum energy may also be calculated using osmotic pressure theory as defined by Van't Hoff.

The following section describes the basics of the thermodynamics and Von't Hoff theories.

Minimum Separation using Second Law Thermodynamic Analysis

Given a mixture of two components (water and salts) with a mole fraction of xw and xs, the minimum separation work to separate the two components is the work required to overcome the entropy generated as a result of mixing process.

The entropy of mixing is given by equation A1;

$$\Delta S_{mixing} = -R \times \sum_i n_i \ln(x_i) \qquad \text{A1}$$

where *R* is the gas law constant, n_i is the number of moles, and xi is the mole fraction of component *i*. Thus, the exergy destroyed ($E_{destroyed}$) can be calculated from equation A2 as:

$$E_{destroyed} = T_0 S_{gen} \qquad \text{A2}$$

Therefore, the minimum separation work for complete separation of the two components is calculated as;

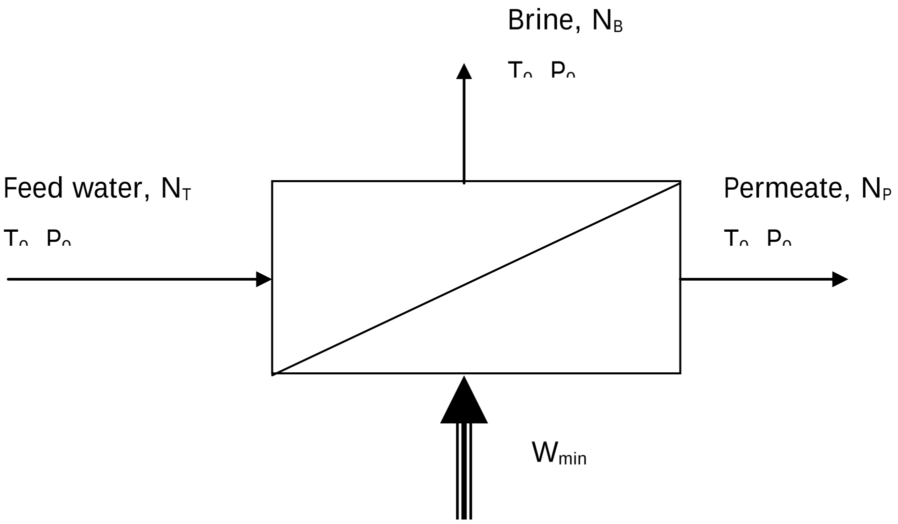
$$W_{\min} = T_0 S_{gen,ideal} = -RT_0 n_T \sum_i x_i \ln x_i \qquad \text{A3}$$

where, n_T is the total number of moles of the mixture.

The relationships derived above are used to calculate the minimum separation work to completely separate the two components into pure components. The same equation (A3) can be used to calculate the minimum separation work in a real desalination process, in which a complete separation of water and salts cannot be achieved.

The minimum separation work for the desalination process is determined by first determining the minimum separation work for the incoming saline water and the minimum separation work for the outgoing streams (brine and permeate). The minimum separation work is then the difference between the two values:

Figure 2 Schematic of ideal desalination process



The schematic diagram shows an ideal desalination process in which the feed water enters the process at T0 and P0, and the outgoing streams leave the process under the same conditions. By knowing the salinity of each stream, the minimum separation work of each stream can be calculated independently from equation (A3) as follows:

$$W_{\min,brine} = -N_{brine} R T_0 \left(x_{s,brine} \ln(x_{s,brine}) + x_{w,brine} \ln(x_{w,brine}) \right) \qquad \text{A4}$$

$$W_{\min,permeate} = -N_{permeate} R T_0 \left(x_{s,permeate} \ln(x_{s,permeate}) + x_{w,permeate} \ln(x_{w,permeate}) \right) \qquad \text{A5}$$

$$W_{\min,process} = W_{\min,Complete} - (W_{\min,brine} + W_{\min,permeate}) \qquad \text{A6}$$

where $W_{min,complete}$, is the minimum work for complete separation of incoming saline water, and is give by equation(A3). Therefore, combining the above equations of the minimum separation work for the brine and permeate streams with equation (A3) yields the minimum separation work required for desalination process as follows:

$$W_{\min} = R T_0 \left(N_{s,brine} \ln\left(\frac{x_{s,brine}}{x_{s,f}} \right) + N_{s,permeate} \ln\left(\frac{x_{s,permeate}}{x_{s,f}} \right) + N_{w,brine} \ln\left(\frac{x_{f,brine}}{x_{w,f}} \right) + N_{w,permeate} \ln\left(\frac{x_{w,permeate}}{x_{w,f}} \right) \right) \qquad \text{A7}$$

Equation (A7) is a general formula for minimum separation work input for the separation of incoming saline water of known salinity x_s into two streams of know salinity $x_{s,brine}$ and $x_{s,permeate}$. It determines the minimum separation work for a range of 0 to 100 % recovery of fresh water, for any combination of salinities of the incoming saline water and the outgoing product water and brine.

Minimum Separation Work from Osmotic Pressure Theory

Minimum separation work can also be obtained using the osmotic pressure (π) calculated from the Van't Hoff equation as follows:

$$\pi = v N_s RT \qquad \text{A8}$$

where π is the osmotic pressure of the solution in kPa, vN_s is the molar concentration of solute in the solvent in kmol/m^3.

Once the osmotic pressure is determined, then the minimum separation work is calculated by multiplying the osmotic pressure by a unit volume of water, and dividing this by 3600 kJ/kWh to get the power consumption in kWh/m^3 as;

$$W_{\min}(kWh/m^3) = \pi(kPa) \times \frac{1}{3600}(kWh/kJ) \quad \text{A9}$$

The minimum separation work obtained from equation (A9) corresponds to the production of pure water, at a negligible recovery ratio ($r \approx 0$). This is because the osmotic pressure of a solution is defined as the applied pressure to maintain the solution in equilibrium with pure solvent when separated by a semi permeable membrane that only allows solvent to pass.

The Van't Hoff equation requires the concentration of solute in the solvent,\. Therefore, in the case of saline water, the salt (NaCl) is considered to be the solute and the solvent is water. The empirical dissociation constant for NaCl is 1.8, which means the concentration of solute in the saline water is almost twice the concentration of NaCl in the solution.

UMST Second Law efficiency model

There is a big difference in minimum separation work calculated by equation (A7), at zero recovery ratio, and the minimum separation work calculated using equation (A9). The source of disagreement comes from the fact that in the Van't Hoff equation model the dissociation constant of NaCl was considered and included in the calculation of the osmotic pressure, whereas in the other model, the concentration of the solute was assumed to be equal to the concentration of NaCl in the solution. In order to adjust this error, it is necessary to assume the binary mixture is solute and water instead of NaCl and water, in which the solute is the dissociated NaCl. As a result, the concentration of the solute will be 1.8 times the concentration of NaCl in the water.

The aforesaid changes will affect the calculation of the number of moles of solute, and therefore will affect the mole fraction of both solute and solvent, as:

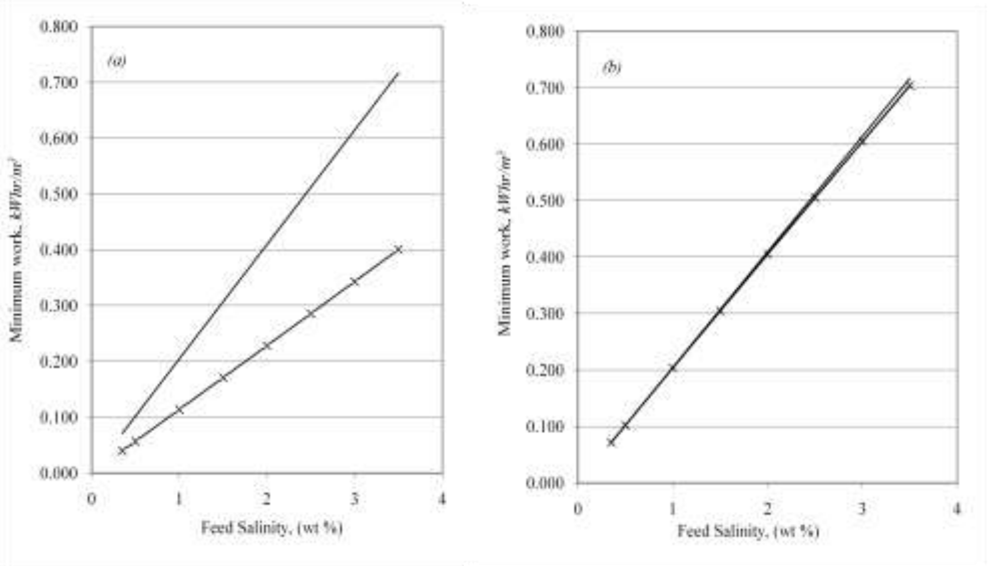
- Salt concentration in the solution (m_{NaCl}) = (mass of NaCl) × 10-6 kg/(kg solution), and
- The molar concentration of NaCl [NaCl], mol/L = (m_{NaCl}) × 1000/58.44(g/gmol).

The molar concentration of solute is then calculated by multiplying the molar concentration of NaCl by the dissociation factor of 1.8:

- [Solute], mole/L = 1.8 × [NaCl]

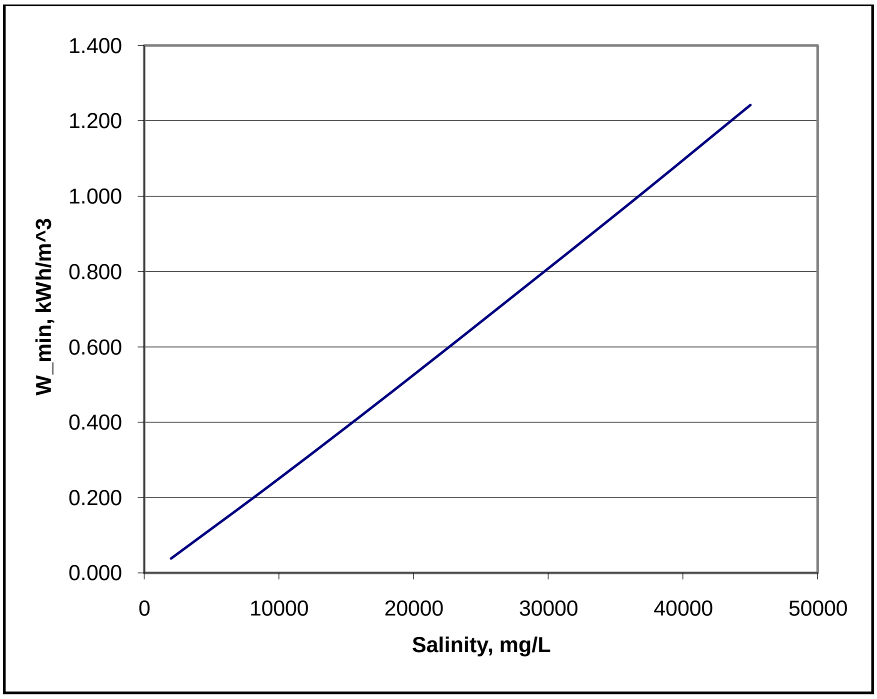
Once the solute molar concentration is calculated, then the minimum separation work calculated from equation (A3) will be approximately the same compared with the minimum separation work calculated based on the Van't Hoff equation (Figure 3).

Figure 3 Effect of feed salinity on minimum separation work input at 15°C and zero recovery ratio. (*a*) without dissociation constant; (*b*) with dissociation constant: (-×-) Second Law of thermodynamic; (-) **van’t Hoff equation.**



The minimum work required to produce one cubic metre of water with TDS of 100 mg/L, from sources of water with different salinities and with a recovery ratio of 40%, is shown in Figure 4.

Figure 4: Variation of minimum work with the salinity of feed water



How is the efficiency of desalination measured and optimised?

The second law of thermodynamics introduces the entropy balance equation in addition to the energy and momentum equations. The resulting formula is a general potential work function called the exergy function. This formula measures the total losses that obliterate the input energy. The exergy also measures the lost work by calculating the difference between the minimum and actual work. The exergy analysis of any process is very useful, because it can be used to quantify and trace the locations where a significant amount of entropy generation (exergy destruction) takes place.

Efficiency of desalination plant

Proportional to the feedwater salinity, the higher the salinity, the higher the osmotic pressure and the more the energy that will be required.

