National Centre of
Excellence in Desalination

AUSTRALIAN DESALINATION RESEARCH ROADMAP

Australian Government
Water for the Future

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Murdoch University is proud to be the Administering Organisation of the National Centre of Excellence in Desalination, working in partnership with Australia's foremost desalination and water research institutions to lead national research and build national capacity and capabilities in desalination.

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Foreword

The National Centre of Excellence in Desalination is taking a unique approach to research strategy by leading the delivery of the first Research Roadmap for desalination in the Australian context.

The science of desalination has progressed rapidly as the international water industry has made significant investment in R&D. Australian researchers must be guided by this context of international development to identify significant opportunities that can deliver tangible benefits to the nation.

The Centre has undertaken extensive consultation with industry, researchers, and government to identify opportunities for improvement, measure their potential for benefit, and validate the prioritisation of those that will provide the greatest value for Australia.

The Roadmap will guide the Centre to deliver on its mandate to:

- Optimise and adapt desalination technology for use in Australia's unique circumstances;
- Develop suitable desalination technology for use in rural and regional areas ;and
- Efficiently and affordably reduce the carbon footprint of desalination facilities and technologies.

The Roadmap will be a living document, updated regularly, that focuses Australian desalination research investment and activity to develop valuable technical improvements, contribute to public policy and build Australia's research capabilities and capacity. The Centre aims to become the global leader in desalination breakthroughs and collaborative R&D, and expects to do so through continued close engagement with industry.

I would like to thank all the people who have contributed their valuable time, insights and effort to this Roadmap.

David Doepel
Interim CEO
National Centre of Excellence in Desalination

SUMMARY

Purpose

The National Centre of Excellence in Desalination will base research investment on the strategy formulated in this Research Roadmap, in order to best address identified and validated priority research themes.

Structure

The structure of this Research Roadmap comprises:

The motivation, being the acquittal of Australian Government research funding in a strategic manner and alignment to the Research Mandate attached to that funding (see section 1.4);

Research Mandate (1.4)

1 Australia's unique circumstances
2 Rural and regional areas
3 Reducing the carbon footprint

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The strategic framework for the Centre, being its strategic objectives, the objectives for the Centre's Research Program, and the Centre's resulting vision for desalination in Australia (see section 1.5);

Vision for Desalination in Australia (1.5)

Efficient and sustainable augmentation of traditional water sources to provide security against the natural variability of rainfall and potential future impact of climate change

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The demands on technology, being Australia's water needs in relation to desalination (see section 2);

Australia's Water Needs (2)

- Developing technological solutions to sustainably reduce the cost of current and future desalination facilities
- Cost-effective water for inland communities and agriculture
- Fit-for-purpose water for industry

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The current technology performance and the resulting gaps in meeting current and future needs (see section 3); and

State of the Technology (3)

- Source water intake
- Pre-treatment
- Desalting systems
- Waste product management
- Product water
- Managing energy usage and carbon footprint

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The gamut of opportunities for both incremental and step-change improvement in the technology, prioritised into key research themes (see section 4).

Priority Research Themes (4)

- Pre-treatment
- Reverse osmosis desalting
- Novel desalting
- Concentrate management
- Social, environmental and economic issues

State of the Technology

Key water industry issues were identified, including opportunities for:

- Management of the entrainment of small marine organisms in intake infrastructure associated with seawater reverse osmosis (SWRO) plants;
- Precise characterisation of source waters for municipal SWRO plants as an input to the optimisation of pre-treatment systems;
- Reduction in operational and capital costs associated with brackish water desalination pre-treatment systems;
- A range of membrane improvements;
- Application of electrodialysis (ED) and electrodialysis reversal (EDR) to brackish water desalination in Australia;
- Development of technologies and systems for the economic management or recycling of ferric sludge;
- Detailed understanding of the salinity and toxin tolerance of marine species in the vicinity of SWRO outflows;
- Development of technologies and systems for the economic management of concentrate waste produced by inland brackish water reverse osmosis (BWRO) plants;
- Investigation into the effect of the constituents of various desalinated water sources in Australia on key Australian agricultural products;
- Optimisation of municipal SWRO design, construction and contracting to reduce capital and operating expenditure associated with municipal SWRO plants;
- Plant simplification, and operations and maintenance simplicity for remote plants;
- Development of simple, low maintenance renewable energy systems that can supplement power supply for small desalination facilities; and
- Audit of opportunities in Australia for the harnessing of waste heat for desalination purposes and development of suitable technologies.

Priority Research Themes

Key improvement opportunities for the Centre are grouped into five thematic research focus areas:

Pre-treatment:

1.1 Preheating using waste heat or renewable energy and the use of lower-pressure membranes;

1.2 Optimal use of chemicals;

1.3 Specific issues for pre-treatment in rural and remote areas relating to seasonal and location variability in feedwater composition; and

1.4 Characterisation of groundwater and seawater sources and mapping those to best fit desalination technologies.

Reverse osmosis desalting:

2.1 Anti-fouling technologies and membranes and oxidant-resistant membranes;

2.2 New membrane materials that reduce operating pressure while maintaining or increasing flux rates and maintaining ion rejection;

2.3 Contaminant removal without the need for second-pass RO;

2.4 Direct use of renewable energy via kinetic, electrical, or thermal means;

2.5 Real-time monitoring and classification of potential foulants; and

2.6 Operational optimisation.

Novel desalting:

3.1 Novel technologies including those for direct agricultural use;

3.2 Low-maintenance, reliable evaporative technologies using waste heat or renewable energy;

3.3 Coupling water production with renewable energy; and

3.4 Piloting breakthrough near-commercial desalination technologies in real-world situations.

Concentrate management:

4.1 Novel zero liquid discharge processes;

4.2 Waste minimisation based on value adding;

4.3 New materials for lower-cost corrosion management; and

4.4 Extraction of desalted water at source or concentrate injection.

Social, economic and environmental issues:

5.1 Appropriate disposal or reuse of spent membrane cartridges;

5.2 Total life cycle analysis and sustainability assessment of desalination against other water sources;

5.3 Public perception analysis and improvement through education and communication;

5.4 Policy development to better understand energy-water interdependence;

5.5 Centralised understanding of national desalination deployment, performance, and lessons learnt;

5.6 Detailed understanding of the salinity and toxin tolerance of marine species in the vicinity of SWRO outflows; and

5.7 Managed entrainment of small marine organisms in SWRO intakes.

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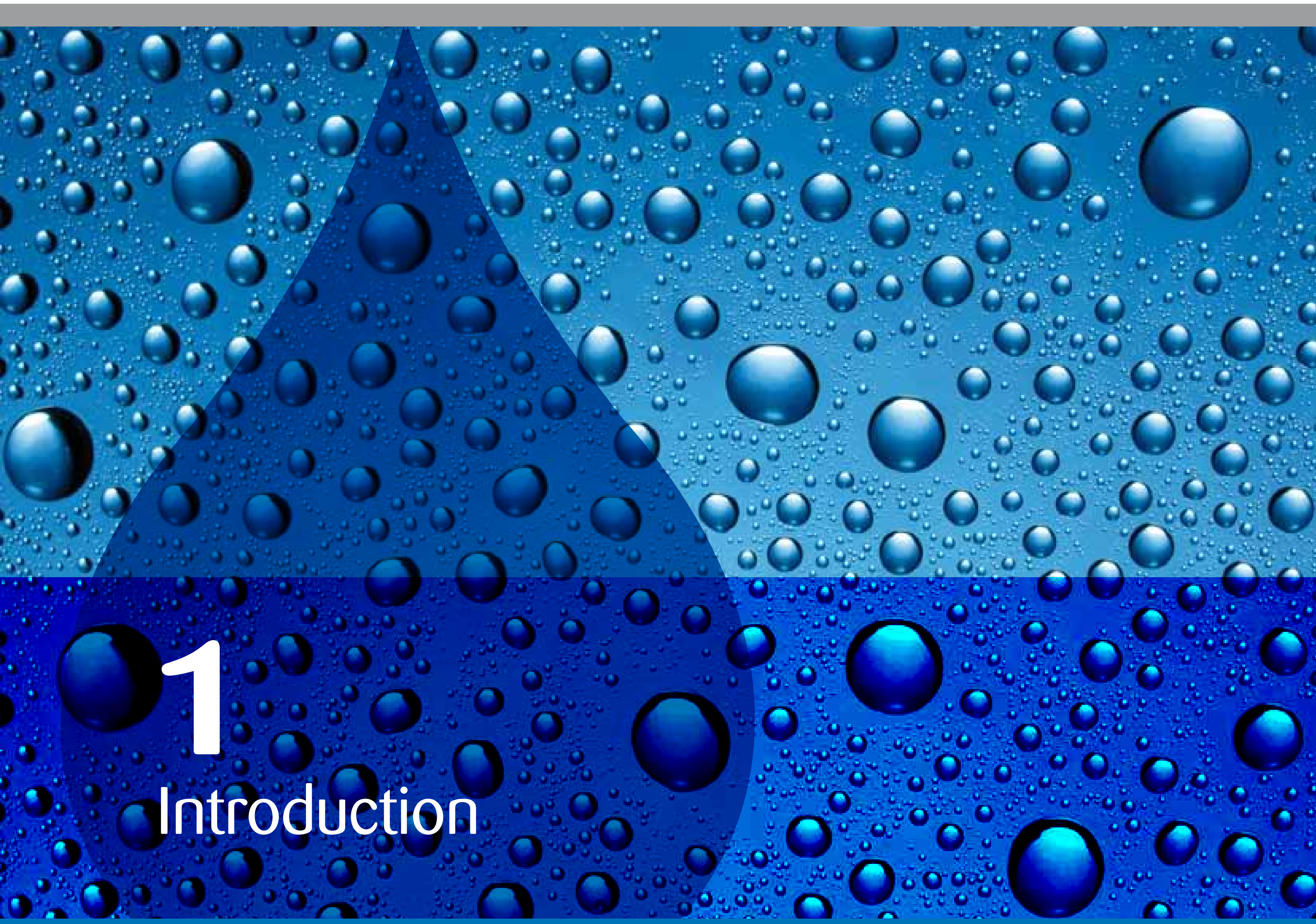

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Introduction

1.1 Purpose

The National Centre of Excellence in Desalination will base research investment on the strategy formulated in this Research Roadmap, in order to best address identified and validated priority research themes. The Roadmap delivers a clear picture of Australia's water needs and gaps in desalination technology. From these will spring opportunities for desalination research. These opportunities will point the way forward for targeted research activity to guide the Centre and its members in delivering the Centre's mission.

A key evaluation criterion for the Centre's proposed research projects will be alignment with this Roadmap and the degree of priority of the research theme proposed to be addressed. The research priorities in section 4 are expected to drive investment recommendations by the Research Advisory Committee and research investment decisions by the Centre's Board.

In addition to determining the technology needs to allow desalination technologies to be successfully implemented, the Roadmap will also provide Centre members and collaborators with knowledge management of desalination technology development. By regularly updating this Roadmap, the Centre will track national and international research activity, providing valuable information in research direction for Centre members.

1.2 Research roadmaps

A research roadmap is a planning tool developed through a consultative process where stakeholders are actively engaged in mapping the current state of technology and service delivery in a particular industry and correlating this against future aspirations for that industry. The resulting map then guides researchers and institutions in their activities by prioritising research that will best deliver the desired incremental and disruptive improvements in technology and process to achieve expected or needed new or higher levels of service delivery, product quality, and sustainability.

In the international field of desalination, two landmark roadmapping efforts were undertaken, one by Sandia National Laboratories in its *Desalination and Water Purification Technology Roadmap* (2003, on behalf of the US Congress), and the other more recently by the US National Research Council in its report *Desalination: A National Perspective* (2008).

1.3 Roadmap framework

The structure of this Research Roadmap comprises:

- The motivation, being the acquittal of Australian Government research funding in a strategic manner and alignment to the Research Mandate attached to that funding (see section 1.4);
- The strategic framework for the Centre, being its strategic objectives, the objectives for the Centre's Research Program, and the Centre's resulting vision for desalination in Australia (see section 1.5);
- The demands on technology, being Australia's water needs in relation to desalination (see section 2);
- The current state of the technology performance and the resulting gaps in meeting current and future needs (see section 3); and
- The gamut of opportunities for both incremental and step-change improvement in the technology, prioritised into key research themes (see section 4).

These elements of the roadmap structure are illustrated and colour-coded for reference in Figure 1.

Research Mandate (s1.4)

1 Australia's unique circumstances
2 Rural and regional areas
3 Reducing the carbon footprint

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Vision for Desalination in Australia (s1.5)

Efficient and sustainable augmentation of traditional water sources to provide security against the natural variability of rainfall and potential future impact of climate change

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Australia's Water Needs (s2)

- Developing technological solutions to sustainably reduce the cost of current and future desalination facilities
- Cost-effective water for inland communities and agriculture
- Fit-for-purpose water for industry

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State of the Technology (s3)

- Source water intake
- Pre-treatment
- Desalting systems
- Waste product management
- Product water
- Managing energy usage and carbon footprint

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Priority Research Themes (s4)

- Pre-treatment
- Reverse osmosis desalting
- Novel desalting
- Concentrate management
- Social, environmental and economic issues

Figure 1: Conceptual framework of the National Desalination Research Roadmap

1.4 Motivation

On April 29, 2008, the Minister for Climate Change and Water, Senator the Hon. Penny Wong, announced the Government's $12.9 billion national plan Water for the Future, a program to provide national leadership in water reform and secure the long term water supply of all Australians. A key element of the Water for the Future framework is the $1 billion National Urban Water and Desalination Plan, which seeks urban water security independent of rainfall. The Plan committed to funding the establishment of a National Centre of Excellence in Desalination in Perth, Western Australia. The Department of the Environment, Water, Heritage and the Arts (DEWHA) published Funding Guidelines for the Centre containing research priorities, adopted as the Centre's Research Mandate.

The Centre's Research Mandate

- To optimise and adapt desalination technology for use in Australia's unique circumstances
- To develop suitable desalination technology for use in rural and regional areas
- To efficiently and affordably reduce the carbon footprint of desalination facilities and technologies

The backgrounds to these three elements of the Research Mandate are described below:

1.4.1 Australia's unique circumstances

A defining characteristic of Australia's unique circumstances is water scarcity. The International Panel on Climate Change, in its 2007 Fourth Assessment Report, predicted that less precipitation and increased evaporation will cause water security problems to intensify by 2030 in southern and eastern Australia. Production from agriculture and forestry by 2030 is projected to decline over much of southern and eastern Australia due to increased drought and fire. In these circumstances, the need is urgent for large scale production of potable water from alternative water supplies for Australia's metropolitan regions, including affordable and sustainable desalination technologies.

Australia has limited water resources and there is a need to ensure efficient water use and management appropriate to geographic location. Most populated urban centres in Australia are located close to the coast with relatively easy access to the ocean. However, there is a significant inland population, including agricultural and industrial activities, which also have intensive demands for freshwater.

Within five years, Australia will accelerate desalinating seawater for drinking water. Only Israel, Singapore, Spain, and countries around the Persian Gulf will have greater dependence on seawater-sourced drinking water.

1.4.2 Rural and regional areas

There is a substantial energy cost in delivering potable water to inland Australia from the coast and therefore seawater desalination is currently not a viable option for the populations of rural and remote communities. The development of desalination technologies suitable for hypersaline groundwater and brackish in-land aquifers will be an important need, as will the provision of freshwater solutions for industry affected by salinity in rural and remote situations.

1.4.3 Reducing the carbon footprint

The desalination industry faces a growing global need to access sustainable energy sources. Awareness of the effect of greenhouse gas emissions on climate change has escalated and is now prompting governments and industry to invest in finding cleaner ways to meet energy needs. This awareness coincides with a continuing growth in global power consumption. As desalination is energy intensive, a major challenge for the desalination industry is in the development of more sustainable or less carbon intensive approaches to energy use.

1.5 Strategic alignment

1.5.1 The Centre's strategic objectives

The Centre's founding strategic objectives have been adopted from goals outlined by DEWHA in its Funding Guidelines. Therefore, to support the development of programs and activities within this proposal, six strategic objectives have been established. These are:

The Centre's Strategic Objectives

1. To lead research in energy efficient desalination technologies
2. To provide facilities to researchers and industry to support the development of new desalination technologies
3. To commercialise resultant new desalination technologies
4. To build national capacity and capabilities in desalination research and industry
5. To promote increased public acceptance of alternate water sources
6. To become a sustainable research centre through commercialisation and industry partnerships

As a core activity of the Centre, the Research Program and its activities demonstrate clear links to each of these strategic objectives. In turn, the Research Program has additional strategic objectives. These are:

Research Program Strategic Objectives

1. To lead and coordinate national research in energy efficient desalination technology
2. To build national capacity and capabilities in desalination
3. To advance the science of desalination with specific application to Australia's unique needs and challenges

The Centre's chosen research activities, through the investments approved by the Centre Board, will align with the Centre's strategic objectives and the objectives of the Research Program.

1.5.2 Vision for desalination in Australia

In order to define the best research pathway, a proper vision must be constructed, and research that is suggested must lead to the realisation of this vision. Firstly, the vision should promise advances in technology that optimise cost reduction, carbon reduction, and performance increase. Secondly, the vision should facilitate the introduction of the most appropriate existing technology into Australia. In developing this Research Roadmap, the Centre has therefore adopted the following vision for desalination in Australia:

The Centre's Vision for Desalination in Australia

Efficient and sustainable augmentation of traditional water sources to provide security against the natural variability of rainfall and potential future impact of climate change

1.6 Methodology

Murdoch University, in its capacity as the Administering Organisation, led and coordinated the roadmap exercise, with oversight from a Roadmap Advisory Group and the endorsement from the Centre's Interim Board.

The Centre reviewed established roadmapping methodologies, including Sandia National Laboratories' *Fundamentals of Technology Roadmapping* (1997) and Cambridge University's *Fast Start Technology Roadmapping* (Phaal 1999) methodologies, before selecting the Sandia methodology as the preferred model and adopting appropriate elements for the Australian context.

Input

The Sandia National Laboratories (2003) and US National Research Council (2008) desalination roadmaps have been used as templates for this Australian roadmap.
The Centre has directly drawn upon the expertise of the primary authors of those documents to undertake a similar (but appropriately scaled) effort for the Australian context.

Australia's Water Needs

To provide a background for the effort of improving desalination technology, the roadmap process begins with establishing the context of Australia's Water Needs. There has been considerable work done to understand Australia's water situation, particularly in the environment of recent drought and expected climate change. The Centre reviewed recent national and state publications on water and desalination, including the CSIRO report *Desalination in Australia* (2009), in order to establish Australia's Water Needs.

State of the Technology

The Centre commissioned white papers on technology issues in desalination research aligned with the mission of the Centre. A literature review and primary research was undertaken to determine the current state-of desalination technology that is relevant to Australia, Australian desalination industry technology needs and gaps in desalination technology. The Centre also benchmarked the technical and economic performance of Australian municipal and commercial desalination facilities.

Priority Research Themes

Identifying relevant and achievable technology improvements is a key portion of the roadmapping process. A National Desalination Roadmapping Workshop was held in Fremantle, WA in October 2009. Over 80 national and international delegates attended, including potential Centre members, representatives from the water and desalination industries, water regulators and utilities, and representatives from a number of government departments. This diverse stakeholder group considered topics including the context of the Centre's mission and research objectives, Australia's water needs, state-of-the-art research areas (such as special properties of water), the carbon footprint of desalination, the direct use of renewable energy for large scale desalination, and brine management. Small groups of delegates considered opportunities for improvement in five technology areas as well as national research infrastructure requirements.

These research opportunities identified at the roadmapping workshop were augmented with input from the International Desalination Association's biennial World Congress in Dubai in November 2009, and with verification and validation from the Roadmap Advisory Group. These opportunities were then published online for comment as the roadmap's Draft Strategic Research Agenda (2009). The Roadmap Advisory Group carefully considered all improvement opportunities and only key national research priorities have been retained.

Collaboration

All potential university members of the Centre were invited to participate in the research roadmapping exercise in order to validate national desalination research capabilities, resources, and resulting gaps and opportunities. Potential members used preliminary results of the roadmap to confirm the collaborative potential each institution would bring to the consortium and to assist in negotiations of collaboration agreements. More than 80 delegates from around Australia and overseas attended the National Desalination Roadmapping Workshop in October 2009, and over 60 academics, industry representatives, and community members have joined the Centre's online roadmapping community.

2

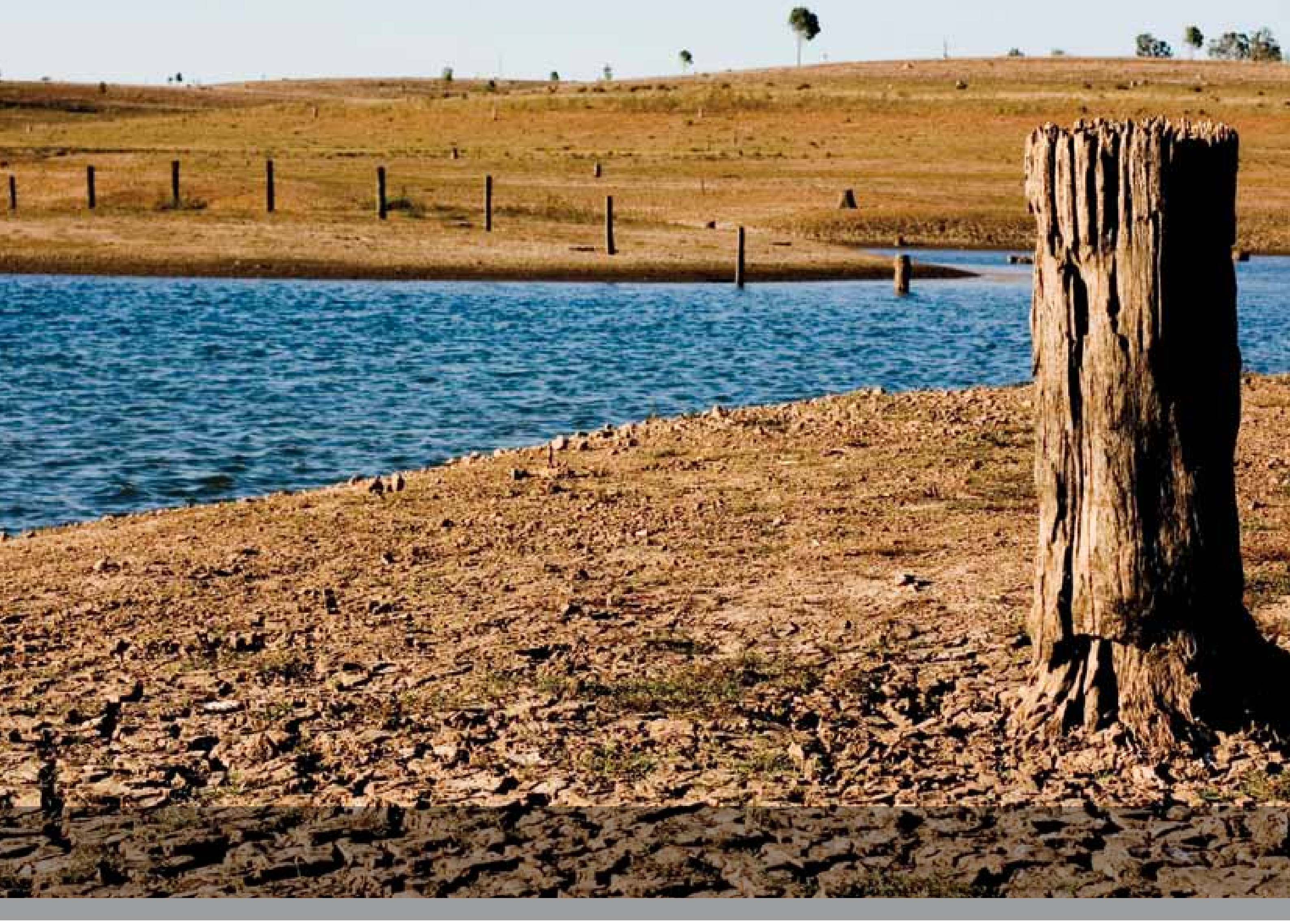
Australia's Water Needs

2.1 Purpose

Australia as a nation has abundant sources of rainfall. According to the National Water Commission (2007), annual consumption is actually less than 1% of freshwater inflows. However, the problem is that Australia's rain falls largely in areas where the population and industry cannot access it. Australian needs are therefore not an inflow issue, but rather one of not getting the water to where it is most needed. In places where water is needed, climate change is accentuating naturally occurring droughts and rainfall variability adding to water security issues.

The following section analyses Australia's water balance, where the demand for water emanates, the likely impact climate change will have on water resources, and the role desalination can play in alleviating some of the water supply issues facing the country. Through an analysis of water inflow, extraction, consumption, and reservoir capacity, the state of Australian water assets can be assessed.

These analyses are intended to provide only a summary of Australia's water needs, and draw upon considerably detailed work by, among others, the National Water Commission (2007, 2009) and the Department of the Environment, Water, Heritage and the Arts (2007). In addition, the Australian Bureau of Statistics publishes Australia's water account every four to five years.



2.2 Australia’s water balance

Australia’s rainfall is sufficient to cover the country’s annual consumption of 18,767 GL of water nearly 150 times over (National Water Commission, 2007). The country is even more richly endowed in groundwater resources. Australia’s Great Artesian Basin alone holds enough to cover annual consumption hundreds of times over. Even though reservoir resources are more precarious, as of June 2005 they still held enough water to cover annual consumption twice over. In total, Australia’s dams have the capacity to hold over four times the annual consumption rate.