For example, in the SWRO desalination, the second law of thermodynamic analysis can be used to measure the efficiency of the desalination process (η_{II}), by comparing the actual work (W_{act}) required with the minimum work (W_{min}) required for the same inlet and outlets stream conditions, as shown in equation (1).

$$\eta_{II} = \frac{W_{\min}}{W_{act}} \tag{1}$$

The efficiency of desalination plants is influenced by different variables, including:

- Salinity and temperature of feed water
- Product water recovery ratio, and
- Actual power consumed.

Generally, the power required to desalinate water using reverse osmosis is governed by the osmotic pressure of the feedwater, and is directly related to the salinity level. For example, the plant in Kwinana, Perth [2] consumes around 3.56 kWh/m^3 to produce water with TDS of 200 mg/L from seawater with TDS of 35000 mg/L. Using the same feed and outlet conditions, the minimum work consumed is around 0.951 kWh/m^3. Therefore, based on equation (1), the second law efficiency of the plant is around 26.7 %.

The efficiency of most desalination plants is between 8 and 30%[1]. This is very low when compared with the efficiency of other major industrial operations such as power generating plants, for which the second law efficiency is well above 50%.

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[1] This value is higher than the one reported in the literature because the minimum separation work calculation in this report is based on the UMST 2nd law efficiency (Kempt, 2005) model, which takes into account the dissociation constant of the NaCl salt.

Table 1: Variation of Second Law Efficiency with Feedwater Source

Feed water (TDS, mg/L)	Permeate (mg/L)	W_{min} (kWh/m^3)	Process	Energy source	$W_{act}{}^{b}$ (kWh/m^3)	Efficiency η_{II} (%)
Arabian Gulf (45,000)^{a}	200	1.24	RO	Electricity	4.0	31.00
	50	1.26	MSF	Thermal	12^{c}	10.50
	50	1.26	MED	Thermal	$8^{c,e}$	15.75
	50	1.26	MVC	Electricity	$11^{c,e}$	11.45
Average Seawater (35,000)^{a}	200	0.95	RO	Electricity	3.6^{d}	26.39
	50	0.97	MSF	Thermal	12	8.08
	50	0.97	MED	Thermal	$8^{c,e}$	12.13
	50	0.97	MVC	Electricity	$11^{c,e}$	8.82
Brackish water (5400)	200	0.16	RO	Electricity	0.82^{f}	19.51

(a)[3], (b)[4], (c)[5], (d)[2], (e)Average value, (f) [6]

In order to increase the efficiency of the desalination plant, and to facilitate the reduction of greenhouse gas emissions, the wasting of energy in the plant (exergy destruction) must be minimized. One way is to maximize the energy recovery rate from the outgoing streams (i.e., brine solution in SWRO plants). There are different types of energy recovery devices used for recovery, depending on the technology used in the desalination plant. For instance, in MSF distillation technology, in which thermal exergy is supplied as heat, heat exchangers are used to recover the exergy from the outlet steams. Meanwhile in RO processes, pressure exchanger devices are used to recover the pressure exergy of the outgoing streams. The effectiveness of the different types of energy recovery devices is discussed in the following section.

Energy Recovery Options

The energy requirement of an RO system rises almost proportionally with increasing operating pressure. Brackish water systems have specific energy consumptions that typically range from 1.0 to 3.0 kWh/m^3, whereas SWRO system energy requirements range from 3.5 to 4.5 kWh/m^3 due to their higher operating pressures and lower product water recoveries. Most SWRO systems are therefore equipped with energy recovery devices to reduce energy requirements to more cost-effective levels.

After passing through the membrane, permeate is reduced to near atmospheric pressure while the concentrate retains most of the pressure energy from the feedwater pump. An energy recovery device can recover most of the energy from pressurized concentrate and reduce overall system energy requirements by more than 50%.

Turbine-type energy recovery devices convert the concentrate's hydraulic energy into mechanical power to assist the high-pressure pump motor. Turbines were the first energy recovery devices deployed in sea water reverse osmosis plants. Initially, Francis-type turbines were applied, but they were replaced in the 1980s by Pelton turbines that operated at higher efficiency in high-head applications like sea water reverse osmosis plants. Pelton turbines are widely accepted in sea water reverse osmosis plants due to their familiarity and proven reliability. These devices have energy recovery efficiencies of between 60% and 85%.

A "work exchanger" or "pressure exchanger" energy recovery device transfers hydraulic energy directly from the concentrate stream to the incoming seawater across a piston, using positive displacement technology.

While the natural inclination is to use the most efficient device possible (i.e. a pressure exchanger rather than a Pelton wheel), it is necessary to evaluate the system as a whole for each specific application. Each device has its own merits: some offer a greater degree of operating flexibility, while others offer a lower capital cost or higher efficiency.

Optimizing energy efficiency

The fact that energy costs may represent up to 50% of the operating expenses of a seawater desalination plant usually provides sufficient incentive to implement energy conservation and efficiency measures wherever possible.

Frequently employed energy optimization methods include:

- High efficiency energy recovery devices
- Variable frequency drives (VFD)
- Premium high-efficiency pumps
- The use of rooftop solar photovoltaic cells to augment the external power supply, and
- Incorporation of Leadership in Energy and Environmental Design (LEED) principles for plant offices and commercial buildings.

The most energy efficient desalination process to date was achieved in a demonstration plant operated by the Affordable Desalination Collaboration (ADC) which has reported a value of about 1.6 kWh/m^3 [7]. Additional power is required for intake, pretreatment and discharge. The Affordable Desalination Collaboration demonstration used the best available highly permeable (HP) membranes and state-of-the-art energy recovery exchangers [8].

Another approach to reducing energy consumption is the use of a multistage process, with inter-stage booster pumps and energy recovery devices. If the feed-side pressure profile is stepped up to match the rising osmotic pressure profile through the plant, and if highly permeable membranes are used it may be possible to save about 35% of the energy [9] (based on the ADC minimum, this could mean ~ 1.0 kWh/m^3).

The development of a multi stage process would involve a radical redesign of RO cascades and would probably come with higher capital cost. However, this example does illustrate the potential for further energy reduction. In order to approach the thermodynamic minimum of just over 0.5 kWh/m^3, it will be necessary to successfully develop one or more of the other desalination options described in this section. The most likely candidates are Membrane Distillation (MD) (in niche areas) and Forward Osmosis (FO). The energy issues around desalination have also prompted considerable R&D activity is desalination using renewable energy, including MD + solar, and RO + solar, wind or wave energy.

What is the role of renewable energy in desalination?

Desalination is the most energy-intensive water treatment process when compared to other pure water supply options. However, in many locations, it may be the only available option able to deliver a reliable quantity and quality of fresh water. Consequently, in order to offset the energy required to operate a desalination plant water authorities may consider accessing power generated using renewable resources.

Renewable energy sources are those that use natural resources such as sunlight, wind, tides or geothermal heat sources, which can be naturally replenished in a short period of time. The availability of renewable energy sources and the maturing of the technology make it possible to consider coupling desalination with renewable energy production processes.

In practice the "green electrons" generated by a renewable energy source are only used to power a desalination in small scale applications. There are examples of small desalination plants that operate directly from renewable energy supplies, however, these have a capacity of less than 1 MLD and are often located in remote locations. The best option for using renewable energy is for desalination plants that use thermal processes. A recent report by the German Aerospace Centre entitled *Concentrating Solar Power for Seawater Desalination* [10] suggests that concentrating solar power (CSP) may soon be a cost-effective method of renewable energy for desalination plants.

Concentrating solar power technologies are based on the concept of concentrating solar radiation to provide heat for electricity generation in conventional power cycles. Systems can use parabolic troughs, glass mirrors or solar dishes that track the sun's position to concentrate solar energy to generate steam to drive a turbine and produce up to 200 MW of electric capacity. A CSP system could produce up to 50 MW of power on 1 km^2 of arid land.

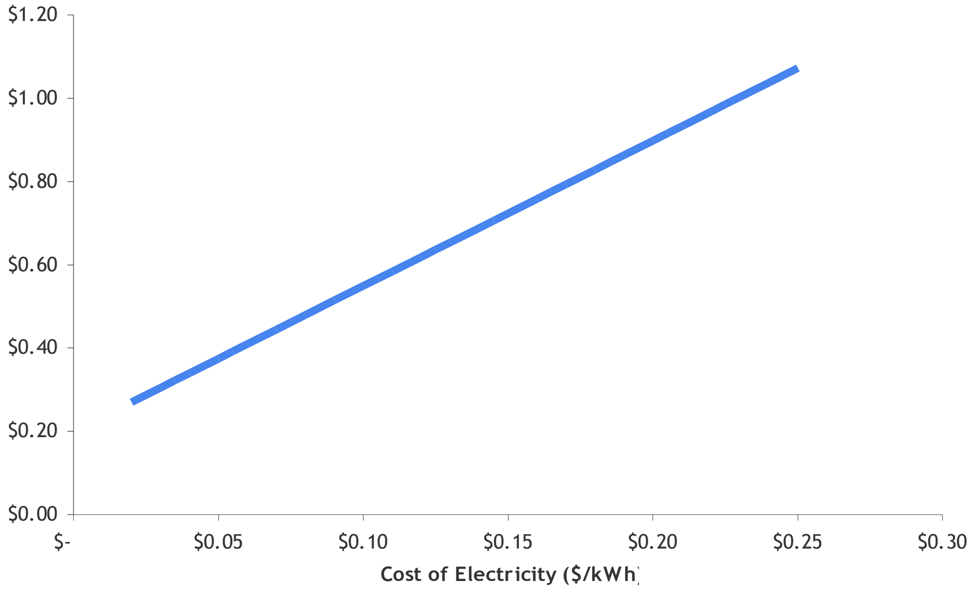
A 64 MW plant was recently constructed in Nevada, USA for US$266 million and produces electricity at US$0.15–0.17/kWh, It is estimated that the cost will reduce by 10 to 15% each time the world's installed capacity doubles.

At present for large-scale seawater desalination systems located near major urban centres the use of renewable is restricted to the purchase of renewable energy that has been fed into the main power grid. Perth's plant in Kwinana is one example of such an arrangement in which the plant pays for electricity generated at a wind farm and fed into the regional grid. However, the amount of renewable energy in a given market is in limited supply, thus the use of renewable energy exposes desalination plants to increasing power costs. The following section considers how the cost of power impacts the operation and maintenance cost of desalination and how the desalination industry could be affected by the cost of carbon under an emissions trading scheme

What is the impact of the costs of power and carbon on desalination?

The energy cost in the form of electrical power represents the largest operating cost of running an RO desalination facility. As the energy requirements contribute approximately 60% of the total O&M costs, a doubling of the cost of electricity from $0.10/kWh to $0.20/kWh would correspond to an overall increase in the O&M cost by 70% - such that the total unit cost of production would increase from $0.66/m^3 to $1.12 /m^3 (Figure 5)

Figure 5: Sensitivity of unit cost of production to electricity prices



It is likely that within the lifespan of any new major capital works, such as a desalination facility, the government will impose additional costs for carbon emissions. Accordingly, it is prudent to evaluate the impact or sensitivities this would have on a new desalination facility.

The amount of carbon emitted to produce a cubic meter of potable water by seawater desalination will depend on the source of energy used to generate electricity, the amount of chemicals used in the process and life of consumable items such as the membrane. Using estimates from the Australian Greenhouse Gas office (www.greenhouse.gov.au) it is possible to estimate the kg CO_2/m^3 of desalinated water Table 2. The largest component of the kg CO_2/m^3 for desalination is power. Consequently, water utilities in Perth, Sydney and Melbourne have committed to buying renewable energy credits to offset the greenhouse gas emissions.

Offsetting the carbon emissions associated with desalination is an important part of managing potential increases in the cost of water as a result of the introduction of an emissions trading scheme or equivalent system that puts a price on carbon. For example, based on the reported use of 24.1 MW at the Kwinana facility the total energy used per unit of water is approximately 4.6 kWh/m^3. The total carbon dioxide equivalent volume generated based on the average energy supply would be 4.7 kg to 6.0 $CO_2\text{-e}/m^3$. From this value the increase in the unit cost of production for a carbon tax of between $5 and $100/tonne C is given in Figure 6. The inclusion of a carbon tax at $50/tonne C would correspond to a 16% increase in the unit cost of production (Figure 6).

Table 2: Typical equivalent CO_2 emissions for a 100 ML/d single pass reverse osmosis plant

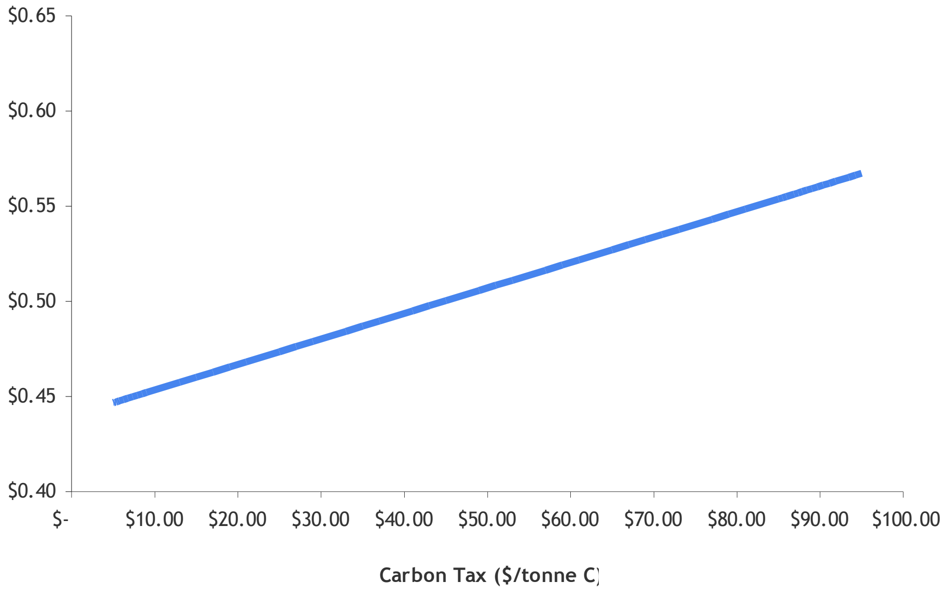
Process Input	Purpose	Typical amount (mg/L)	Typical amount (kg/d)(1)	Emission factor (kg CO_2-e/kg produced)(2)	Tons of CO_2-e/d
Power	Feed electrical pumps	4.5 (kWh/m^3)		1.467 (kg CO_2-e/kWh)	660.15
Cl_2	Pre-treatment process	50	12345	1.2	14.81
$FeCl_3$	Pre-treatment process	5	1234	3.23	3.98
Antiscalant	Pre-treatment process	3	740	7.4	5.48
HCl	Pre-treatment process	20	4938	0.76	3.75
NaOH	Second pass pr-treatment	6.34	704	3.23	2.27
Nylon	Membranes	4595 elements	30 (3)	84.4	2.55
Total carbon emitted in 100 ML/d single pass desalination plant (kg CO_2/m^3)					

[1] Based on a typical amount of 100 ML/d.

[2] Data sourced from AGO Factors and Methods Workbook, December 2005.

[3] Based on five years life time of the membrane element.

Figure 6: Sensitivity of Unit Cost of Production to a Carbon Tax



What are the prospects of further reductions in desalination energy requirements?

This section canvasses future prospects in desalination R&D, and the likelihood of a breakthrough emerging from current or future research that could reduce the energy associated with the desalination process. The history of desalination development and current industry trends offer important lessons on the prospects.

1. The major breakthroughs occurred in the 1960s when very significant funds were provided to investigate a broad range of concepts.
2. Industry and researchers subsequently achieved major improvements by incremental changes (e.g. the 500 fold increase in the Forward Osmosis membranes for the Spiral Wound Membrane).

Prospects for further incremental improvements are high, based on improved understanding of existing processes, powerful simulation techniques and market forces. The prospects for a major breakthrough are less evident. It would probably require adopting the Office of Saline Water (OSW) approach, in which the intellectual property from government funded R&D activities could be held in trust, and the technology commercialized by independent companies via a licensing agreement. This mechanism would allow several manufacturers to achieve the competition and economies of scale that have driven the desalting industry to date. If the technology is to be licensed on an exclusive basis, it must offer significant energy and cost savings if end users (water authorities/municipalities) are to tolerate a monopoly. Since the water industry is conservative and risk averse, demonstration scale plants are necessary before any new technology is used at the municipal scale. This is important when considering the potential of research into sustainable desalination systems that use renewable forms of energy. Any innovations will require developments in novel infrastructure to support the technology. Accordingly, the capacity of desalination systems that use renewable energy is typically less than 1000 m^3/d.

Table 3 summarizes the opportunities and the (arguable) probabilities of either incremental improvement or breakthrough in the various desalination options and related ancillaries.

Brief snapshots of different techniques and processes for the further development of desalination follow.

- Thermal Processes - These are very mature processes and a breakthrough would be very unlikely. However further improvements are anticipated and present R&D opportunities exist – in operations, materials and modelling of hybrid processes.
- Electrodialysis: ED/EDR - ED is a mature process and is unlikely to experience breakthrough, but there may be incremental changes in membranes and modules. EDI offers R&D opportunities for process optimization, rather than breakthrough.
- Capacitive Deionisation: CDI - This technique is not yet applicable to seawater desalination, and to be effective it will require incremental improvements in module design and scale-up. To be sufficiently energy efficient to out-compete RO, this technique would require a breakthrough in electrode materials and fabrication giving very high-energy recovery. This may be possible.

- Reverse Osmosis: RO - RO is a mature technology, but further incremental improvements in membranes and modules are probable. Breakthrough may come from novel nano-engineered membranes. However improved membranes will require improved (breakthrough) fouling control. Radical redesign of RO cascades may be required.
- Forward Osmosis: FO - The existing FO membranes need to be improved and this can be anticipated. The viability of FO will require a breakthrough in draw solute specification and regeneration. There is a strong probability that this will occur.
- Membrane Distillation: MD - While it is difficult to anticipate a breakthrough in MD, this process is in need of R&D – to provide the incremental improvement to modules and process needed to make it a commercially attractive option.
- Bio-enabled - This option is not yet proven for seawater desalination. It is intrinsically attractive but will need breakthroughs for successful fabrication and scale-up.
- Pretreatment - This is a major issue for any of the desalination options. Improved pretreatment by R&D can be anticipated; the major focus will probably involve low pressure membranes. It may be possible to exploit a novel phys-chem or biological process in a new approach.
- Energy - The strong incentive to reduce energy usage will ensure the continuation of R&D efforts directed towards that goal.

Table 3: Incremental & breakthrough opportunities for desalination options

Process	Incremental improvement	Breakthrough	Major Opportunity/Challenge Analysis
Thermal	High prob. -	- Negligible	Better scale control, materials, hybrid optimization. (No obvious opportunity for breakthrough.)
ED/EDI	High -	- Negligible	Lower cost membranes & EDI optimization. (No obvious opportunity for breakthrough.)
CDI	Possible -	- Possible	Practical modules and scale-up. Novel nano-structured (non carbon) electrodes with high energy recovery.
RO	High -	- Possible	Better membranes and module design (track record). High performance membranes from nanotechnology (mixed matrix, C nanotubes). High flux needs improved CP[1] control. Osmotic pressure is unavoidable.
FO	High -	- Probable	Improved membranes. Effective draw solute + efficient regeneration.
MD	High -	- Unlikely	Improved membranes and modules. (No obvious opportunity for breakthrough).
Bio-enabled	-	- Possible	(No established process to optimize as yet). Proof of concept, scale-up, CP[1] control.
Pretreat	High -	-Possible	More efficient removals at lower energy and cost. Exploit novel physico-chem-biological processes
Energy	High -	- Possible	Improved energy recovery, lower losses, modelling. Process specific opportunities

[1] CP is concentration polarization, which occurs at the surface of separation (i.e. membrane) and is usually controlled by fluid mechanically induced mass transfer (fluid flow management in the module).

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Direct Coupling of Renewable Energy and Desalination

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Purpose and Drivers

As the population and demand for water increases across Australia and the supply of freshwater in both coastal and rural regions dwindle and become more stressed, the importance of providing a secure, sustainable and weather independent source of freshwater has become a political and social focal point. Desalination has been adopted by all major cities in Australia and many cities around the world as an answer. However, widespread adoption in a sustainable manner that does not trade rainfall dependence for increased non-renewable energy dependence has proved challenging and elusive.

This paper presents a brief review of the current application of renewable energies used in large scale desalination plants within Australia. It also identifies the key shortcomings and barriers to the universal use of renewable energy systems for large scale seawater desalination plants. From these challenges, a range of potential research opportunities are derived and postulated.

Seawater and brackish water desalination will play a greater role in the future water supplies for inland and coastal populations for Australia. Sustainable desalination is demanded by water planners and the public to address climate change and a desire for more secure water supply – independent of non-renewable fossil fuels and rainfall. Inland communities within Australia, whose water supplies are slowly turning brackish or have little alternative but to use brackish groundwater reserves, will also need to find a way of providing cost effective, climate responsible and sustainable freshwater supplies. Lastly, there is a desire and potential to provide global leadership; pushing Australia to the forefront of sustainable desalination technology.

Status of Renewable Desalination in Australia

Many Australian cities have recently constructed desalination facilities to provide a secure, reliable and rainfall independent water source. This investment in desalination has occurred against a backdrop of declining dam storage levels and the longest drought in Australia's modern recorded history. In this context immediate water security has been given the highest short-term priority and other longer range considerations, such as increasing dependence on non-renewable fossil fuels, have been deferred to the future.

While seawater desalination is less politically and socially charged than water recycling, the energy intensity of the desalination presented a significant public acceptance hurdle and this aspect continues to draw negative attention. To mitigate this criticism, the first large Australian desalination facility (in Kwinana, WA) was powered by purchasing power from a wind farm thereby offsetting the greenhouse gas emissions by the desalination facility[2]. This strategy paved the way forward for all Australian desalination plants which followed. To power its desalination plant in Kurnell, Sydney Water has constructed a wind farm to generate sufficient power to offset the power consumed by its desalination plant. Other recent Australian desalination facilities (Adelaide, Gold Coast, Melbourne and Western Australia's second desalination plant) have committed to purchasing renewable energy credits.

It is unquestionable that these strategies are moving desalination in the right direction, however, they are not without their critics and concerns that such practices are trading rainfall dependence for energy dependence. Ultimately, the purchase of renewable energy credits does not reduce a desalination facility's dependence on non-renewable fossil fuels. Fossil fuel derived energy must still be used during periods when renewable energy is not readily available (windless days for example). This shortcoming highlights an issue with the desalination technology used by all large desalination facilities, none of them are well suited to being directly and solely powered by renewable energies.

Desalination using renewable energy

So how then do we ever achieve a desalination facility that is entirely powered by renewable energy and can truly claim to be carbon neutral without resorting to offsets and carbon credits? To design a desalination system powered entirely by renewable energy, the approach has been to couple existing and mature desalination processes with different forms of renewable energy. This coupling has been successfully demonstrated using many of the mature desalination processes such as reverse osmosis. Desalination techniques can be summarised as follows:

- Traditional Thermal & Mechanical Processes
    - Multiple Effect Distillation (MED)
    - Multiple Stage Flash (MSF)
    - Thermal Vapour Compression (TVC)
    - Mechanical Vapour Compression (MVC)
- Pressure Driven Membrane Separation
    - Reverse Osmosis (RO)
    - Nano filtration (NF)
- Membrane Distillation
- Solar Distillation (SD)
- Humidification-Dehumidification (HD)

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[2] The Water Corporation of Western Australia originally claimed that Kwinana was "carbon neutral" and powered by 100% renewable energy. These claims were later examined by the ACCC and these claims of carbon neutrality and 100% renewable energy usage have been modified or withdrawn by the Water Corporation.

- Electrical Separation
    - Electrodialysis (ED)
    - Electrodialysis Reversal (EDR)
    - Capacitive Deionisation (CDI)

The most common forms of alternative renewable energies which have been investigated and piloted include: solar, geothermal and wind. Wave power has also been used, but its application is somewhat limited. Each of these energy sources can be coupled with a different desalination technique as illustrated in Figure 1 to achieve desalination using renewable energy.