The problem of securing enough water for human requirements in Australia is not an issue of insufficient water resources, but rather an issue of water balance, or more accurately stated, water imbalance. Australia’s high level of rainfall occurs over a large land mass and is highly regional in nature. Likewise, groundwater reserves vary in quality and are widely distributed. Water security is an issue because there is an imbalance between the geographical location of the water assets and where the demand emanates.

2.2.1 Inflows

Although often touted as the driest continent on earth, inflows of water into Australia are generous. Australia's average annual rainfall, 600-1500 mm, is comparable to that of Europe. In 2004-2005, the nation received 2,789,424 GL of rainfall, nearly 150 times the total consumption (National Water Commission, 2007). Only one-tenth, 292,000 GL, occurs as runoff, with the vast majority going to rivers and lakes and only a small amount recharging underground aquifers (National Water Commission, 2007). Of the total run off amount, 49,200 GL, (less than 2% of annual rainfall) replenishes underground aquifers. Nine-tenths of rainfall inflow evaporates back into the atmosphere from the surface before it can become runoff.

In terms of existing resources, the greatest groundwater asset in Australia is the Great Artesian Basin. This is one of the world's largest aquifer systems, covering 22% of the country. This basin stretches 1.7 million km^2, and holds a massive 64,900,000 GL of water (National Resources and Water, 2009). Ocean water represents an almost infinite source of potential potable water for human requirements. The world's oceans hold 1.3 billion km^3 of water, 97% of total water reserves on earth (Elert, 2003).

Although Australia benefits from sufficient water inflows and healthy groundwater resources, the country suffers from a water imbalance issue, creating problems for the country's water security. Most of Australia's rainfall occurs in the northern part of the country, while water demand is mainly situated in the southern regions of the country. For example, in 2004-2005, over 60% of water runoff occurred in northern Australia, but only 6% in the Murray-Darling Basin, a region which accounted for half of Australia's total water consumption (National Water Commission, 2007). Such highly regional rainfall means Australia does not have a water scarcity issue as such, because annual rainwater runoff and groundwater recharge both surpass annual consumption, but there is a disparity between the geographical location of water assets and water demand.

2.2.2 Ground water extraction

Less than a quarter of the water extracted in Australia is actually consumed. Hydro power stations extract a large amount of water, but return most of it back to the environment. Of the nearly 80,000 GL of water extracted in 2005, 61,017 GL, or 76% was returned to the environment as regulated discharge (National Water Commission, 2007). Of this discharge, 96% comprised in-stream water use from the hydroelectric power generation industry. Further losses occur in the form of leakage and evaporation in water transportation for agriculture. Most of the water extracted was by water users, as water providers only accounted for 14% of extractions (National Water Commission, 2007). Over half of water extraction is generated from major engineering infrastructure while the remaining 48% is sourced directly from the environment for local needs.

Department of the Environment, Water, Heritage and the Arts estimates indicate 29,173 GL of groundwater can be extracted sustainably in Australia every year (2007). Only 72% is of adequate quality for stock, irrigation, and domestic purposes. Although based on 1997 data, an estimated 4,962 GL of groundwater was extracted in Australia, or 6% of total extraction (Department of the Environment, Water, Heritage and the Arts 2007). This means the country is only utilising 17% of its sustainable annual yield. In terms of capital cities, Perth is the only city with heavy groundwater reliance. Western Australia's use of groundwater over the 13 years from 1984–1997 grew 205%, to 1,138 GL or 23% of total groundwater extraction in the country (Department of the Environment, Water, Heritage and the Arts, 2007).

Although dealing with different time periods, groundwater extraction rates are soaring. Total water extracted from the environment over the four years from 2001-2005 only increased 4%, while groundwater extraction grew a full 88% over the 13 years from 1984-1997. Interestingly, the amount of water actually consumed fell 14% from 2001-2005.

2.2.3 Production

In 2008, desalinated water production was just 294 ML per day, only 0.57% of total consumption (Hoang, Bolto, Haskard, Barron, Gray and Leslie, 2009). By 2013, desalinated water is expected to comprise 4.3% of total consumption. 294 ML per day of water is currently generated from desalination plants across the country, with 976 ML per day currently under construction and a further 925 ML per day of capacity under proposal.

2.2.4 Consumption

Agriculture is by far the largest water user in Australia, representing a massive 65% of total water consumption. In 2005, the industry consumed 12,191 GL of water (National Water Commission, 2007). Household consumption and water services (sewerage and drainage), were the second and third largest consumers; making up a relatively small 11% of total consumption each. The next largest consumers of water were manufacturing at 3%, mining 2%, and others comprised 8% of total consumption. This consumption was mostly (79%) sourced from surface water such as dams, rivers, and lakes, while the remainder came from groundwater (Department of the Environment, Water, Heritage and the Art, 2007).

2.2.5 Reservoirs

Australians are the third highest per capita consumers of water in the world (Department of the Environment, Water, Heritage and the Arts, 2007). Even so, Australia stores more water per person than any other country in the world, more than four million litres per person, or 12 times the average household consumption. Perhaps it is due to the Australian climate and the voracious appetite of Australians for water that makes the country's reservoir infrastructure so impressive. Australia's large dams have an overall capacity of 83,853 GL, four times more than the country's annual industrial and domestic water usage. However, as of 2005 only 48% of this capacity was full of water (National Water Commission, 2007). Since 2002, dam levels have fallen an average of 18% across the country. Climate change and drought are depleting reservoir levels due to changing rainfall patterns and associated reductions in run off.

Groundwater reserves are immense, but spread over a wide region, often distant from high volume consumers. These reserves also carry a relatively low sustainable yield when compared to the overall volume of extraction. Groundwater is often utilised in an unsustainable manner with many of Australia's recognised groundwater management units operating either at or above their estimated sustainable yield.

2.2.6 Cost of water

Table 1 below compares water tariffs and water usage in some major countries as at June 2009 (Global Water Intelligence, 2009a). Australia's tariffs are well above the average combined water and waste water tariff of a survey of 266 major cities which was $1.89/m^3.

Table 1:
Water tariffs and water usage in key countries

Country	Combined tariff ($/m^3)	Water tariff ($/m^3)	Wastewater tariff ($/m^3)	12 month change (%)	Abstraction (m^3/head/ year)	Domestic use (%)	Domestic use (L/head/ day)
Denmark	8.83	8.83	0.00	4.1	130	32	114
Germany	4.87	3.12	1.75	0.8	460	12	151
France	4.24	3.58	0.66	2.6	530	16	232
United Kingdom	4.23	2.03	2.20	5.0	230	22	139
Australia	3.53	1.80	1.73	9.9	1300	17	605
Czech Republic	3.18	1.61	1.58	6.4	190	41	213
Canada	2.46	1.41	1.05	7.3	1420	20	778
United States	2.45	1.03	1.42	6.5	1730	13	616
Poland	2.36	1.10	1.26	8.7	419	13	149
Spain	2.33	1.22	1.11	6.1	960	13	342
Japan	2.14	1.19	0.95	0.0	680	20	373
Portugal	1.85	1.31	0.55	0.6	1125	10	308
Turkey	1.67	1.28	0.77	15.5	580	15	238
Italy	1.15	0.59	0.56	3.3	980	18	483
South Korea	0.65	0.49	0.16	0.9	560	36	552
Russia	0.59	0.35	0.24	35.6	525	18	368
Mexico	0.58	0.48	0.09	9.9	730	15	300
China	0.39	0.27	0.12	4.3	494	7	95
India	0.09	0.08	0.00	4.1	635	8	139

The 2009 combined tariff for major Australian cities is as follows (Global Water Intelligence, 2009a):

- Adelaide US$3.02 (increase of 8.1% over June 2008);
- Brisbane US$3.97 (increase of 7.2% over June 2008);
- Melbourne US$3.60 (increase of 14.8% over June 2008);
- Perth US$2.80 (increase of 7.9% over June 2008); and
- Sydney US$4.26 (increase of 11.6% over June 2008).

Private water rights in Australia are an emerging asset class. Figure 2 below illustrates the relative volume and value of water allocation trades in the Murray-Darling Basin. It compares market activity during 2007–08 and 2008-09 mid-winter to mid-winter periods. The average price of an allocation fell from A$650/m^3 in 2007-08 to A$350/m^3 in the following year as the drought eased. The market for permanent water rights, known as entitlements, moved in the other direction, with high reliability entitlements trading at an average of A$2,000/m^3 in 2007-08 compared to A$1,750/m^3 the previous year (Global Water Intelligence, 2009b).

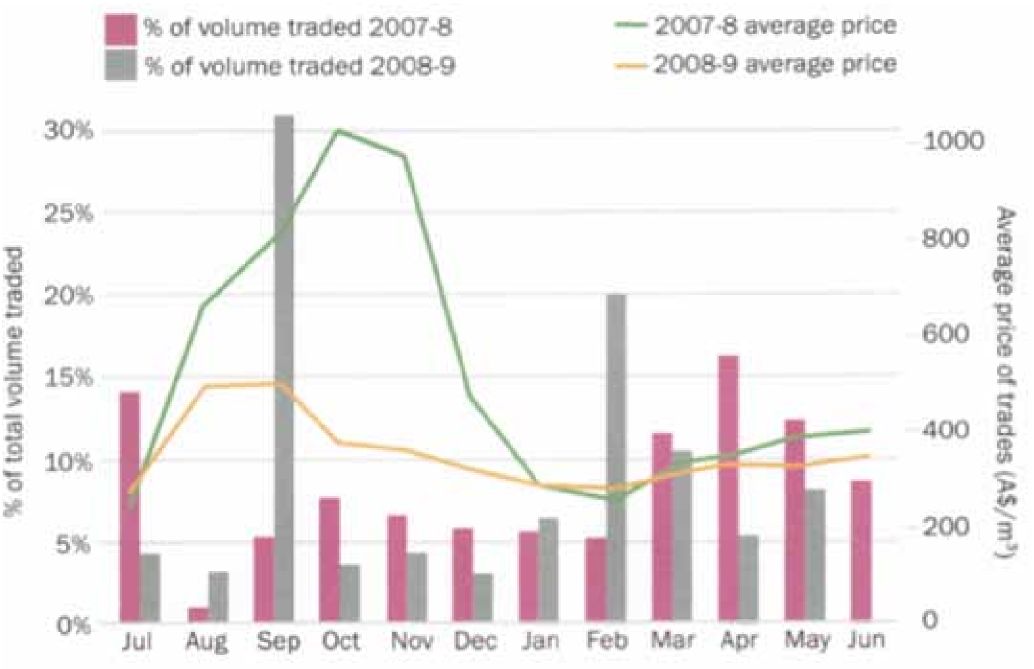


Figure 2:
Water trades in the Murray-Darling Basin (2008 vs 2009)

2.3 Urban needs

Australia's eight capital cities comprise 12.8 million people and represent 64% of the country's population (Australian Bureau of Statistics, 2006). Each city has a different mix of water supply between surface water, groundwater, and desalinated water. Most cities are supplied by surface water reservoirs, but storage levels vary greatly between different urban areas.

Each city has an estimated sustainable yield based on consumption, and surface and groundwater recharge rates. Most cities are harvesting too much water from these resources and will have to either reduce consumption or find alternative sources of supply.

Reservoir storage levels will continue to be variable, but will have less of an impact due to the presence of increased desalination production. Most Australian cities now have either adequate actual or expected water security due to increases in production. The growing trend towards municipal desalination for urban water security means desalinated water will grow from 45 GL per year in 2006 to 450 GL per year by 2013, with expandable capacity to 650 GL per year (Hoang et al., 2009).

2.3.1 Major capital city water supply

Reservoirs provide 96% of the water supply to capital cities, while just 4% is sourced from groundwater. All capital cities rely predominantly on surface water reservoirs, with the exception of Perth, which relies 60% on groundwater for its water needs. In 2009, all major cities had reservoir water levels above 50%, except for Perth at 44% and Melbourne at 28%. Although Melbourne's reservoir level is low, the Wonthaggi desalination plant, which will be the largest in Australia supplying 410 ML per day, will supply water to the city by 2011 (Victorian Government Department of Sustainability and Environment, 2009).

Apart from Darwin, all major Australian cities have been on water restrictions during recent years, with many now permanently on at least the minimum level of restrictions as water storages have emptied (Department of the Environment, Water, Heritage and the Arts, 2007). Since 1997, water inflows to the dams of Australia's five largest cities have halved. Melbourne's dams have received 65% of long-term average inflows, Brisbane 44%, Sydney and Perth 43%, and Adelaide 65% (Department of Climate Change, 2009).

There are very few cities in Australia where planners are not considering strategies for dealing with issues of long-term water availability. Public perceptions have changed and the need to conserve water is now largely understood.

2.3.2 Consumption and sustainable water yield

Population of a city is a reasonable estimate for total water usage, but per capita water usage rates between cities can vary considerably. For example, Darwin's per capita water usage is 348 KL per year, while Sydney's is 124 KL per year, a difference of 64% (National Water Commission, 2007).

When comparing the 2004 per capita consumption rate of Australia's eight largest cities against the estimated per capita consumption rate required in 2030 to stay within sustainable yields, only the city of Canberra was within acceptable limits (Department of the Environment, Water, Heritage and the Arts, 2007). Every other city will have to either reduce per capita consumption or increase supply. The two most extreme cases are the cities of Gold Coast and Brisbane which will have to reduce per capita consumption rates by 38% and 32% respectively by 2030 without future increases to supply.

In spite of the trend to move towards more efficient and careful water use, demand for water is increasing across the nation. Pressure to build new dams and to exploit additional groundwater and river systems, especially in northern Australia, is growing. Current and committed desalination infrastructure seems to have solved the sustainable water yield issue beyond 2030 for all major cities with the exception of Brisbane. It should be noted that future sustainable water yields were calculated based on lower population growth estimates than the most recent prediction of 35 million people living in Australia by 2050, which is much greater than the 28.5 million estimate of just two years ago (Treasury, 2010). Future water requirements may therefore be underestimated.

2.4 Rural population needs

The issue of water scarcity affects rural Australia for many of the same reasons that it affects capital cities. The Goldfields of Western Australia and the agriculturally rich Murray-Darling Basin in Victoria are examples of rural areas suffering from insufficient water supply.
In addition to water scarcity concerns, rural towns must also address water quality problems due to salinity and the presence of nitrates. Saline water is not fit for consumption or irrigation, and nitrates have human health implications. These issues are largely associated with the agricultural industry.

2.4.1 Dryland salinity

Native vegetation has long roots to take advantage of any available water, but has been cleared away in many parts of Australia to make room for agricultural crops that have much shorter roots. Agricultural crops do not absorb as much water, increasing the amount of rain water leaking into the groundwater beneath the root system. Since there is more water going into the ground than is being removed, the water table is rising to the surface. As the water table rises to the surface it mixes with naturally occurring salts in the ground producing high salt content in surface land causing what is referred to as dryland salinity.

Dryland salinity has affected 2.5 million hectares of land in Australia with another 15 million hectares under threat (Commonwealth Scientific and Industrial Research Organisation, 2009). The area damaged by salinity to date represents about 4.5% of cultivated land, and estimated current costs include $130 million annually in lost agricultural production, $100 million annually in damage to infrastructure, and at least $40 million in loss of environmental assets. Western Australia has the largest area of dryland salinity and the highest risk of increased salinity occurring in the next 50 years. An estimated 4.3 million hectares, 16% of the south-west region, have a high potential of developing salinity problems (Australian Natural Resources Atlas, 2009b). Estimates predict that one-third of Western Australia's agricultural land will be under threat from salinity by 2050.

Dryland salinity impacts many features of the natural and built environment. Thirty thousand km of road and rail networks and up to 30 major rural towns may be affected in Western Australia alone. Of 54 wetlands, 21 are under threat, 450 plant species face extinction, 30% of fauna may die, and one-third of the state's catchments showed signs of increased salt loads in rivers and streams (Australian Natural Resources Atlas, 2009b).

2.5 Industrial needs

Industrial users extract a great deal of water, but consume a relatively insignificant amount. Electricity generation alone is responsible for 98% of this sector's extraction, 60,292 GL, but as mentioned, returns all but 1% back into the environment (National Water Commission, 2007). Manufacturing is responsible for 3% of the country's total consumption, and mining is responsible for 2%.

2.5.1 Electricity generation

The power generation industry extracts large amounts of water, but 98% is used by Snowy Hydro, a hydro-electricity producer, who returns 98.5% of the water it extracts back into the environment (National Water Commission, 2009). The industry is therefore only responsible for 1% of the country's total consumption.

Coal-fired power stations are responsible for the majority of actual water consumption within the power generation industry (National Water Commission, 2009), however, they are coming under increasing pressure to reduce their use of fresh water by drawing on other supply options such as sea water, lesser quality water, or treated waste water, or by introducing alternative cooling options (National Water Commission, 2009). Water is a valuable commodity to the power generation industry, with estimates of the marginal value of water ranging from $14,000/ML to $18,000/ML; currently it is trading around $1,500/ML. As coal produces over 80% of Australia's electricity needs, water scarcity carries ramifications for Australia's energy security (Australian Coal Association, 2008).

In coal-fired power stations, 90% of water is used during the cooling process, whereby water is used to cool exhaust steam. At present fresh water is used, but it could be replaced with saline water if equipment modifications were made to the cooling towers. The remaining 10% of consumption stems from water required for the boiler. This water, used to generate the steam that turns the turbines, is the only water that needs to be 100% clean or desalinated.

Dry cooling can reduce water consumption of coal-fired power stations by more than 90% (National Water Commission, 2009). Dry cooling however reduces the efficiency of a power station by around 2-3% and increases carbon dioxide emissions by up to 6%. Potential new large-scale renewable efforts such as solar thermal generation also require a lot of water to operate.

2.5.2 Industrial

Industry or the manufacturing sector represents 3% of total water consumption in Australia (National Water Commission, 2007). The largest consumer within manufacturing is food and beverage, followed by metal products and wood and paper products (Australian Bureau of Statistics, 2006). Regionally, Queensland is responsible for 27% of industrial water consumption, followed by New South Wales and Victoria. As the majority of manufacturing takes place in urban areas, 57% of water used for industrial purposes is supplied via water providers using city water infrastructure, while the remainder is self-extracted.

2.5.3 Mining

Desalination has three potential roles to play in the resources industry:

- Provision of potable water for mining camps;
- Provision of water for mining and processing applications; and
- Desalinating water that is produced from the extraction process.

Many Australian resource projects rely on desalinated water to meet the needs of mining communities. These needs are typically met by small-scale SWRO and BWRO plants.

The main commodities that are mined in Australia are coal, iron ore and gold. The mining and processing circuits that are used to produce these main commodities generally do not require a high quality of water and as such desalination is less relevant. Furthermore, process circuits can often be designed to use low quality water, which is frequently less expensive than desalination.

However, in activities that process acid ores, high quality water is often necessary and desalination plays a larger role. An example of such an operation is BHP's Olympic Dam Copper-Gold-Uranium deposit in South Australia.

Mining represents 2% of total water consumption (National Water Commission, 2007). Metal ore mining is responsible for just over half of mining's total water use, with coal mining the second largest user (ABS 2006). The mining industry receives 85% of its water needs through self-extraction due to the remoteness of many mine sites. Nearly half of the water used by the mining industry occurs in Western Australia, followed by Queensland and New South Wales.

In Western Australia, minerals and energy constitute 24% of the state's water demand (Chamber of Minerals and Energy Western Australia, 2008). The Pilbara region is responsible for over 50% of the mining industry's consumption in the state. The mining industry within the state is expected to need 5.4% more water annually until 2014, when consumption will reach 1,129 GL per annum.

2.5.4 Energy-water nexus

In 2004-05, the electricity and gas sector comprised approximately 1.4% of Australia's total water consumption. Historically, 99.6% of water used in power generation was used in-stream for hydro-electricity (Smart & Aspinall, 2009), as demonstrated in Table 2 below.

Table 2:
Water used in power generation

	Water use (GL)	Electricity generated (GWh)	Water efficiency (GL per GWh)
Hydro-electricity	59,867,227	15,991	3,743.81
Black Coal	153,021	102,180	1.50
Brown Coal	81,887	54,041	1.52
Gas	11,606	20,786	0.56
Other	810	1,473	0.55
Total	**60,114,551**	**194,471**	

In thermal electricity generation water is used in:

- The boiler for steam raising;
- The cooling system;
- Managing and disposing of ash; and
- Services and potable water supplies.

Water use varies between different types of thermal power stations. Typical water consumption for a coal-fired power station with re-circulated cooling is shown in Table 3 below (Smart & Aspinall, 2009).

Table 3:
Water consumption in coal-fired power station

Process	Typical Use (ML/GWh)	Approximate annual consumption for 1000 MW base load coal-fired power station with recirculated cooling
Boiler make up water	0.01-0.03	~0.5 GL/year
Water evaporated in cooling process	1.6-1.8	~13 GL/year
Water for cooling tower blowdown	0.2-0.3	~2 GL/year
Ash disposal	0-0.1	~0.5 GL/year
Other potable uses	Not generation dependent	~0.5 GL/year

2.6 Agricultural needs

Agriculture is by far the largest consumer of water in Australia, representing 65% of total consumption (National Water Commission, 2007). Within agriculture, livestock, pasture, grains represent 36% of consumption, followed by dairy farming, cotton, and sugar (Australian Bureau of Statistics, 2006). Livestock, pasture and grains are typically broad-acre operations in Australia and tend to be spread over large geographical areas. Whereas diary, cotton and, to a much lesser extent, sugar are generally smaller operations concentrated in either high rainfall or highly irrigated areas. Regionally, New South Wales is the largest agricultural water user, representing 34% of total consumption, followed by Victoria and Queensland (National Water Commission, 2007). Over half of the water supply to the agricultural industry is self-extracted, and the balance of 46% is distributed through water suppliers. Three-quarters of the supply is from surface water.

2.6.1 Irrigation

Due to Australia's variable and highly seasonal rain patterns, irrigation of agricultural land is necessary to grow commodities such as grapes, fruit, and grains for livestock. Irrigation places an incredible burden on water supplies and is the reason why the agricultural sector is such a massive user of water. Ninety one percent of the water used by the agricultural sector is for irrigation of crops and pastures (National Water Commission, 2007). This high use is concentrated on a relatively small area, as irrigated land comprises just 0.5% of the 445 million hectares of agricultural land in Australia. The value of irrigated agricultural land is more substantive, worth $9 billion per annum, which is 23% of the total value of agricultural commodities produced.

Water sources for irrigation vary according to state. Groundwater is responsible for 86% of irrigated water in the Northern Territory, but just 48% in South Australia, 25% in New South Wales, and 23% in Queensland. In Tasmania, 92% of irrigated water is sourced from surface water, and is responsible for 84% in Victoria, and 76% in Queensland.

2.6.2 Murray-Darling Basin

The Murray-Darling Basin is the most important agricultural area in the country. As a region, the Murray-Darling Basin is the single largest consumer of water in Australia. The region represents 64% of irrigated land area, is responsible for 75% of water used in irrigation, and consumes over half of all water used in Australia (Australian Natural Resources Atlas, 2009a).

Unfortunately, persistently low levels of rainfall are maintaining the need for artificial irrigation. Murray system inflows in 2009 during the important rainfall months of June and July were just 30% of the long-term average (Murray-Darling Basin Authority, 2009). Useable water storage for the Murray-Darling Basin was low at just 17% capacity by the end of July 2009.

In addition to drought, salinity is affecting the Murray-Darling Basin. The basin covers 1.3 million hectares and 38% of this land has water tables within two metres of the surface, resulting in waterlogging and salinisation of productive land, surrounding rivers, lakes and groundwater (Australian Natural Resources Atlas, 2009a). These issues cause the medium to long-term economic viability of the region to be questioned. The expansion of the Ord River Scheme in Western Australia is likely to spur some migration of businesses from the Murray-Darling Basin to the Ord River.

2.7 Impact of climate change

Climate change poses great challenges for water security in Australia. As the planet warms, Australia is expected to experience reduced rainfall across eastern and far south-western Australia, increased rainfall variability, more evaporation, and significantly increased frequency and severity of both droughts and floods (Department of Climate Change, 2009). All this will be occurring in a country that is already naturally dry, has a growing demand for water, and is struggling to keep up with current demand.

It is also forecast that climate change will affect water quality. Higher water temperatures and reduced stream flows will create conditions that nurture weed growth and algal blooms, starving the water of oxygen and killing aquatic life. Drought conditions are likely to exacerbate erosion and downstream sedimentation.

2.7.1 Rainfall variability

Increasing rainfall variability will be one of the major impacts on water supply stemming from climate change. Rainfall variability should not be confused with reduced rainfall. Total rainfall levels are predicted to remain stable country-wide, but the northern half of the country will receive more rain, while the areas needing it most – urban and agricultural areas in the east and south – are expected to receive less. Scientists already believe that climate change is responsible for the massive drop in water inflows into the capital cities experienced over the last 10 years (Department of Climate Change, 2009).

Rainfall variability due to climate change will also mean more erratic rainfall patterns. Rainfall will deviate, both higher and lower, away from historical levels. This variability will enhance water security risks and place additional pressures on reservoir resources.