Figure 7. Potential combination of desalination techniques and renewable energy systems (adapted from Mathioulakis et al 2006)

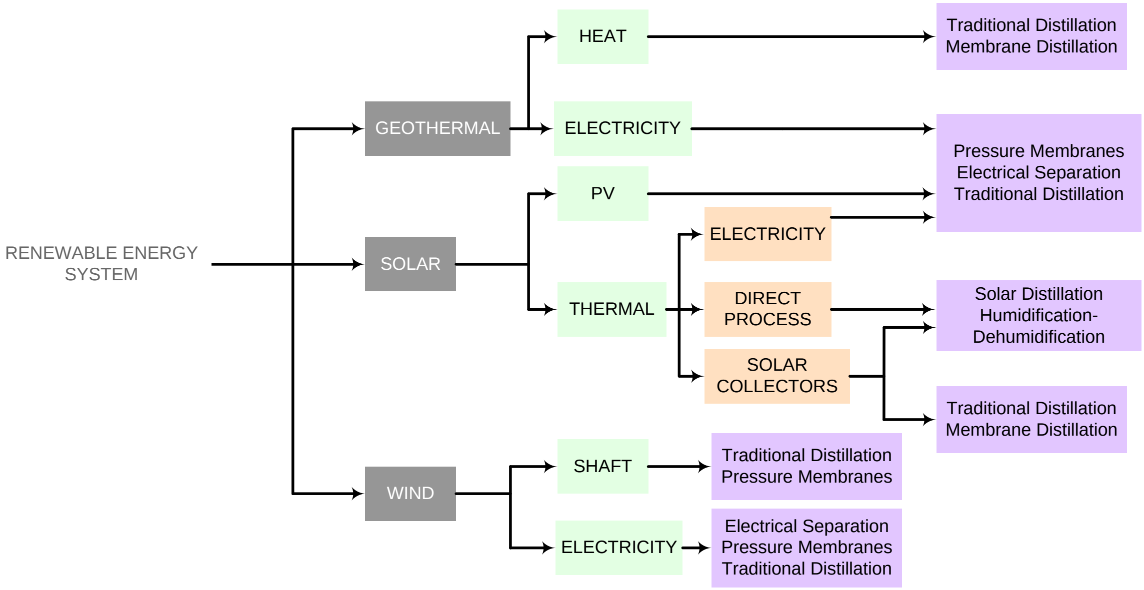
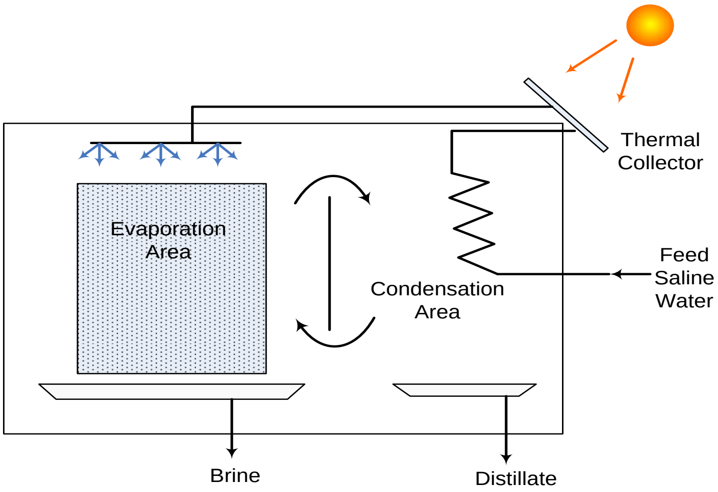


Figure 1 clearly demonstrates the dominance of solar power in providing an alternative source of energy for desalination. Photovoltaic solar power can be used to power pressure driven and mechanical desalination processes (RO, NF or MVC), however solar thermal is by far the more flexible in terms of the number of desalination techniques which it can potential power or drive.

Traditionally and the current accepted practice is the desalination of seawater using thermal/mechanical or pressure driven membrane processes. Thermal/mechanical processes heat seawater to produce a vapour which is then condensed producing distilled water. Membrane processes, on the other hand, use pressure to force seawater through a membrane impermeable to salt. Coupling these steady-state processes to alternative energies, which are intermittent and variable by their nature, has limited the application of alternative energies to date. Some work has been done into the storing of energy (either in the form of heat or electricity) for later use by the desalination processes but this has been hampered by the limitations in the available energy storage technologies (batteries for electricity, geothermal or molten salt for heat).

Recently more focus has been placed on other desalination techniques such as humidification/dehumidification (HD). This process uses a heat source (typically solar) to warm the incoming seawater, creating a humid air which can be condensed against the cool incoming seawater. One large scale and novel application of this process is the "Teatro del Agua" which uses the natural winds to carry humid air to the condensers.

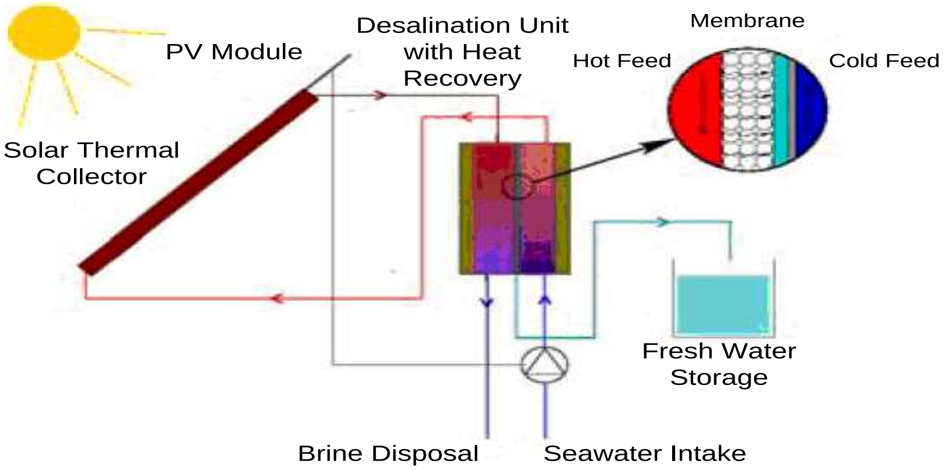
Figure 8. Schematic of humidification-dehumidification process (adapted from Mathioulakis et al 2006)



Membrane distillation is a similar process to HD but includes uses a vapour permeable membrane to separate the warmed seawater from the cooled feedwater. While seawater cannot travel through the membrane, water vapour can allow it to travel to the cooled by side of the membrane where it condenses.

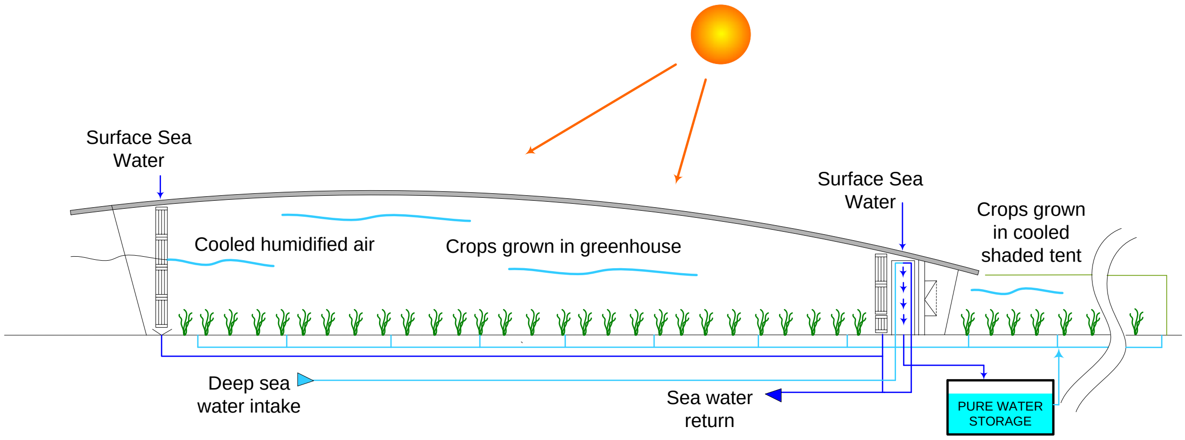
This technology has been successfully trialled by the Fraunhofer Institute for Solar Energy Systems in five different arid countries on a small scale (Koschikowski et al 2003).

Figure 9. Schematic of membrane distillation process (adapted from Koschikowski et al 2003)



Other innovative research directions involve creating desalinated water for a specific purpose. One such example is the Seawater Greenhouse which is a concept combining the HD processes mentioned above with classic solar still technology to create a productive agriculture environment.

Figure 10. Schematic of seawater greenhouse (adapted from www.seawatergreenhouse.com)



Challenges

The adoption of "renewable energy desalination" has been limited for a variety of reasons:

- Operating regime – traditional pressure and thermal desalination processes have been designed and optimised to operate at steady state. Given the intermittent and variable nature of renewable energy, a mismatch between energy availability and energy demand (from the desalination process) exists. The renewable energy must be able to provide a consistent source of power (using batteries for example) or the desalination process must be redesigned to allow for intermittent operation.
- Scale – several sustainable desalination systems have been piloted successfully on a smaller scale. The technology would likely need to be reconfigured to be applied at the scale required for a large centralised water treatment facility.
- Costs – the estimates published in literature indicate that the costs of sustainable desalination facilities are more expensive than traditional ones.
- Residuals – any form of desalination will inevitably produce residuals (concentrated salts for example) which require disposal. This is a more serious issue with in-land desalination where ocean outfalls are not possible.
- Footprint – for a large scale desalination process collecting wind or solar energy requires large amount of land. (Sydney's desalination plant, for example, will be powered by 67 wind turbines) To achieve a sufficient amount of power would require a large expanse of land to supplement energy requirements for large scale desalination (in excess of 1 km2 in Sydney's case).
- Location of renewable energy source – typically the available land used to supply the renewable energy is not located near where freshwater is required. Transmission is therefore needed, either of the treated water or the renewable energy.

Research and Next Steps

Each of the challenges or barriers mentioned above highlights an opportunity for new research, new directions or novel ideas for desalination. Some of these are summarised as follows:

- Desalination processes and renewable energies need to be investigated in unison so each can be optimised for the other. This may include redesigning a thermal process to operate entirely on solar thermal energy or reconfiguring an RO membrane process to allow it to operate intermittently (powered by a renewable source).
- The cost of the renewable energy source and the desalination technology must be reduced. A detailed cost analysis of large scale sustainable desalination processes should be undertaken to understand where cost savings can be realised.
- Scale – for large-scale renewable energy desalination to be a success, the existing small scale pilots would need to be scaled up. The scalability of these processes is not trivial; several of the processes may need to be entirely reconfigured to operate at a large scale.
- Evaluation tools – given the diverse range of desalination processes and renewable energies, it is a challenging (near impossible) task to identify which processes are preferable for a given location or region. Creating a model which could simulate the performance of each desalination process and renewable energy, given a set of inputs (water quality, wind availability, solar radiation, etc.) would create a universal methodology to evaluate any potential sustainable desalination technology.
- Planning tools – most communities and cities considering large scale desalination have other water sources (ground or surface water) which are either too unreliable or too small to meet their particular water needs. For these communities, large scale desalination does not present a complete solution to their water needs but rather an additional resource. Planning the implementation and operation of large scale desalination facilities whose operation fits into a larger water supply scheme requires detailed modelling and analysis tools which are not currently available. Issues such as water quality, operating (demand) regime, and even water pricing could be simulated using a holistic model built around concept of "integrated water management".
- Residuals handling and disposal technologies are essential, not just for sustainable desalination, but desalination in general. Experimentation using different residual handling methods should be investigated. Additionally, investigating the possible beneficial uses which might be derived from the residuals (for example commercially available salt, algal biofuels or saline agriculture) should be also studied.
- Embodied energy – the construction of sustainable desalination plants will be driven by the need for sustainability across the water industry. This construction will consume new materials derived from fossil resources. Very little thought has been given to the ultimate fate of desalination equipment or how this could be made more sustainable (all used RO membranes, for example, are sent to landfill). Developing a "cradle-to-grave" or "cradle-to-cradle" design will be an integral part of the next generation of sustainable desalination.

Conclusion

Considerable challenges must be overcome before the coupling of renewable energy systems and seawater desalination can become a viable large scale solution to freshwater supply in Australia. Key research areas include the optimisation of existing coupled systems focusing on scalability and cost effectiveness, development and deployment of evaluation and planning tools, investigations into novel residuals handling techniques and embodied energy investigations. Water security is a significant concern throughout Australia, and all would benefit from the research in these fields.