2.7.2 Increased evaporation

Hotter weather produces higher surface temperatures, creating more crop transpiration, which then requires more irrigation to make up for the water loss. Increased levels of evaporation will also negatively affect reservoirs, which will further restrict irrigation allocations.

2.7.3 Rising sea levels

Currently, the best estimate of expected sea level rise is provided by the Intergovernmental Panel on Climate Change. They are indicating an increase of 0.2-0.5 m by 2050 and 0.5-0.9 m by 2100 (University of New South Wales, 2009). Although most of the serious implications associated with rising sea levels will be felt longer-term in Australia, the impact is enormous. The Department of Climate Change recently analysed the impact a 1.1 metre rise in sea level by 2100 would have on the country (Department of Climate Change, 2009). The report concluded 157,000 to 247,600 existing homes, valued around $50 billion would be at risk from sea inundation. In terms of public infrastructure, 258 police, fire and ambulance stations; 5 power stations/sub stations; 75 hospitals; 41 land fill sites; 3 water treatment plants; and 11 emergency service facilities that are within 200 metres of the coastline may face the risk of inundation by the sea.

Rising sea levels will also impact coastal freshwater resources. For example, saline water can infiltrate coastal aquifers, damaging groundwater. Fresh water only needs 5% contamination from seawater to render it unsuitable for drinking or irrigation (University of New South Wales, 2009). This holds implications for town water supplies, agriculture, and industry. The affect on irrigated agricultural land is minimal. Less than 1.5% lies close to the sea and is within 5 metres of sea level.

2.8 Conclusions

Australia's rate of rainfall is comparable to those in other global regions, such as Europe, where water security issues are not as severe. The problem is that Australia's rainfall is highly geographically variable and does not tend to fall in regions of highest demand. This situation produces a water imbalance issue, leaving many of these high demand areas in short supply.

Reservoir infrastructure is sufficient for the foreseeable future. Australia's dams are large enough to hold four times the nation's annual consumption, and groundwater can supply the demand hundreds of times over. Key issues, however, are that the sustainable groundwater extraction rate is one-third current usage rates and reservoir water levels are highly variable due to drought.

Historically, Australia has relied on rainwater to replenish its freshwater resources. Additional supply sources should be developed due to the variability of droughts and the potential future impact of climate change. Desalination is economical as an additional source of freshwater in instances where price sensitivity is manageable. Planned and committed desalination capacity at various locations around the country seems to have solved the near term sustainable yield issues, but updated population forecasts may need to be used.

The agricultural industry is a massive user of water and is dealing with both water shortages and a salinity crisis, particularly in the Murray-Darling Basin. In principle, desalination would be extremely attractive option for the industry. Although there are isolated examples of small scale desalination for irrigation purposes, the price sensitivity of this user group makes desalination by all known approaches today an unaffordable option.

There are three main economically viable opportunities for desalination in Australia over the coming 10-20 years. Firstly, desalination can augment urban water supplies to keep up with expected population growth and ensure sustainable extraction rates are maintained. Secondly, smaller desalination operations can accomplish these same goals in rural towns. And thirdly, desalination can provide water for industrial applications in non-urban settings such as in the power generation and mining industries.

Australia's Water Needs

- Developing technological solutions to sustainably reduce the cost of current and future desalination facilities
- Cost-effective water for inland communities and agriculture
- Fit-for-purpose water for industry

3

State of the Technology

3.1 Introduction and scope

Three key factors will continue to drive global investment in the water sector at a pace greater than the rate of growth of global GDP for the foreseeable future:

- Available freshwater is defined as less than 0.5% of total water stock, and global consumption of freshwater is doubling every 20 years, which is more than twice the rate of human population growth (Kim, 2009);
- Urbanisation and cities are growing at twice the rate of the population as a whole (Global Water Intelligence, 2009a);
- Warmer and dryer climate in many of the food producing areas is placing further pressure on water demand in those areas; and
- The provision of water in such an environment is presented with a number of technical challenges that will require investment to resolve (Global Water Intelligence, 2009a).

Australia has not been an exception to the global trend of growing investment in the water sector. Figure 3 illustrates that annual capital expenditure in water infrastructure in major Australian cities has grown from approximately A$1.25 billion in 2002-03 to over A$2.5 billion in 2007-08.

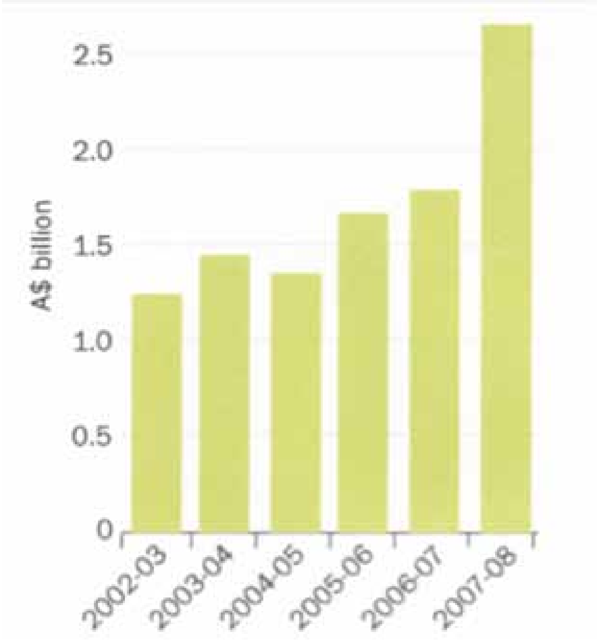


Figure 3: Water related capital expenditure in major Australian cities (2002-03 to 2007-08)
(Global Water Intelligence, 2009b)

The desalination of saline waters, reuse or recycling of wastewaters and the harvesting of rain water are emerging as the main strategies for generating additional supplies of freshwater (Kim, 2009). While the focus of this analysis is technologies associated with desalination, it should be noted that a number of desalination technologies have application on other forms of water manufacturing or harvesting.

There are many ways to define the salinity ranges of water. However water salinity is generally categorised as potable, brackish or seawater. Potable water is defined as water that is considered acceptable for human consumption and while water with a Total Dissolved Solids (TDS) concentration of less than 1,000 mg/L is generally considered fit for human consumption, water with TDS greater than 500 mg/L can be distasteful and water with a TDS greater than 700 mg/L has a noticeably 'salty' taste. On the other end of the spectrum, the seawater that comprises 97% of the world's water supply has a TDS concentration that is typically in the range of 33,000 mg/L to 37,000 mg/L, with some seawaters in the Persian Gulf averaging a TDS concentration as high as 48,000 mg/L. The brackish water that accounts for approximately 1% of the world's water supply is defined as water with TDS concentrations between that which is considered acceptable for human consumption (500-1,000 mg/L) and seawater (more than 33,000 mg/L) (National Academy of Science, 2008). The purpose of desalination systems is to convert brackish and seawaters into potable water by reducing the TDS concentration.

A considerable amount of global water investment has focused both on the installation of desalination facilities and improving the performance of desalination facilities.
This has occurred to the extent that desalination is emerging as the primary means by which potable water is manufactured. Indeed, 2009 saw the most rapid expansion of desalination capacity in any 12 month period, with 700 new desalination plants being commissioned globally, increasing the world's installed desalination capacity by some 12% to 59.0 million m^3/day (Global Water Intelligence, 2010). Figure 4 illustrates the global growth of new desalination capacity since 1980, together with the growth in contracted new installations. The notable decline in new contracts since 2007 is primarily the result of delays in a number of major new desalination projects that occurred as a consequence of the global financial crisis.

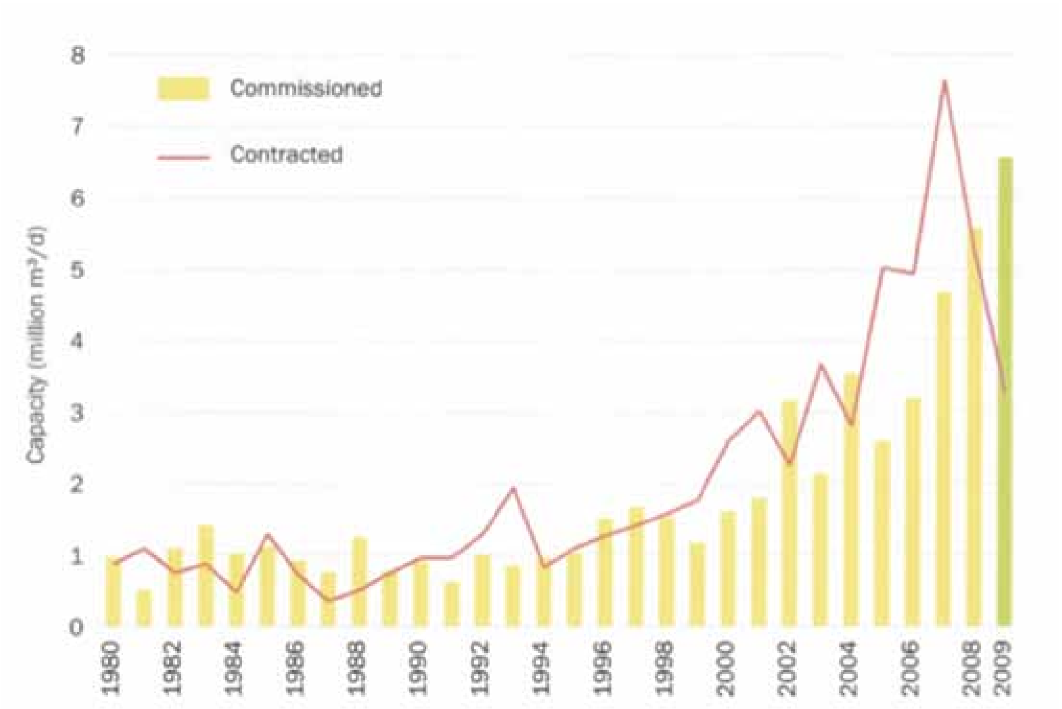


Figure 4: New desalination capacity (1980-2009) (Global Water Intelligence, 2009c)

There are currently approximately 14,450 seawater and brackish water desalination plants worldwide, with an additional 244 plants under contract or construction. In 2009, the global market for desalination equipment was estimated to be approximately US$11.7 billion, representing 2.3% of the total estimated global water equipment market (Global Water Intelligence, 2009a).

The choice of desalination technology is determined by a number of factors including the availability and form of energy, source water quality and various site specific conditions. Nevertheless, globally, thermal and reverse osmosis membrane processes are the two major processes, with other desalination technologies accounting for less than 1% of current installed capacity (National Academy of Science, 2008). Thermal desalination is used predominately in the Middle East for the following reasons:

- Seawaters in the Middle East are very saline, warm and periodically have high levels of organics which have historically proven to be problematic for reverse osmosis membrane desalination systems, and pre-treatment systems for reverse osmosis plants have only recently resolved this issue;
- Reverse osmosis plants have only recently approached the production capacities that are required to provide adequate potable water for water markets in the Middle East;
- Dual purpose co-generation facilities have historically been constructed in the Middle East that integrate thermal desalination processes with available steam from power stations, improving the overall thermodynamic efficiency of the thermal desalination plants; and
- Generally lower local cost of energy in the Middle East (National Academy of Science, 2008).

Seawater desalination is the fastest growing sector, having expanded by 29.5% to a total installed capacity of 35.0 million m^3/day over the past two years (Global Water Intelligence, 2010). Furthermore, the scale of municipal seawater reverse osmosis plants (SWRO) is growing, further entrenching its position as a major component of many country's water supply solutions. For example, while the largest municipal SWRO plant in the more mature

SWRO market of Europe is Barcelona's 200,000 m^3/day plant, a number of newly contracted plants are at least twice the capacity of Barcelona such as Melbourne's 411,000 m^3/day plant and Algeria's 500,000 m^3/day plant (National Academy of Science, 2008).

Building desalination capacity has been a major focus of recent Australian water infrastructure investment. Australia's current inventory of municipal (or municipal-scale) SWRO plants that are operational or under construction is as follows:

- Kwinana, Western Australia (144,000 m^3/day)
- Binningup, Western Australia (150,000 m^3/day)
- Gold Coast, Queensland (125,000 m^3/day)
- Sydney, New South Wales (250,000 m^3/day, expandable to 500,000 m^3/day)
- Adelaide, South Australia (150,000 m^3/day, expanding to 300,000 m^3/day)
- Melbourne, Victoria (411,000 m^3/day)
- Cape Preston, Western Australia (Industrial, 170,000 m^3/day)

Indeed operating at full expanded capacity, the six major municipal SWRO desalination plants that are either operational or under construction in Australia are estimated to have the capacity to supply as much as 47% of the water currently supplied to Australian capital cities (Global Water Intelligence, 2009b).

There is also estimated to be between 400 and 600 smaller BWRO and SWRO plants operational across Australia with capacities in the range of 50 KL/day to 10 ML/day (Palmer, 2010). Furthermore, most State water utilities have plans to roll-out additional smaller SWRO and BWRO plants in the short to medium term to service regional communities. For example, in South Australia, an estimated 15 BWRO plants with capacities of less than 5 ML/day are expected to be required over the next 25 years as well as at least one mid-sized plant (15-20 ML/day) on the Eyre Peninsula that will supply local townships (West, 2010).

Table 4 summarises Australian state government budgets for water investment for 2008-09 and 2009-10 as published in June 2009 (Global Water Intelligence, 2009a). For the 12 months ended 30 June 2010, Australian states will spend a total of A$6.7 billion on the water sector.

Table 4: Australian state water budgets (2008-09 to 2009-10) (Global Water Intelligence, 2009a)

State	Total (A$m)	Desalination (2008-09)	Desalination (2009-10)	Recycling (2008-09)	Recycling (2009-10)	Sewerage	Treatment & pipelines	Rural towns	Dams & storage	Small projects
ACT	13.9									13.9
NSW	1,860	886.3	338.5	139.3	185.8	100	303.3	61.7	56.8	813.9
NT	1.4							0.5	0.3	0.6
QLD	595.5	448.1	95.5	795	130.7				248.1	121.2
SA	292	96.5	228	426	44				20	N.A.
TAS	31.1					9	17			5.1
VIC	2,800	117.4	1,500		400	150	200	50	200	300
WA	1,100	1,100	200		519	54.6	13.5	300		12.9
TOTAL	**6,694**	**2,648.3**	**2,362**	**1,360.3**	**1,279.5**	**313.6**	**533.8**	**412.2**	**525.2**	**1,267.6**

The data in Table 4 indicates that the vast majority of near-term capital expenditure associated with the Australian water sector, some A$5 billion, is directed at the completion of the major municipal SWRO desalination plants currently under construction in New South Wales, Queensland, South Australia and Western Australia.

Australian expenditure on municipal SWRO is expected to peak in 2011 or 2012, with the next significant growth in water related capital expenditure widely expected to be focused on water reuse infrastructure. Figure 5 illustrates that the volumes of recycled water used in major Australian urban centres has grown from a total of just under 80 million m^3 in 1999-2000 to approximately 150 million m^3 in 2007-08. However, this still represents less than 15% of the wastewater that could potentially be reused in Australian urban centres (Global Water Intelligence, 2009b). In Sydney there are fifteen water recycling schemes recycling approximately 24 GL of wastewater per annum (Blayney, Chapman, Landers & Storey, 2009).

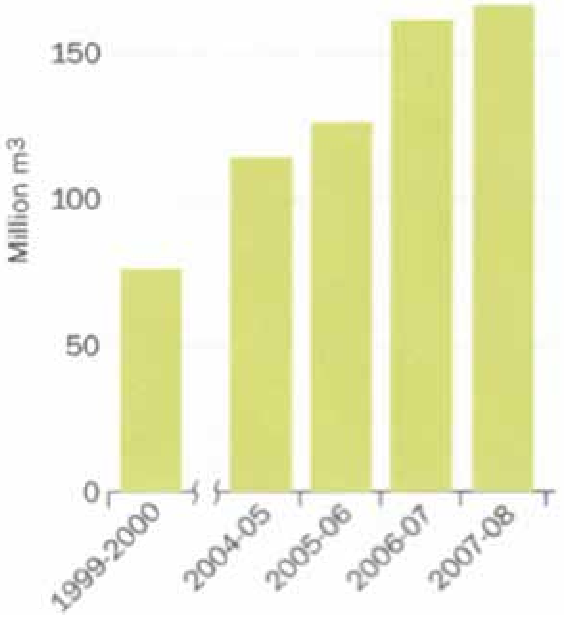


Figure 5: Consumption of reused water in major Australian urban centres (1999-2000 to 2007-2008) (Global Water Intelligence, 2009b)

This potential trend in capital expenditure toward greater installed water reuse capacity in the future is pertinent to an analysis of technology developments in desalination. This is because the treatment of wastewater often requires the use of desalination technologies to meet the water quality needs of one or more customers of the recycled water (Fasham, Papps & Jones, 2009). For example, reverse osmosis may be used to remove a range of contaminants (National Academy of Science, 2008) and electrodialysis or electrodialysis reversal may be used to remove unwanted ionic species.

In Australia most water reuse plants produce water for the watering of parks, gardens and sporting facilities or for industrial or commercial uses, in order to remove pressure from existing supplies of potable water. As illustrated by the following examples, water reuse projects in Australia are highly variable in size but are currently only used to service non-potable applications:

- Western Corridor Recycled Water Project in south-east Queensland, which when completed will be one of the world's largest recycled water projects, comprising three water treatment plants with a combined capacity equivalent 232 ML/day of recycled water (Morgan, Solley, Thew, Edge & Schimmoller, 2009);
- Kwinana Water Reclamation Plant in Western Australia (16.8 ML/day), which supplies local industries with average annual flows of 6GL of recycled water (McGuiness, Zhara & Oughton, 2009);
- Epsom Spring Gully Recycled Water Project in Victoria, which supplies parks, gardens, sporting facilities and industry in Bendigo with 4.4 GL of recycled water per annum;
- Murrumba Downs Advanced Water Treatment Plant in Queensland, which provides Moreton Bay industry with 1.7GL of recycled water per annum (Staib, Buschman & Sloan, 2009);
- Rosehill-Camellia Recycled Water Project in New South Wales that when operational will supply industrial and commercial customers in western Sydney with 4.3GL per annum of recycled water (Gyzen, 2009);
- North Head Recycled Water Plant in New South Wales, which provides northern Sydney industry with 100 ML per annum of recycled water (Wang, 2009);
- Toowoomba Reuse Plant in Queensland, which will provide 3,000 ML per annum of recycled water for local industrial use (Mueller, 2009);
- Kuring-gai Local Government Area reuse plant that provides 300 KL per day of recycled water to the Gordon Golf Course (Davies & Muston, 2009);
- Port Kembla Water Recycling Project that will replace 1 ML/day of potable water that is used primarily for dust suppression with recycled water from the adjoining Wollongong Sewerage Treatment Plant (Chalk & Muston, 2009); and
- Bluescope Steel Western Port Potable Substitution and Recycling Project that will provide 660 ML per annum of recycled water for BlueScope's steam generation, cooling systems and manufacturing process needs (Chapman et al, 2009).

The water reuse rate is highly variable from country to country, as is the public acceptability of the production of potable water from wastewater sources. In 2007, the State of Florida in the United States had the world's highest total water reuse rate of 52%, whereas jurisdictions such as Singapore that have been actively promoting water reuse projects had water reuse rates as low as 6.7% (Kim, 2009). In most cases reclaimed water is used as either industrial water or indirect drinking water (Kim, 2009). A number of Australian water utilities are investigating the potential to use recycled wastewater to recharge aquifers and then recover freshwater from aquifers as a means of rendering potable recycled water palatable to the Australian public (Molloy, Helm, Lennon & Dillon, 2009). An example of such a project is Water Corporation's Beenyup Ground Water Replenishment Trial (Palenque, Swain & Jackman, 2009), whereby secondary treated sewage is processed through microfiltration, reverse osmosis and ultraviolet disinfection before it is injected under pressure into the aquifer. After a period of time, the water will be abstracted via a bore pump and passed through a water treatment plant.

When compared as processes for manufacturing water, both water-reuse and desalination have pros and cons. For example, seawater desalination is often cited as having a strategic benefit in that it is creating a truly new source of freshwater from a feedwater supply that contains 97.5% of the world's water, the world's oceans. Whereas water reuse investments are limited in capacity by the supply of wastewater that they can source. However, water reuse infrastructure has the advantage of generally having a lower unit cost and carbon footprint than seawater desalination, primarily by virtue of its lower energy usage (Mrayed & Leslie, 2009).

While Australian governments have not totally abandoned conventional water sourcing strategies, the implementation of conventional water sourcing strategies is becoming increasingly challenging in Australia. For example, in late 2009, the Queensland government opted to construct the Traveston Crossing Dam, which had an estimated yield of 70 million m^3/year and a development cost of A$1.5 billion, over an alternative proposal to construct two SWRO plants at a cost of approximately A$1.2 billion each (Global Water Intelligence, 2009c). However, in December 2009, the Federal Minister for the Environment prevented the Traveston Dam from proceeding on grounds of the negative impact that it would have on the environment, forcing the Queensland government to reconsider other options including desalination.

While a significant amount of investment in innovation in the water sector, particularly in the area of desalination, pre-dates the recent increase in capital investment in the water industry (over US$1.0 billion was invested in the development of reverse osmosis by the United States Government during the 1960s and 1970s), there is some evidence that the water sector is generating renewed innovation interest. During the 11 years to January 2009, a total of US$1.2 billion of venture capital was invested in developing new water technologies. While this pales in comparison to the amount of venture capital invested in the traditional hi-tech sectors such as information and communication technology, biotechnology and clean technology, it is worth noting that 50% of the total US$1.2 billion of venture capital that has been invested in the water sector over the last 11 years (1998–2009) was invested during the past two years (2007–2009) (Global Water Intelligence, 2009a).

Global research and development targeted at desalination primarily focuses on the following broad issues (Kaligirou, 2005):

- Improving plant efficiency through a greater understanding of source water quality, membrane fouling mechanisms and pre-treatment;
- Improving the performance of the desalination process through enhancing existing membrane pre-treatment and RO technologies for higher productivity, lower energy usage and improved product water quality;
- Development of non-membrane salt separation technologies;
- Minimisation of concentrate and improved concentrate disposal methods; and
- Application of renewable energy sources to desalination.

In the United States, State funded desalination research and development programs typically fund low-risk projects that are designed to achieve short-term results (National Academy of Science, 2008) such as:

- Location specific feasibility evaluations for desalination concentrate management;
- Project management and technical support services for desalination and concentrate management studies;
- Location-specific feasibility of co-locating seawater treatment facilities with power plants; and
- Concentrate reduction/zero liquid discharge demonstration.

The purpose of this section of the NCED Technology Roadmap is to provide an understanding of the state of desalination technology as far as it is relevant to the Australian context and to identify issues that are pertinent to the Australian desalination sector. The analysis will briefly cover emerging new non-membrane and hybrid desalination technologies. There is a general consensus that most of these emerging technologies are five to ten years from practical full-scale application (Voutchkov, 2009). For the immediate future, seawater reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) technologies and their related upstream and downstream systems will be the dominant desalination technologies.

This section will analyse the status and trajectory of technologies according to the stages of a typical desalination process as depicted at a high-level in Figure 6. The analyses that follow in this chapter are derived from a review of the literature and from interviews with national and international water treatment experts. The needs developed in this chapter provide guidance and direction for the Priority Research Themes presented in section 4.