About the authors

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GEO-PROCESSORS USA, Inc.

Inland Desalination Brine Management

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Foreword

This white paper is not intended to provide an exhaustive review of the status of desalination brine management, as historically desalination has played a minor part of water supply schemes in inland regions of Australia. Furthermore, brine management approaches elsewhere have varied significantly from one place to another and most have limited or no applicability to Australian conditions. The paper is instead about the identification and synthesis of the key inland desalination brine management issues in an Australian context. Our objective is to highlight the needs for removing this major impediment to the development of the inland desalination industry through a strategic research agenda that is led by the National Centre of Excellence in Desalination (NCED) and its research partners, and incorporates the development of sustainable desalination brine solutions.

Why inland desalination?

Until recently Australia had less than one per cent of the world's installed desalination capacity with the majority of desalination plants using small RO plants to treat brackish or mildly saline water for water supply to remote settlements in the arid interior of the continent, such as those serving the mining towns in South Australia, water supply on Kangaroo Island (South Australia), and Rottnest Island (Western Australia), tourist resorts including Heron and Hayman Islands in Queensland, and some offshore oil platforms. RO plants are also operated by mineral processors and power plants; for example, the RO plant at Bayswater Power Station in NSW was until recently the largest of its kind in the world (35 ML/day). Although desalination brine has long been considered an asset and several feasibility studies have been undertaken to assess the potential for salt harvesting and recovery of other minerals, the bulk of brine effluent from these facilities have been discharged to landscape because of the cost of further treatment and remoteness of the sites from potential product markets.

However, in the past decade with the onset of prolonged drought and significant population increase, seawater desalination has become an important component of water supply portfolio of the major population centres in Australia. Desalination of inland brackish and mildly saline water resources has also increasingly become a necessity in Australia primarily because of the following mix of economic and environmental drivers:

- As a component of inland community and industrial/regional water supply portfolios
- Control of (a) urban salinity (dewatering), (b) salt intrusion to inland waterways (Murray-River) or coastal fresh ground water resources
- As a measure for enhancing the beneficial uses of recycled water
- As a measure for water recovery from waste water and volume reduction, and
- As a measure for disposal of produced water from large resource development projects.

From the above list it can be seen that a key contributor to the heightened interest in inland desalination is the "multi-functionality" of desalination processes beyond their primary purpose of community water supply. Take the example of inland rural towns where the desalination of shallow groundwater can secure not only a decentralised freshwater source, but provide also a means for the reduction of salinity impact on the infrastructure and private assets and meantime potentially generate values for local communities through beneficial use of desalination brine.

Or take another example of the emergence of a massive coal seam gas (CSG) and the associated liquid natural gas (LNG) industries in inland Queensland, where desalination has been touted as the only practical means for beneficial use and reduction of the massive volumes of produced water, which is expected to be generated as part of the projected >$40 billion worth of LNG development projects. In this latter case, because of the project's massive water flows, volume reduction will take a precedent to the supply of freshwater for beneficial use. Another example of the multi-functionality of inland desalination processes, relates to the role of desalination as a means for both the reduction of large volumes of mildly saline recycled water from inland water treatment plants and supply of desalted water for downstream beneficial use.

Thus, beyond the prime object of water production, desalination processes are poised to provide the only practical means for effective reduction of massive flows of produced water that are projected to be generated in inland Australia in the coming years. Accordingly, apart from salinity, volume reduction is another key driver of the need for desalination processes for safe disposal of such waters in inland regions. Otherwise, both the beneficial use and cost efficiency of brine disposal would be problematic and potentially pose a major impediment to the full development of inland resources.

Desalination brine solutions in the context of broader salinity management in inland Australia

All desalination processes produce a reject stream, commonly known as brine or concentrate, that is more concentrated than the feed water, therefore needing proper disposal. The appropriateness of brine management practices is critically important in inland Australia, particularly in arid regions where the impacts of dryland salinity and human-induced salinisation of land and water resources are prevalent. As the desalination industry develops, there will be concerns within communities and regulatory bodies regarding the potential of desalination brine to further aggravate the existing salinity problems, particularly in farming areas and rural towns where both public and private assets are involved. The concerns with appropriateness of brine management measures are expected to be highlighted in the cases where desalination brine carries the overprints of other water quality issues such as, alkalinity, acidity, sodicity, toxic element spikes and the presence of chemicals of concern - all sources of significant public apprehension for their potential adverse impacts on the health of waterways, soils and local water supply. However, the primary concern is expected to revolve around the issue of long-term surface storage of concentrated brine, particularly where engineering solutions, such as evaporation ponds, enhanced evaporation systems and surface transfers through drainage channels have failed. This is exemplified by recent vocal opposition of inland communities in Queensland to the storage of untreated ground water co-produced with coal seam gas generation in evaporation ponds. This concern has since been resolved through recent state legislation that bans the use of evaporation ponds as a primary measure for managing untreated produced water. Using the case of Queensland, the expected key drivers of public concern will firstly be the scale of brine production from future desalination facilities (which in turn will define the volume of the salt load potentially transferred from groundwater to landscape) and secondly, the further aggravation of existing salinity issues.

On the basis of the above situation analysis it is argued that the future options for sustainable management of inland desalination brines shall embrace the principles of waste minimisation right through project planning to the design and implementation stages. Further, the solutions will need to conform to local regulatory and community expectations while also addressing the externalities such as regional salinity and climatic change. In this context, the scale of future desalination projects will exert a direct influence on the nature and intensity of the issues and thus future research directions to offer innovative and smart brine solutions.

Characteristics of inland desalination brines

The different applications of desalination methods to the treatment of saline water involve a broad range of salinity and composition. Not only are performance and cost of desalination processes strongly dependent on feed water quality characteristics, but the feasibility of the management options for the brine produced are also strongly dependent on source water quality characteristics.

Figure 1 and the text describing it (below) reflect the several different applications of desalination methods. Figure 2 and Table 1 (below) document the broad range of salinity and composition encountered in the various applications.

Applications of desalination methods

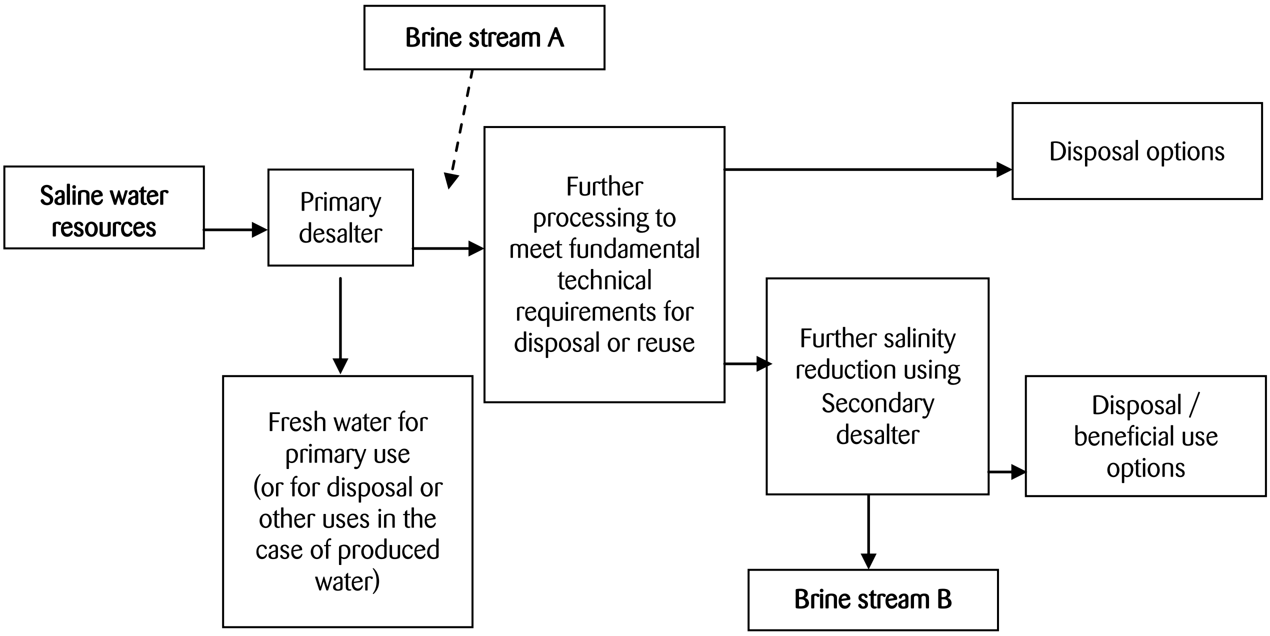
Desalination brines are a reflection of the type of feedwater and salt reduction method applied for the recovery of freshwater for the intended beneficial use. Although for recycling/reuse purposes salt reduction may involve two or more steps of desalination, feed water type exerts a fundamental influence on the quality of brine to be managed and the following overview specifically deals with water types and desalination brine types.

Broadly defined, saline water resources subjected to desalination in inland areas are:

- Surface or groundwater not impacted by human activities
- Surface or groundwater impacted by human activities (impaired waters), and
- Produced water.

Desalination is a salt reduction method that is applied primarily for recovery of fresh water for beneficial use of the above water resources. However, as schematically shown in Figure 1, desalting methods may equally be applied to meet reuse requirements as well as for enabling the safe and sustainable disposal of brine from primary desalination processes. A distinction is made herein between conventional definition of primary and secondary desalination systems (which may involve the use of either enhanced RO systems or various combinations of RO and EDR desalination trains to improve water recovery rate or reduce the cost of treatment systems), and the one used herein that implies treatment of desalinated water after its primary beneficial use, as shown in Figure 1.

Figure 1. Schematic of application of desalting methods.



Although varying from one industry to another, the fundamental drivers for application of multiple desalination steps are the technical requirements to overcome the limitations with the disposal of brines from primary desalting source (i.e., for regulated discharge) and to address the opportunities for value adding including additional water recovery and recovery of valuable byproducts from brine streams and ultimately achieving a zero liquid discharge (ZLD) or near-ZLD outcome.

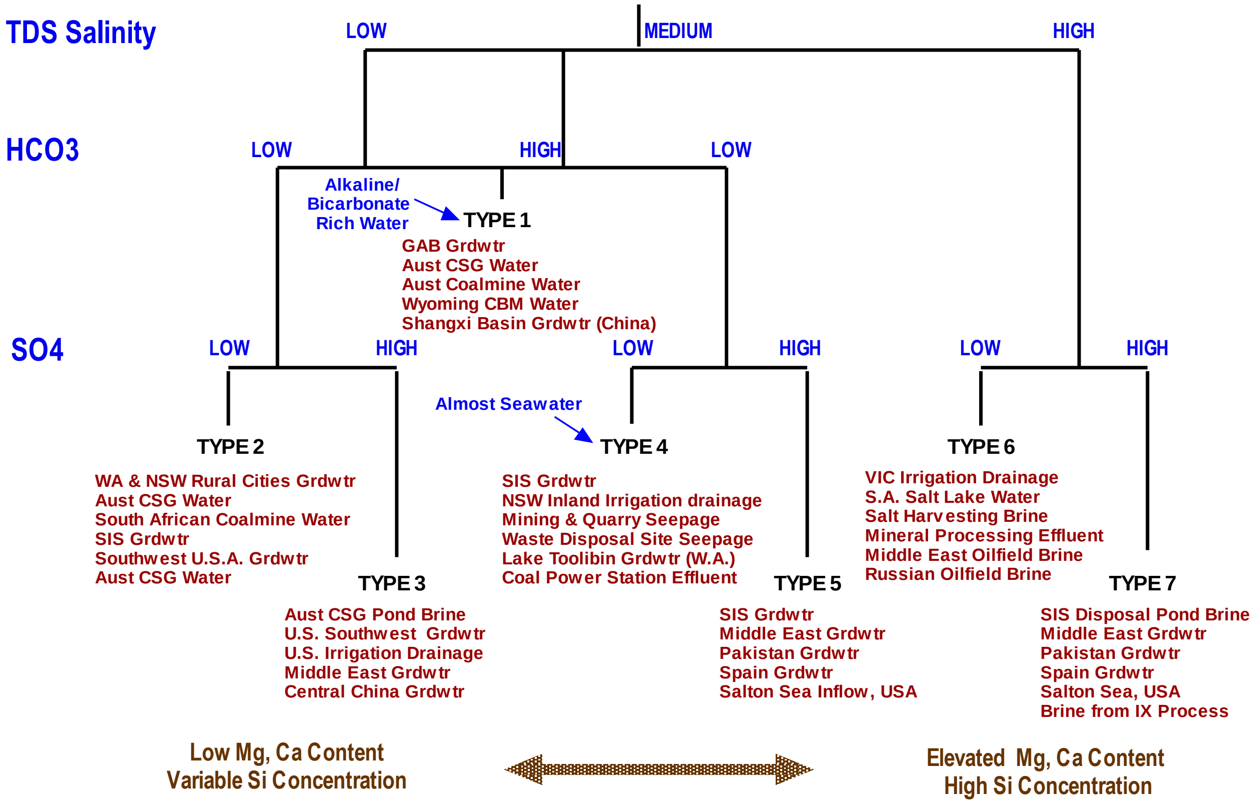
As the constraints with disposal of brines are largely influenced by the local and regional regulatory regimes, the extent of treatment by desalination processes is largely environmentally and cost driven and this in turn varies significantly between different industries subjected to different effluent discharge guidelines and with different financial capabilities. Several studies on beneficial use of concentrate from desalination facilities have been carried out in the US (for example CH2M Hill 2006) with nearly all concluding that the options for the beneficial use of RO brines are limited unless it is further treated. As indicated earlier, the problem is compounded by the risks associated with land application of untreated brines, particularly landscape contamination due to elevated salt load, sodicity, acidity and/or concentration of toxic metals and chemicals of concern. With the onset of a low carbon economy and growing emphasis on life cycle costing, there is an additional concern with the influence of the cost and liabilities associated with disposal of untreated brines. This particularly applies to the long-term economics and sustainability of operations generating large volumes of produced water for which desalination is a necessity to enable beneficial use and also a means for volume reduction of the residual streams. For example, in large-scale coal seam gas generation or large municipal water recycling projects, it is critically important that the selected desalination-based treatment system is capable of dealing with large volumes of water and is sufficiently scalable and flexible to provide economies of scale while minimising the footprint of future salt reduction requirements through increase or decrease in flow rates.