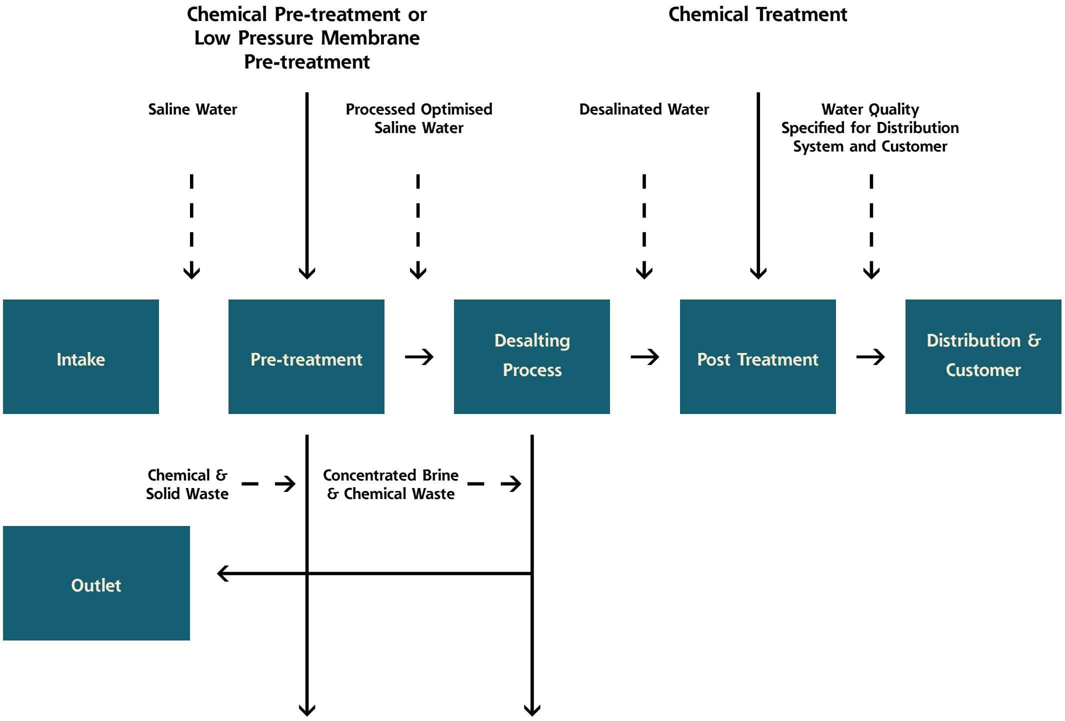
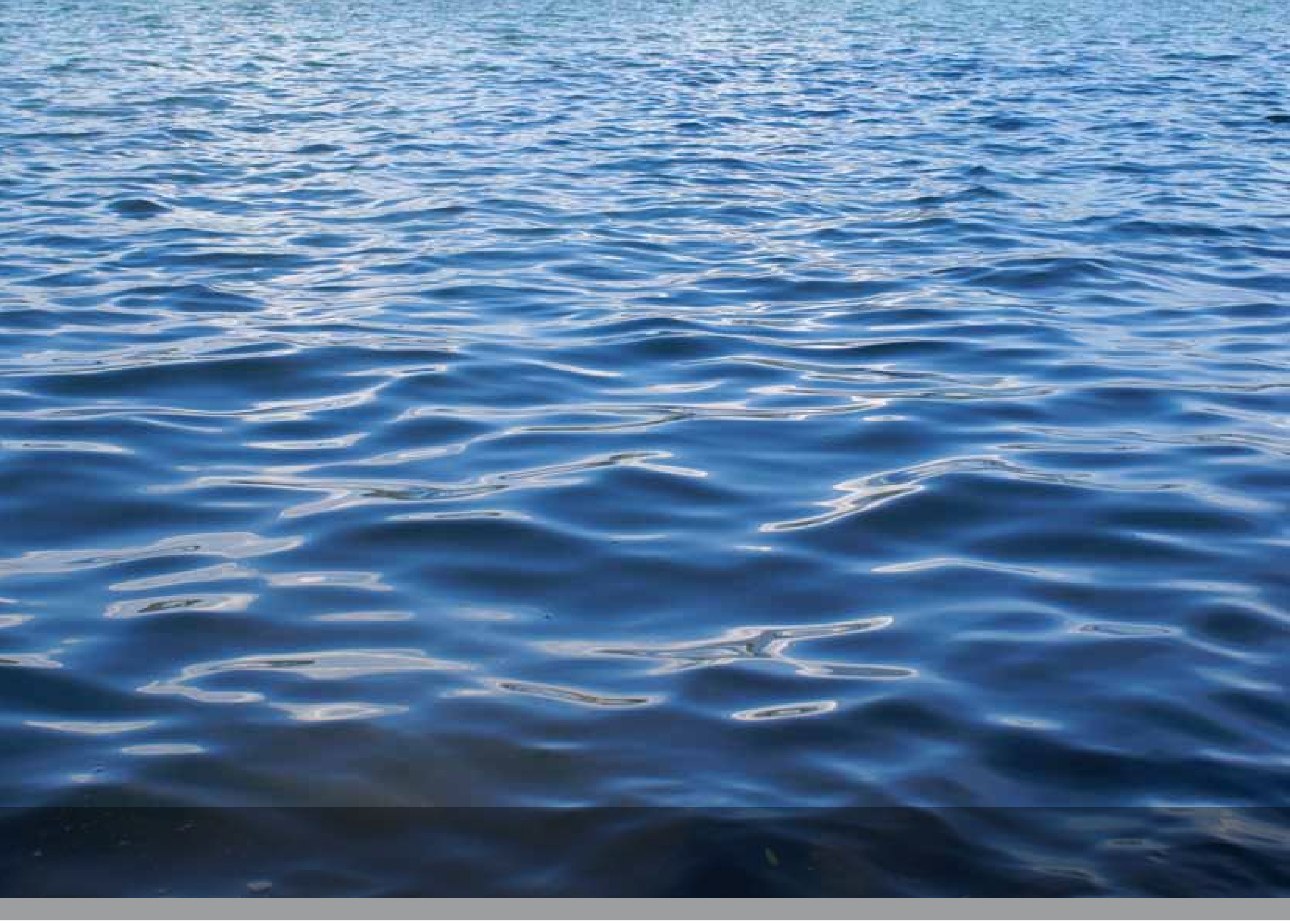


Figure 6: Typical desalination procss flow



3.2 Source water intake technology

3.2.1 Overview

Intake systems are required for any desalination process that is sourcing water from a natural source. There are two basic types of intake systems:

- Open intakes, that are used to collect water from surface sources; and
- Subsurface intakes, that are used to collect water from ground sources such as wells and infiltration galleries.

Almost all large scale SWRO and thermal desalination plants collect feedwater from open intakes that are positioned in the ocean and transport the feedwater to the plant via a subsea pipeline or tunnel. Small scale SWRO plants utilise both open intakes and subsurface intakes where the water is sourced from coastal aquifers via wells and infiltration galleries.

Similarly BWRO plants utilise both open intakes for sourcing brackish surface water and subsurface intakes for sourcing brackish water from wells and infiltration galleries.

3.2.2 General issues

The key issue associated with intakes for desalination systems is the environmental impact associated with impingement and entrainment of aquatic organisms and the impact of impingement and entrainment on operations and maintenance costs.

Impingement, where aquatic organisms become trapped against the intake screens as a result of the velocity and force of the water being pulled into the intake, and entrainment, where aquatic organisms pass through the screens and enter the treatment systems, present challenges to desalination facilities from two perspectives:

1. The resulting destruction of organisms has environmental regulation and perception implications that require management; and
2. Managing impingement and entrainment and the required cleaning that results from impingement and entrainment has a negative effect on operations and maintenance costs.

Impingement and entrainment are more significant issues for open intakes as two characteristics that are inherent to subsurface intakes substantially reduce impingement and entrainment problems, namely:

1. Subsurface water is naturally filtered through granular formations, minimising organisms that can become entrained in the system; and
2. Because there are minimal organisms in subsurface water, screens are usually not used in the intake system resulting in limited scope for impingement.

Subsurface intakes present the additional advantage that they often result in a higher quality of feedwater that requires less pre-treatment. However, to date their use has been confined to mostly BWRO plants and some small SWRO plants, with the notable exception of the Fukuoka SWRO plant in Japan. The limitation of their use is mostly related to the absence of any long-term data relating to Silt Density Index (SDI) reduction, bio-fouling control efficiency in terms of Total Organic Carbon (TOC) removal and turbidity removal associated with subsurface intakes or how the productivity and water quality associated with subsurface intakes might change over time (Fukuoka District Water Works Agency, 2010). An additional potential problem associated with subsurface intakes is that the infrastructure can potentially conflict with alternative beach uses. The Metropolitan Water District of Orange County in California is currently conducting a long-term trial of a slant drilling technique that overcomes the problem of public beach interference and mitigates the entrainment and impingement issue via subsurface intakes.

Impingement and entrainment issues are exacerbated in the case of SWRO and BWRO plants that are using open intakes to draw water from surface sources such as lagoons, estuaries, rivers and inland lakes where greater concentrations and variety of organism are likely to be found when compared to open ocean intake environments.

3.2.3 Issues for the Australian desalination industry

Experience with operating the Kwinana SWRO plant has demonstrated that entrainment of certain crustacean species is potentially problematic as spat penetrates the intake screens and the intake pipes are a very suitable habitat. For the SWRO plants on the southern coast of Australia, such as the Adelaide and Melbourne plants, there is potential for entrainment of abalone to be a considerable operations and maintenance challenge as they are a larger species that attaches more firmly to a surface than mussel species. Such entrainment is typically resolved through shock chlorination. However, this process has had limited success in Kwinana. In the case of the subsea tunnel that is part of the Adelaide intake system, it is likely that a Remotely Operated Vehicle (ROV) will be used to inspect and maintain the tunnel and remove any significant bio-growth from tunnel walls (Pelekani, 2010). Methods for cost effectively managing or eliminating entrainment from intake systems would be seen as a future need for the Australian SWRO desalination industry.

An interesting area of study for control of these organisms is the use of pulsed electrical currents. Temporary immobilisation of aquatic nuisance species through application of short electric pulses has been explored as a method to prevent biofouling in cooling water systems where untreated lake, river, or sea water is used. In laboratory experiments, electrical pulses with amplitudes on the order of kilovolts/centimetre and sub-microsecond duration were found to be most effective in stunning hydrazoans, a common aquatic nuisance species. The results showed that the pulsed electric field method provides full protection against biofouling when pulses of 0.77 µs width and 6 kV/cm amplitude are applied to the water at the inlet of such a cooling water system. Even at amplitudes of 1 kV/cm, the protection is still in the 90% range, at an energy expenditure of 1 kWh for the treatment of 230 KL of water (Amr & Shoenbach, 2000).

Key industry issue

Management of the entrainment of small marine organisms in intake infrastructure associated with SWRO plants

All six of the municipal SWRO plants in Australia that are currently either operational or under construction utilise open intakes that draw water from the adjacent coastal environment via capital intensive subsea pipelines. Furthermore, it is likely that given the slow uptake of subsurface intakes for SWRO plants globally, that any additional municipal SWRO installations that are contemplated in the immediate future will utilise open intake systems.

The Kwinana municipal SWRO plant has reported that the management of the entrainment of mussel species on the inside walls of its intake infrastructure has proved problematic from an operations and maintenance perspective (Mercer, 2010). Mussel spat is sufficiently small to pass through the grates and inside walls of the intake pipe have proven to be a very suitable habitat for the mussel species that are found in Cockburn Sound.

The responsiveness of the mussel populations growing on the walls of the intake pipe to shock chlorination has been variable, but manageable because the mussels are relatively small and attach fairly loosely. Nevertheless, the management of this issue represents additional operational expenditure. For plants that are positioned on other parts of the Australian coast the problem may prove considerably worse if there are local species that attach more firmly and grow larger in size such as is the case for various abalone species that are commonplace on the southern coast of Australia.

As such, there is a need to develop systems to prevent the entrainment of small marine organisms in intake infrastructure or to provide a solution that is more cost effective than current strategies.

3.3 Pre-treatment

3.3.1 Overview

Desalination technologies manufacture potable water from source waters that vary in quality as the result of site specific factors such as source water depth, turbidity, boat traffic, hydrocarbon contamination, local outfalls, wind conditions, tides, contaminated groundwater return flow (an initial worry at Cockburn Sound), and local runoff. The water quality of seawater varies from location to location, but mostly contains chloride and sodium ions together with low concentrations of other ions that can be problematic to the desalination process and product water quality such as bromide and boron. The ionic composition of brackish water source waters on the other hand can vary greatly depending on the geological origin of the source (National Academy of Science, 2008).

Pre-treatment systems and regimes are tailored to the source water quality and desalination systems to achieve three key objectives:

1. Improve the overall performance and efficiency of the desalination system;
2. In the case of SWRO and BRWO desalination systems, protect the RO membranes from a range of foulants that can reduce the performance of the RO membranes and/or damage the RO membranes; and
3. In the case of thermal desalination systems, reduce scaling and control corrosive elements and compounds in the source water.

Chlorine or hypochlorite have traditionally been used as the standard oxidants for bio-fouling control. However, thin-film composite polyamide membranes that are commonly used in RO desalination cannot tolerate oxidants like chlorine and as such chlorine needs to be removed by the pre-treatment process by the addition of a reducing agent such as sodium bisulphite. Ultraviolet (UV) and ozone are being trialled in some small RO systems as potential replacements for chlorine-based biological growth control of RO feedwater (National Academy of Science, 2008).

Foulants that affect the performance of RO membranes include particles, colloids, natural organic matter, scaling compounds, microorganisms and various other organics. Scaling is caused by the precipitation of minerals such as calcium carbonate from solution and is controlled by temperature control, nanofiltration designed to remove calcium ions or the use of antiscalant chemicals. Similarly, corrosion can be reduced by removing corrosive gases during the pre-treatment process. Table 5 summarises some of the chemicals that are used in a conventional pre-treatment process.

Historically, the basic pre-treatment process has involved the following:

- Removal of suspended solids by coagulation/flocculation and filtration;
- Lowering of pH to protect the RO membranes and control the precipitation of salts;
- Addition of scaling inhibitors to control calcium carbonates and sulphates; and
- Addition of a disinfectant such as chlorine species, ozone or ultraviolet light to control biofouling of membranes (World Health Organisation, 2007).

This conventional approach to pre-treatment is common to most current SWRO installations. However, some new SWRO plants are adopting the low pressure membrane based pre-treatment systems that have been commonplace in BWRO for some time.