Range of salinity and composition of desalination source waters

Figure 2 categorises inorganic saline waters according to 7 basic compositional types developed and used by Geo-Processors. These types were determined from analysis of a great number of waters across the globe and provide insight into both treatment approaches and salts that can be practically obtained from the different waters.

Of note is the wide range of salinity and composition in general and for different source waters. Table 1 represents several Australian saline waters according to Percent Difference From Balance (PDFB) parameters developed by Dr Mickley. The PDFB parameter compares a water composition to that of seawater diluted or concentrated to the same salinity. Thus it eliminates salinity as a variable and reflects the compositional makeup of the water relative to seawater. A water of having a relatively greater amount of a major ion than seawater at the same salinity has a positive PDFB value for that ion. Similarly, a water having a relatively lesser amount of a major ion than seawater at the same salinity has a negative PDFB for that ion. Seawater by definition has PDFB values zero percent. While originally developed as a predictive indicator for major ion toxicity in groundwaters (Mickley, 2000) the parameter also serves to characterise the composition of waters relative to seawater.[3]

Figure 2. Classification of saline waters into water types according to molar ratios of Cl/HCO_3 and Cl/$2SO_4$ (Geo-Processors, 2008) and selected Australian and overseas saline and alkaline water resources falling into these water types.



Abbreviations:
Grdwtr: Groundwater
GAB: Great Artesian Basin
CSG: Coal Seam Gas
CBM: Coal Bed Methane
IX: Ion Exchange

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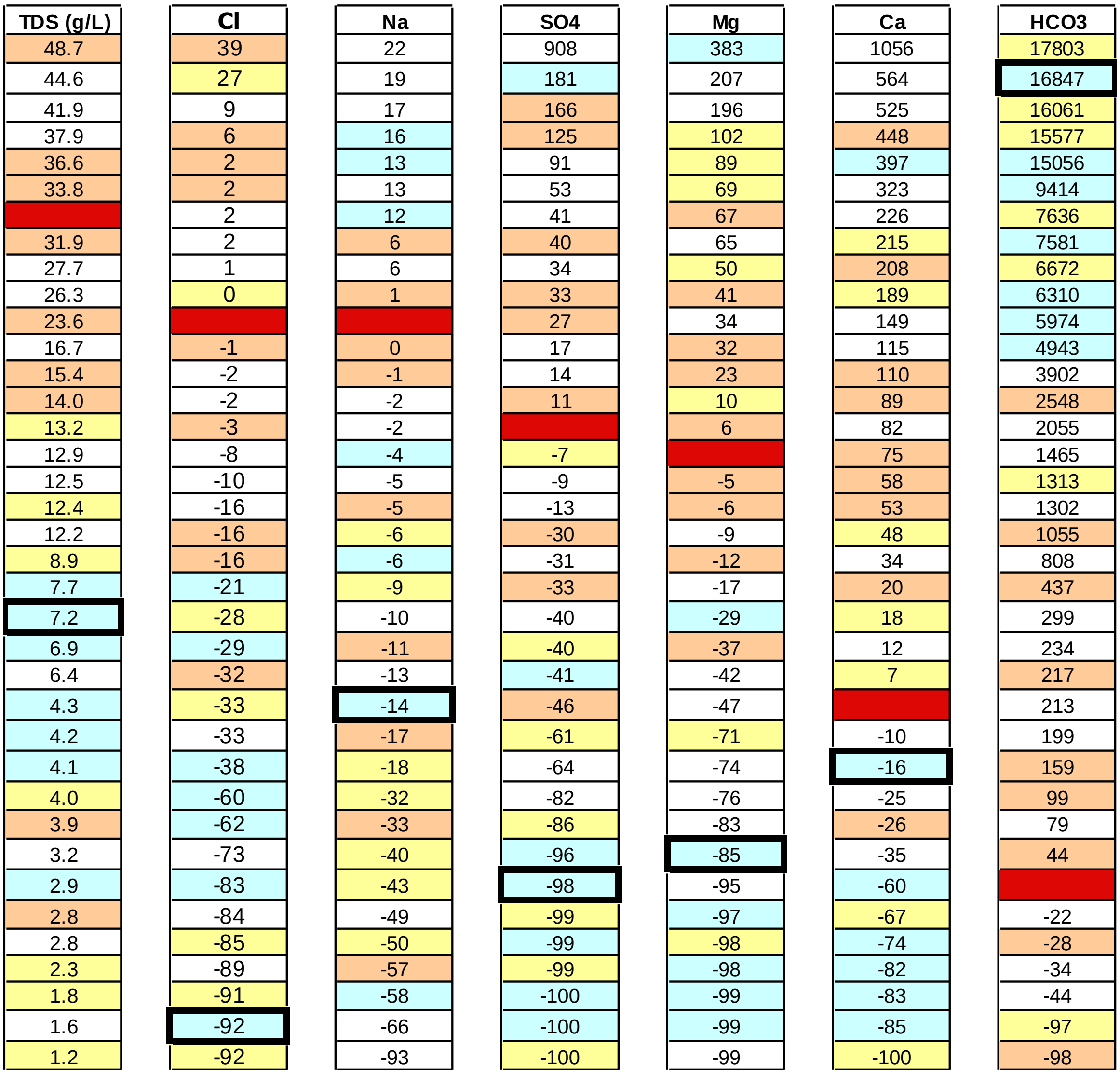
[3] From a physiological perspective, seawater and more specifically the relative major ion composition of seawater at any salinity is considered a 'balanced' water. Freshwater and marine organisms are least challenged by major ion concentrations that are 'balanced' at a salinity appropriate for the particular organism.

Table 1. Ranking of various Australian waters by TDS and PDFB values.

Type of source water represented by color according to:

🟨	**Groundwater underlying rural towns facing salinity (WA and NSW)**
🟦	**Coal mine and coal seam gas produced water**
🟧	**Groundwater associated with Salt Interception Schemes (NSW, VIC and SA)**
⬜	**Various groundwaters, mine seepage waters and storage lake water**
🟥	**Seawater**



TDS (g/L)	Cl	Na	SO4	Mg	Ca	HCO3
48.7	39	22	908	383	1056	17803
44.6	27	19	181	207	564	**16847**
41.9	9	17	166	196	525	16061
37.9	6	16	125	102	448	15577
36.6	2	13	91	89	397	15056
33.8	2	13	53	69	323	9414
🟥	2	12	41	67	226	7636
31.9	2	6	40	65	215	7581
27.7	1	6	34	50	208	6672
26.3	0	1	33	41	189	6310
23.6	🟥	🟥	27	34	149	5974
16.7	-1	0	17	32	115	4943
15.4	-2	-1	14	23	110	3902
14.0	-2	-2	11	10	89	2548
13.2	-3	-2	🟥	6	82	2055
12.9	-8	-4	-7	🟥	75	1465
12.5	-10	-5	-9	-5	58	1313
12.4	-16	-5	-13	-6	53	1302
12.2	-16	-6	-30	-9	48	1055
8.9	-16	-6	-31	-12	34	808
7.7	-21	-9	-33	-17	20	437
7.2	-28	-10	-40	-29	18	299
6.9	-29	-11	-40	-37	12	234
6.4	-32	-13	-41	-42	7	217
4.3	-33	**-14**	-46	-47	🟥	213
4.2	-33	-17	-61	-71	-10	199
4.1	-38	-18	-64	-74	**-16**	159
4.0	-60	-32	-82	-76	-25	99
3.9	-62	-33	-86	-83	-26	79
3.2	-73	-40	-96	**-85**	-35	44
2.9	-83	-43	**-98**	-95	-60	🟥
2.8	-84	-49	-99	-97	-67	-22
2.8	-85	-50	-99	-98	-74	-28
2.3	-89	-57	-99	-98	-82	-34
1.8	-91	-58	-100	-99	-83	-44
1.6	**-92**	-66	-100	-99	-85	-97
1.2	-92	-93	-100	-99	-100	-98

Each column of Table 1 ranks the PDFB value for a given ion from the highest value to the lowest found in the 39 saline waters representing four different general sources of water. The color code identifies the general water source. The dark red cell denotes the zero value for seawater. The columns are independent of each other; i.e., columns in a given row do not correspond to the same water.

The data shows that most sites have (relative) levels of chloride less than that of seawater (negative values) while most of the sites have bicarbonate levels greater than that found in seawater (positive values). The wide range in composition of waters is evident from the wide range in PDFB values for each ion. In addition, each of the four general sources of water demonstrates a wide range in PDFB values (and thus in composition).

In summary, Table 1 and Figure 2 demonstrate the wide range in salinity and composition from the various source waters found globally (Figure 2) and in Australia (Table 1). This variability is one of the challenges to definition of cost-effective and environmentally sustainable brine management solutions.

Current desalination brine management practices

The issue of safe and cost-effective disposal of reject brine from inland desalination processes is not new but in view of the increased interest in inland desalination it has the potential to be a challenge for the Australian desalination industry because of the extent and perplexity of issues associated with dryland salinity and the land and water resources threatened by secondary salinisation.

In terms of the broader context of brine management issues and options, perhaps the closest corollary to Australian conditions is the arid to semi-arid region in the southwest US, where the issues with the disposal of brine from inland advanced water treatment processes have been well documented (Mickley, 2008a, 2008b, 2006, 2001, Mickley et al, 1993). There are, as of the end of 2003, 422 municipal water and wastewater treatment plants of size 25,000 gpd (0.95 ML/D) or larger utilising membrane technology in the 50 US states (Mickley, 2006) of which 234 employed desalination technology. Present estimates by the authors are for approximately 300 municipal desalination facilities and 300 low-pressure membrane facilities. While disposal options have been largely site-specific, until the late 1990's one or more of the following desalination brine disposal options were available to nearly every site or location (some of these final fate options have required minor treatment):

- Discharge to surface water
- Discharge to sanitary sewer
- Subsurface injection
- Land application
- Evaporation ponds, and
- Landfill of solids.

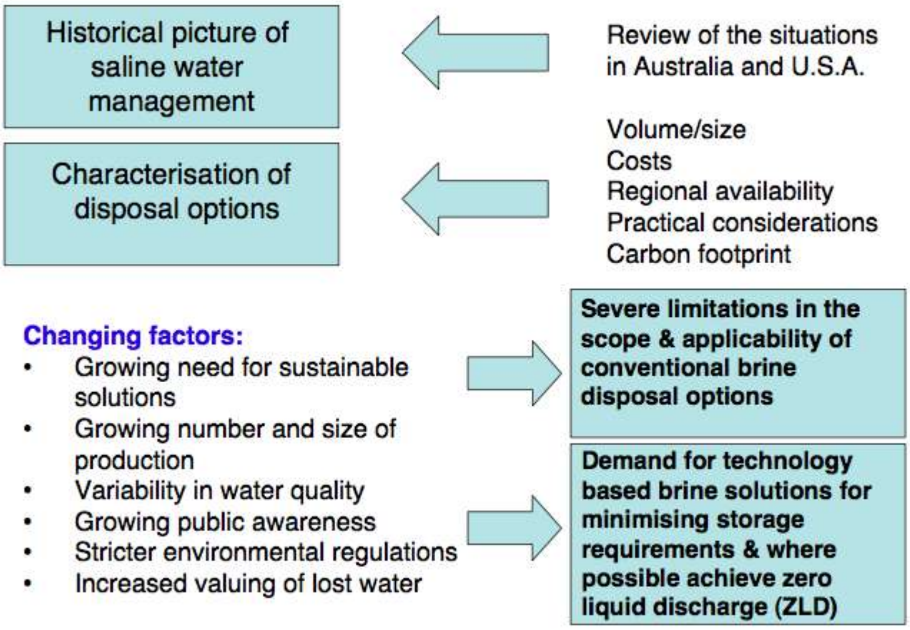
However in the past 10 years the number and size of both desalting and low-pressure membrane plants have increased significantly, and consequentially the disposal of brine has become a greater challenge (US Bureau of Reclamation, 2003; Brady et al., 2005; Mickley, 2006). Like Australia, the prolonged drought in the western United States has also generated a higher level of awareness and interest in recovering and/or recycling all potential sources of fresh water – including membrane brine.

Despite some recent efforts, particularly in catchment-scale evaluation of technology-based brine minimisation options (CASS, 2006), about 75% of desalination brine generated in the States are still disposed to surface water or to the front end of wastewater treatment plants. While disposal to surface water has been used with brines of all flow rates, disposal to the sewer is not typically used for larger volume brines, where concerns are raised about the effect of the brine TDS on process microorganisms and on the effluent TDS.

The growing number and size of plants, the more stringent discharge regulations, and the growing public awareness of environmental issues and concerns with the potential adverse impacts of climate change have increasingly resulted in desalination brine disposal becoming a growing challenge. It is also increasingly being recognised that technology-based solutions are needed beyond higher water recovery membrane systems for waste minimisation and reduction in the cost of disposal – such as by thermal evaporative technology (Figure 3). This is particularly the case in the Southwest where both the options of surface water disposal and disposal to treatment plants are severely limited. At present there are several inland sites where membrane desalting plants could provide needed drinking water if brine disposal solutions were available.

The primary problem associated with desalination brine is proper disposal. Improper brine disposal can just shift a water quality problem from one area (or one user) to another. A water problem is not resolved just by relocation. One example of technology limitations is the use of brine wetlands which has been extensively trialed overseas (and particularly in the Middle East) with mixed results; another example is the application of serial biological concentration (SBC) systems trialed in California and Australia. One major conclusion out of these efforts is that salt load buildup through relocation can reach a level that will limit additional discharges or scalability of the solution. This is unless the salt load and metals content are reduced by physical extraction from water using an appropriate technology (Blackwell and Arakel, 2005). Interest in technology-based brine solutions in the US is also driven by other factors including increased valuing of 'lost water' (such as disposed brine) and more recently the move towards sustainability of the brine solutions - a desirable and ultimately necessary direction.

Figure 3. Changing factors that drive the demand for technology-based brine solutions



The sustainability of brine solutions is particularly important in the case of brines from desalting of produced waters, wastewaters including coal mine water, coal seam gas (CSG) water, advanced treatment of recycled water as well as waste brines from treatment of effluent generated by activated sludge and/or lagoon processes. It is argued here that any technology-based brine solution will need to address both the issues of salinity and elevated spikes of metals and the chemicals of emerging concern before it is considered as a sustainable solution option. As direct disposal of brine is increasingly being considered as a loss of resource, there is an immense market opportunity for technology-based brine management solutions that enable maximum water recovery and lead to cost-competitive ZLD outcomes. To be cost-effective the technology behind the solution shall be sufficiently flexible for scale up in order to provide a reasonable economy of scale. Probably the most sustainable solution for a desalination brine (whether based on ZLD or involving regulated discharge) will come from the conversion of the residue from secondary membrane or thermal desalination and volume reduction processes into useful byproducts. The beneficial use or sale of these by-products could, in most cases, improve the economics of inland desalination projects, aimed at producing freshwater or salinity control, through the off set of operating costs.

From the point of water production and salinity perspectives, considering current and projected flow rates, brines associated with coal seam gas and municipal water recycling projects (for non-potable use) would probably represent the best candidates for satisfying the economy of scale requirement. Also, the closely located inland urban desalination projects could satisfy the scale requirement through the aggregation of brine resources for operating a central treatment facility, particularly where other benefits from centralised desalination are also considered in the cost-benefit analysis.

Review of literature indicates that the Australian occurrences of elevated spikes of particular metals and chemicals in inland brine streams will be largely site and industry specific and will therefore require evaluation on a case by case basis. However, the reduction technologies (for safe disposal or beneficial use of the treated brine) shall have application at catchment or regional scale as the availability of dissolved metals, metalloids and chemicals will be influenced by pH and redox conditions, both influenced by prevailing hydrological conditions at a large scale. As the Australian inland desalination industry grows into providing multiple benefits (i.e., combined water and volume reduction options) an effective approach to avoiding limitation with such benefits may lie in a systematic monitoring of the metals and chemicals of concern, particularly where chemical-specific risk assessment becomes necessary for regulation of a contaminant or for project permitting purposes. In the case of known occurrences or where brine resources from desalination of industrial effluent or produced water are expected to bear a significant contaminant footprint, some form of brine management guidelines may become necessary. In such a case a better approach would be to implement a baseline information gathering process and establish a clearing house, along the line of a brief discussion provided in the following sections.

Characterisation of the issues and the needs for sustainable desalination brine solutions

There are broad issues that are beyond the subject but that impact brine management. These include:

- The historic and ongoing under-valuing of water, and
- Inequity of economic clout between municipalities, agriculture and industries; many industries (including some municipalities) are increasingly realising the economic benefits of efficient water management (including the use of recycling and desalination). They are being driven towards more sustainable practices because they seek long-term viability and have found that it also makes mid-term economic sense (Glennon, 2009). Their economic situation allows them to explore short-term cost-intensive solutions.

These two issues together contribute to the difficulty of municipalities and the agricultural sector of realising cost-effective and environmentally sustainable brine management solutions.

The focus on brine management issues and needs for sustainable solutions are within this broader context. Issues and needs fall under several general categories (with some examples given) including:

- Cost
  - Need for cost-effective approaches for brine management that minimise potential environmental impacts
  - Need for broad total cost practices that include life-cycle analysis and consideration of physical, energy, CO2, and water footprints
  - Need to overcome inefficient economies of scale
- Technology
  - Need for understanding and dealing with the influence of variability in feed water composition on the quality of brine
  - Need for reduced processing (CAPEX and OPEX) costs where brine is further treated
- Limitations of brine disposal options
  - Need for expanding solutions beyond that of disposal to include beneficial uses of brine and possible treatment by-products such as salts
- Environmental/regulatory
  - Need to understand the environmental impacts of desalination and develop approaches to minimise these impacts relative to other water supply alternatives; reduce uncertainty about environmental impacts.
  - Need to develop science-based desalination brine-specific regulations
  - Need to anticipate the effects of climate change, decreasing source water qualities, changing regulations, and emerging contaminants.
- Decision-making support
  - Need for background information and guidance documents
  - Need for focusing on catchment-scale salinity management strategy
- Federal and state financial support
  - Need for leadership in terms of vision, policy, investment and incentives.

In summary, the key issues for brine management include:

- The influence of variability in feed water composition on the quality of brine
- Limitations with brine disposal options
- Inefficient economies of scale/need for cost reduction, and
- Lack of over-riding policy and vision for the role of desalination and sustainability.

The *best* and only long-term approach is to push toward sustainability and this requires a focus on waste minimisation; the framework for this exists but broad implementation requires innovation, cost-reductions, and incentives for this to happen.

While not exhaustively presented, these areas frame the considerations for the recommended areas of research discussed in the following sections.

The role of science and technology in finding sustainable brine solutions

Brine solutions need market demand and from earlier discussions there is an unmet demand globally, particularly where the conventional disposal options have increasingly become limited in scope and applicability. As the solutions will increasingly be based on waste minimisation through beneficial use of brine as a resource, it is expected that the solutions will become largely technology driven. As science and technology (S&T) have been the backbone of the tools developed and applied Australia wide, to manage complex salinity issues across the country, we are confident that it will retain its fundamental role in developing and implementing sustainable desalination brine solutions in the coming years.

In taking up the challenge of desalination brine, we believe that the role of S&T will be multi-faceted. Central to this role will be to provide science-based information to guide the research and technology development for brine minimisation solutions and the push towards sustainability. For example, the brine solution packages will require optimisation of recovery, recycle and reuse options to be considered cost effective before adoption for remote areas.

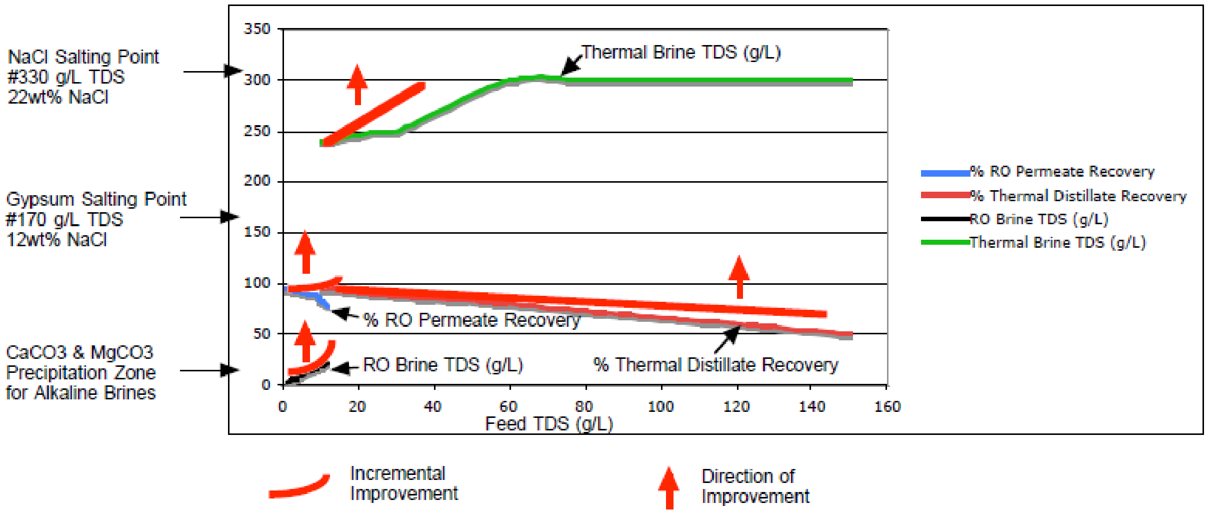
For large-scale inland application, significant research will be needed into integration of desalination, thermal reduction and selective salt recovery processes to achieve considerable reduction in the footprint of future facilities (Ahmed et al. 2001). Also, brine minimisation approaches for large resource development projects will require innovative technologies to enable maximum water recovery and maximum use of recovered salts to achieve waste reduction targets. Research to push the sustainability of inland desalination will need a systematic evaluation of all possibilities for maximising the beneficial use of desalination brine as a resource, including efforts to develop markets for downstream use of treated brine, and recovered salt and other by-products.

Technology advancement is generally either by achieving incremental improvements in the existing core technologies or through introduction of new technologies (with some becoming breakthrough technologies). In terms of brine management, incremental technology advancements are already on the way particularly in thermal processes for brine volume reduction where the variation in TDS of feed water can now be controlled, and the concentration point of end brine can be adjusted to control the flow of feed brine. These allow guaranteed energy usage based on the feed volume and supply concentrated brines for by-product recovery at desired salting point of various salts. However, as exemplified in Figure 4, there remains a significant space for further incremental advancement in appropriate volume reduction and salt recovery technologies that, coupled with salt recovery processes, can potentially improve the economics and enhance the sustainability of future brine solutions.

Considering the imperatives in Australia for salt load reduction it is expected that technologies for waste minimisation through the recovery of valuable salt and chemical compounds will play a significant role at both local and regional scale.

In the Australian context, breakthrough technologies will particularly go a long way to addressing the key water quality problems (salinity, sodicity, alkalinity, acidity and metal spikes) that are expected to be associated with brines from desalination of inland saline water resources across the country. These problems will need breakthroughs to enable the implementation of integrated schemes for large-scale volume reduction and salt load reduction – two cornerstones of sustainable brine solutions. The breakthrough technologies are expected to be based on new processes and/or novel material, and result in direct and indirect solutions. Direct solutions may be exemplified by the success of energy recovery from seawater desalination brines. The indirect solutions can be anything from the use of new building material made from brine waste streams to enable significant energy conservation in the building industry, to the use of treated brine (weighed brine) for large-scale saline agro-forestry and renewable energy industries. As a breakthrough technology will have a widespread application following the discovery, a technology commercialisation strategy shall be decided at the outset to ensure the realisation of its full potential.

Figure 4. Schematic example of potential areas of enhancement in brine minimisation through incremental improvements in the performance of membrane and thermal processes. Note that Y-axis is both % recovery and TDS (g/L); red colour stands for both % Thermal Distillate recovery and for incremental improvement.



On top, the concerns with climate change together with a global move towards sustainable resource utilisation have significantly increased the opportunity for the use of brines in a multitude of emerging industries seeking new generation chemicals with low life-cycle cost. The potential non-conventional uses of treated desalination brine, referred to in recent literature (i.e., CH2M Hill, 2006) cover a wide spectrum of industries and applications, including but not limited to:

- Dust control
- Remediation of sodic soils
- Additives for road base stabilisation
- Sewage stabilisation
- Biosaline agriculture/irrigation
- Solar ponds
- Liquid feedstock for chlor-alkali production
- Aquaculture
- Algal biofuels generation
- Wetland construction/restoration
- Water and wastewater treatment chemicals, and
- Mineral processing

Considering the brine volumes involved in the proposed inland resource development projects, through strategic alliance with the end user industries, this opportunity shall be tested to establish the potential against a set of criteria which may include:

- Characteristics of treated brine needed (quality, availability and storage requirements)
- Cost considerations,
- Market demand and dynamics,
- Regulatory issues,
- Health, safety and ecological risk factors, and
- Implementation issues

Brine management guidelines

A guidance document can span both technical brine management system issues (e.g., intricacies of various brine management options), as well as a broad suite of "institutional" issues (e.g., regulations and permitting, energy and environmental impacts, economics, and public acceptance) that create many of the critical implementation barriers. The institutional factors can pose significant barriers to more streamlined implementation of brine management solutions.

The term "guidelines" is open to a wide range of possible interpretations – from informal guidance and suggestions at one end of the spectrum – to highly prescriptive or numeric design specification at the other. When priority issues and challenges are more technical and of a design nature, such as in implementing a given technical solution, guidelines might be conceived of as formal specifications, such as defining "standards" or "best practices" by setting numeric limits that establish critical thresholds, target performance ranges, or design specifications. Where priority issues and challenges are less technical in nature and more related to decision making on approach or technology, solutions are available and ultimately feasible, the most helpful guidelines are more informal.

Brine management guidelines can consist of a suite of products that are in the form of both "guidelines" and other forms of useful information. This might include comprehensive "checklists" designed to ensure that utilities, private companies, and other interested parties do not overlook key issues or take missteps. It could include useful case studies and summaries of technical or regulatory information as well as a resource guide that will help the various parties locate and access relevant documents, information sources, and more detailed guidance.

Guidelines need be applicable to:

- The various situations involving desalination
- The various desalination processes producing brine, and
- The various brine management methods.

While the stages of a desalination and brine management situation include planning, construction, operation, and future issues, most brine management issues and the need for guidance occur at the planning stage.

As an example, guideline areas for surface discharge of brine might include:

- Permitting overview and procedures
- Brine analysis:
    - Chemical analysis of and characterisation of brine, compatibility of brine with receiving water:
        - Water quality characterisation
        - Whole effluent toxicity determination, and
        - Assessment of impact on aquatic life
- Criteria and methods for feasibility assessment
- Treatment requirements and technologies
- Basic design, and
- Monitoring of discharge impacts:
    - Water quality monitoring, and
    - Aquatic life impact monitoring

Guidelines may be required for each brine management option as well as for consideration of regional brine management, for evaluation of beneficial uses of brine, mixed salts, individual commercial grade salts, and other areas.

Background information is helpful in communicating the issues, challenges, and the history of brine management practices. These guidance items for each brine management option might include information about:

- Generation and quantity of brine
- General brine, and solids characterisation
- Characterisation of the management option
- General design practice
- General cost model, and
- Review of regulatory history

Guidelines could also include other decision-support tools such as:

- Checklists
- Case studies, and
- Information clearing house

While this is not an exhaustive list of guideline items, the authors are presently involved with two guideline development projects one for municipal desalination in the US (Mickley in AwwaRF, 2009) and the other for municipal concentrate (brine) and salt management in the US (Mickley and Arakel in WRF, 2009). Thus some experience and templates for the consideration of brine management guidelines will be available.

Baseline information gathering and clearing house

A clearinghouse of baseline information can be an important decision-support tool. It can include global information on brine management and related situations, experiences, practices, and issues. It provides a means of accessing state-of-the-science relevant information to support informed decision-making.

The information base can include published articles, funded reports, conference presentations, and other available material. The information can be catalogued to allow easy identification of references and other background material pertinent to the brine management issue/challenge/option, at hand.

Both of the previously mentioned US guideline projects are developing a clearinghouse of information.

Critical research areas for underpinning next generation brine solutions

Because of the complexity of landscape salinisation and water quality issues in inland areas and the high quality of salinity research in Australia, we suggest that the main thrust of brine research by NCED and its partners should be directed towards building up next generation brine solutions rather than dwelling on the overseas approaches and/or addressing the shortcomings of previous research. A major difference in approaches is in the general Australian view that while safe brine disposal is a critical management issue, brine by itself is a valuable resource for further treatment and beneficial use. It has long been recognised that the beneficial use of brine can lead to the reduction of the salt load of landscape and thus provide a solution that has a lower environmental footprint compared with the current disposal practices.

Based on this analysis in Table 2 we provide a list of the critical areas of research that we consider necessary for desalination to become an attractive option for inland communities facing water shortage and/or salinity issues and for industries that are actively seeking effective produced water and salinity reduction options.

We also suggest that all brine related research, supported by NCED, should conform with the guidelines of a strategic desalination research agenda to be developed by the Centre and its partners, and should also meet the following two overarching long-term research goals for establishing a sustainable Australian desalination industry:

- Understand the environmental impacts of desalination brine and develop brine management tools for waste minimisation, which reduce the environmental impacts relative to other water supply and/or salinity reduction alternatives, and
- Develop approaches and technologies to lower the financial costs of desalination through beneficial use of the generated brine

A coordinated research program developed by the Centre for strategic research on brine solutions will also ensure that future government and industry investments in desalination are integrated and prioritised and address the topics of national interest and support sustainable growth of desalination industry in inland regions of Australia.

It is for these reasons that we have categorised the research areas according to topics that from our past experience could offer high potentiality for the uptake of research outcomes by desalination industry and regulatory agencies for timely implementation of appropriate desalination brine management guidelines that are compatible with Australian conditions.

Concluding remarks

This paper serves as a wake-up call to our research colleagues that it's time to get serious about finding sustainable brine management solutions. There is an unmet demand for innovative solutions to decouple the desalination brine debunk that has until now hampered the full growth of the brackish water desalination industry in many regions and countries. These solutions shall focus on waste minimisation principles for conforming with local requirements while also addressing the externalities such as regional salinity and climatic change. The demand for collaborative research in support of developing practical brine management guidelines is more than ever evident in Australia. Such guidelines will be needed for timely implementation of meaningful design standards for sustainable management of brine from the proposed water, energy and mineral resource projects. As this demand is both economically and environmentally driven it offers a unique opportunity for the NCED and its research partners to contribute significantly to the sustainability of the future desalination industry for the benefit of communities, businesses and environment, alike.

Table 2. Critical research areas recommended for consideration by NCED and its research partners

Research area	Focus
Cost models	Develop cost models for inland brine management options for use in planning and design stage costing Develop life cycle cost models (total cost models) commensurate with Australian conditions
Environment	Understand the environmental impacts of desalination and approaches to minimise these impacts Conduct site-specific assessments of source water withdrawals and sustainable brine management Promote and work on the concept of 'water footprint' in conjunction with physical, energy, and CO2 footprints
Technology	Remote area brine solution packages (optimisation of recovery, recycle and reuse options) Integrated treatment technologies for footprint reduction (as part of R&D of new desalination technologies) Symbiotic technologies (i.e. recovery of energy from brines similar to SWRO plants) Brine minimisation through byproducts recovery Research to improve water recovery and push sustainability – i.e., maximum water recovery, maximum use of recovered salts, minimum wastes and combinations thereof
Reuse/use	Regional markets for brine solution value adding opportunities Beneficial uses of brine in downstream industries Contaminants reduction for maximising beneficial use
Supplementary research topics/areas	Decentralised (Point of Use) treatment and recycling as a way of managing concentrate Material/brine interactions and materials compatibility as applied to ZLD processing of higher salinity brines using membrane and thermal processes Co-location of inland desalination with wastewater treatment or power facilities from mutual water resource utilisation and concentrate disposal perspectives
Regulatory	Collaborative research to guide/influence the (environmental) regulatory framework to underpin the sustainability of brine solutions Develop science related desalination brine-specific regulations
Information, gathering, guidelines & standards	Develop a baseline information gathering and clearing house Map location-related general feasibility of brine disposal options by climate, surface water availability, hydro-geological conditions, etc. Develop practical and realistic brine management guidelines that fit with the regional (catchment-scale) salinity management strategies Develop design standards for key brine management options
Solution implementation	Promote participation of Commonwealth, state, and local governments to fast track the implementation of sustainable brine solutions Partnership projects with private sector for uptake of research outcomes Partnership with local communities to support site-specific research projects Support Commonwealth and the states in establishing science based protocols using the outcomes from site-specific research

About the authors

Aharon Arakel is an authority on land and water salinisation issues and at the forefront of technology development that includes innovative salt recovery processes for salinity management and saline wastewater minimisation. Dr Arakel has spent some 30 years in practical experience with a wide range of scientific research, university teaching, academic and industry research centre, research management, and technology development and commercialisation, and is now President and Chief Technologist of Geo-Processors, Inc. Dr Arakel is a pioneer of zero liquid discharge (ZLD) processes that involve the recovery of values from saline and alkaline waste stream streams, including reject brine from desalination processes. He has actively participated in collaborative research projects in the US and elsewhere on various technical aspects of ZLD processes for the management of saline and alkaline effluents. He was until recently a member of the Management Committee of Specialist Group on Membrane Technology of the International Water Association.

Mike Mickley is recognised nationally and internationally as a leading expert in the issues of saline effluent management; he has over 43 years' experience in the field of membrane and process technology. Since 1990 most of Dr Mickley's efforts have focused on addressing challenges of membrane concentrate and, more generally, effluent management. He has been principal investigator in several projects addressing effluent management issues and funded by AwwaRF, Bureau of Reclamation and WateReuse Foundation. He is presently principal investigator in a WateReuse Foundation project, entitled *"Development of an Information Clearinghouse on Concentrate and Salt Management Practices – Phase I.* Phase II will be developing guidelines for concentrate management. Dr Mickley was a subcontractor to CH2M-Hill in the WateReuse Foundation project: *Beneficial and Non-Traditional Uses of Concentrate* where he authored the chapter on Salt Separation of Membrane Concentrate – reflecting Dr Mickley's advocacy of sustainable processing technologies. Presently, Dr Mickley is a subcontractor to Stratus Consulting in a Water Research Foundation project *Guidelines for Implementation of Desalination Facilities.* Dr Mickley is on the editorial boards of *Desalination* and *Desalination and Water Treatment*.

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