Conventional pre-treatment

The first stage of conventional pre-treatment processes involves intake water being chemically dosed to effect coagulation/flocculation and then processed through a granular media filtration technology to remove suspended solids from the feedwater. The feedwater then undergoes further chemical dosing, primarily to maintain the performance of the RO membranes and to protect the RO membranes. Brackish water desalination systems that treat groundwater usually require very minimal pre-treatment to remove particulates, if any, because groundwater is naturally filtered through the geological formations through which it travels. However, brackish groundwater may require pre-treatment to remove selected constituents such a dissolved iron, manganese and sulphides, which if oxidised are problematic for RO membranes (National Academy of Science, 2008).

Table 5 summarises some of the chemicals that are used in a conventional pre-treatment process.

Table 5:
Typical chemical regime for conventional pre-treatment processes (World Health Organisation, 2007)

Chemical type	Purpose	Typical dose	Application
Scale inhibitors Polyelectrolyte polymer blends	Increases the solubility of sparingly soluble salts such as calcium and magnesium carbonates and sulphates. In some applications, additional chemicals may be used to target specific species such as silica	2-5 mg/L	Primarily in brackish water and water reclamation using RO and ED/EDR operating at high recoveries
Scale inhibitors Usually sulphuric	Reduction of pH for inhibition of scaling and for improved coagulation	40- 50 mg/L is required to reduce pH to the range of 6-7	Primarily in SWRO applications
Scale inhibitors Usually ferric chloride or ferric sulphate	Improves suspended solid removal	5-15 mg/L	Primarily in SWRO systems incorporating an open intake, but also used in other systems using surface intakes
Scale inhibitors Usually cationic polymer	Improvement of suspended solids removal	1-5 mg/L	Primarily in SWRO systems incorporating an open intake and other RO systems using surface intakes. Sometimes used intermittently if variable feedwater quality results in periods of high SDI
Scale inhibitors Usually a form of chlorine, albeit biocides are sometimes used in smaller systems	Control of biofouling and aquatic organism growth in the intake and pre-treatment facilities. Chloramines may be used for pre-treatment in reclamation systems and their use is usually avoided in SWRO systems	3.7 mg/L for 30-120 minutes every 1-5 days	Used for large surface and seawater intakes. Small systems and those using wells, especially where the water in anaerobic may not require oxidisation
Scale inhibitors Usually a form of bisulphite	Elimination of oxidising impacts on the RO membrane	Generally 2-4 times higher than oxidising agent dose	In all membrane processes using polyamide RO membranes (less common cellulose acetate membranes have a greater tolerance of oxidants)
Scale inhibitors	Offline, membranes must be sterilised and preserved. Sterilisation may utilise hydrogen peroxide or acetic acid to create peracetic acid. Preservation most commonly uses sodium metabisulphite		

Conventional pre-treatment can also involve settling, flotation and two-stage filtration. However, this has not been necessary for Australian plants to date (Cadee, 2010).

While conventional pre-treatment using granular media filtration and a chemical dosing regime similar to that prescribed in Table 5 has evolved significantly over the past decade, it is often costly, difficult to operate and displays inferior performance in terms of turbidity, SDI, and consistency of water quality of the filtered water and uses more chemicals and space than the emerging low pressure membrane based pre-treatment processes (Voutchkov, 2009). It is important to note that much of the effectiveness of conventional pre-treatment over membrane alternatives depends upon the water source (e.g. Pt. Lisa's SWRO plant has successfully used gravity filtration).

Low pressure membrane pre-treatment

The use of low pressure membranes to replace granular media filtration and a number of chemical processes that are typical of conventional pre-treatment involves the application of the following membrane technologies:

- *Microfiltration (MF) Membranes* – are membranes with a nominal pore size of approximately 0.1-3 µm. Intake water is processed through MF membranes to remove particulates, bacteria and protozoa.
- *Ultrafiltration (UF) Membranes* – are membranes with a nominal pore size of approximately 0.01 to 0.1 µm. Intake water is processed through UF membranes to remove viruses and organics such as pyrogens (Trussell Technologies, 2010).

While MF and UF pre-treatment systems do not typically require water conditioning, they can use significant amounts of chemicals for the Chemically Enhanced Backwash (CEB) process and a periodic deep cleaning process, known as a Clean-in-Place (CIP) process that is required to keep the pre-treatment system operating effectively.

Typically, CEB is required to be practiced one to two times per day, while CIP of the MF and UF membranes is required every 60-90 days of operation (World Health Organisation, 2007).

Table 6 summarises some of the main chemicals used in MF and UF based pre-treatment systems. The advantages and disadvantages of low pressure membrane pre-treatment systems (Voutchkov, 2009) are listed in Table 7.

MF and UF membranes are commercially available in flat-sheet, tubular, hollow-fibre and spirally wound configurations (National Academy of Science, 2008) and are yet to be standardised in size or design. Most of the latest MF and UF membranes used for pre-treatment are made of polymers based on polyvinylidine diflouride (PVDF) or polyethersulphone (PS/PES), which provide improved mechanical and chemical resistance over earlier MF and UF membranes. Additionally, ceramic membranes are beginning to be adopted in municipal SWRO applications because of their higher resistance to oxidisation and low fouling potential (Kiwa Water Research, 2007).

Table 6:
Chemicals typically used in low pressure membrane pre-treatment systems

Chemical type	Purpose	Typical dose	Application
Acid Usually citric, phosphoric or hydrochloric acid)	Cleaning of solids and biological material from membrane filtration	Batch size is a function of process train size. Frequency of bathes is function of the number of process trains and site specific conditions	MF and UF membrane CEB and periodic deep cleaning of MF and UF membranes
Sodium Hypochlorite	Cleaning biological material from membrane filtration	Batch size is a function of process train size. Frequency of batches is a function of the number of process trains and site specific conditions	MF and UF membrane CEB
Phosphates Tri-polyphosphate or similar	Cleaning of membranes	Batch size is a function of process train size. Frequency of batches is a function of the number of process trains and site specific conditions	Periodic deep cleaning of MF and UF membranes
EDTA	Cleaning of membranes	Batch size is a function of process train size. Frequency of batches is a function of the number of process trains and site specific conditions	Periodic deep cleaning of MF and UF membranes
Speciality cleaning agents	Unusual deposits on membrane surfaces may be removed offline using specialty chemicals and treatments specified by the manufacturer		

Table 7: Advantages and disadvantages of low pressure membrane pre-treatment systems

Advantages	Disadvantages
• Superior solids removal compared to conventional pre-treatment • Smaller footprint compared to conventional pre-treatment systems • Less sensitivity to changes in source water quality compared to conventional pre-treatment systems • Simpler to operate than conventional pre-treatment systems • Pressure UF systems do not require basins as do submerged membranes or gravity filtration systems. These basins are cumbersome, require large areas and the concrete finish has to be perfect to ensure longevity	• MF and UF membranes are also prone to fouling • Costs of MF and UF membrane cleaning often exceeds cleaning costs associated with RO membranes • The current life of MF and UF membranes is shorter than the typical life of RO membranes, albeit that the life of MF/UF membranes is increasingly similar to that of RO membranes • The unit cost of MF and UF membranes is at least comparable to the unit cost of RO membranes • Current commercially available MF and UF membranes for use in pre-treatment are not standardised in size or configuration meaning different Original Equipment Manufacturers (OEM) products are not interchangeable

3.3.2 General issues

Effective and optimised pre-treatment is widely considered to be the most important factor in the successful operation of an RO plant and as such, extensive piloting of pre-treatment systems using location specific source water is a key component of RO plant design.
The key issues associated with pre-treatment systems are:

1. Increasing the fundamental understanding of specific source water foulants and their mechanisms and their rate of removal by various pre-treatment options. The performance of various pre-treatment technologies is currently only understood at a high level and is measured by simplified water quality parameters such as turbidity, total suspended solids, Silt Density Index (SDI) or Total Organic Carbon (TOC). Whereas membrane fouling is the result of a number of specific types of compounds present in the source water, including:
    - Solid foulants or particulate foulants;
    - Colloidal silica and iron;
    - Scaling foulants such as sparsely soluble mineral compounds of calcium, magnesium, barium and strontium;
    - Natural organic foulants such as pigments, humic and fulvic acids; and
    - Microbial foulants (microorganisms and their byproducts).
2. Improving the performance and cost effectiveness of existing pre-treatment technologies or the development of new pre-treatment technologies.

3.3.3 Issues for the Australian desalination industry

Pre-treatment systems for Australian municipal SWRO plants that are currently operational, under construction or planned have a total capacity of more than 4,000,000 m^3/day (Butler, Lazaredes, Johnson & Biltoft, 2009). The municipal SWRO plants that utilise conventional pre-treatment in Australia typically use chemical coagulation/flocculation combined with dual media filters. The Kwinana SWRO plant uses pressure dual media filters, whereas the Gold Coast SWRO plant uses gravity dual media filters. A more precise understanding of the composition of feedwaters supplying Australian municipal SWRO plants could potentially lead to better optimisation of those plants through fine-tuning (Dickson, 2010).

In the case of inland BWRO plants, the quality of most Australian brackish ground and surface water is reasonably good with low suspended solids and low levels of organics. However, there are site specific issues including:

- Ground water that has high levels of calcium, iron, magnesium and arsenic;
- Ground water that has high levels of silica; and
- Surface water that has high levels of bromide (Kavanagh, Findlay, Taylor & Pelekani, 2010).

Reduction of pre-treatment capital expenditure and operational expenditure is highly desirable for inland BWRO plants as is process simplicity. Applying BWRO to ground water sources that have high levels of iron, magnesium and arsenic is problematic as it requires an additional upstream process to remove iron and arsenic. The presence of high levels of silica is also problematic due to its poor solubility, which results in low recoveries in the range of 35-65% meaning that recovery of freshwater from the brackish source is not optimised and larger more expensive evaporative ponds are required to manage the larger volumes of concentrate (West, 2010).

In inland operations the disposal of cartridge filters is a significant element of operational expenditure because of the transportation of new and spent cartridges to and from the sites. As such, the development of longer life cartridge filters or an alternative solution to cartridge filters for inland BWRO or small scale SWRO plants would be seen as advantageous (West, 2010).

Furthermore, low pressure membrane pre-treatment is only applicable to surface water sources because most ground water in Australia requires the oxidisation of magnesium and iron that is present in the water. As such, the development of more robust micro-filtration systems for BWRO systems would be seen as advantageous (Palmer, 2010). It should be noted that companies such as Siemens focus considerable research resources on the development of micro and ultra-filtration systems and as such the NCED would face considerable challenges in investing in this area in isolation from the major pre-treatment membrane original equipment manufacturers.

Key industry issue

Precise characterisation of source waters for municipal SWRO plants as an input to the optimisation of pre-treatment systems

Globally there is a recognised need to increase the fundamental understanding of specific SWRO source water foulants, their mechanisms and their rate of removal by various pre-treatment options. The performance of various pre-treatment technologies is currently only understood at a high level and is measured by simple water quality parameters such as turbidity, total suspended solids, Silt Density Index (SDI) or Total Organic Carbon (TOC). Whereas fouling is the result of a number of specific types of compounds present in the source water.

As such more detailed characterisation of the Australian source waters for:

- Current installed municipals SWRO plants and SWRO plants currently under construction may allow the fine tuning of the existing pre-treatment systems that results in overall improvement of the performance of the desalination plant; and
- Potential sites for future municipal SWRO plants in Australia will serve as an important input to the optimal choice and design of pre-treatment systems for plants that will eventually be deployed at those sites.

Key industry issue

Reduction in operational and capital costs associated with brackish water desalination pre-treatment systems

The application of desalination to brackish ground water sources in inland Australia with high levels of iron, magnesium and arsenic is problematic as it requires additional upstream processes. The presence of high levels of silica in many Australian inland ground water sources is also problematic for BWRO as it results in low levels of recovery. Research that leads to the development of pre-treatment systems that can more cost effectively remove iron, arsenic and silica in particular is a prerequisite for wide-scale implementation of inland desalination.

Furthermore, the inland disposal of cartridge filters is a significant element of operational expenditure because of the need to transport new and spent cartridges to and from the sites. As such, research that leads to the development of longer life cartridge filters or an alternative solution to cartridge filters for inland BWRO plants that averts disposal and replacement costs could also be a research opportunity.

3.4 Desalting systems

There are three basic processes by which water can be separated from salt, namely:

1. *Physical separation processes*, that use pressure and membranes to separate water from salt;
2. *Phase change processes*, that predominately use thermal energy to separate water from salt; and
3. *Chemical separation processes*.

3.4.1 Technologies for physical separation

Reverse osmosis

Overview

Reverse osmosis (RO) processes use semi-permeable membranes and a driving force of hydraulic pressure that is typically in the range of 10-83 bar to remove dissolved solids, including dissolved salts, from brackish (BWRO) or seawater (SWRO) (National Academy of Science, 2008). By virtue of its relatively high level of efficiency, RO membrane technology has become the primary means of separating water from salt in both seawater and brackish water contexts. Furthermore, given the cost and greenhouse gas implication associated with mature phase change processes and the immature nature of emerging physical, phase-change, chemical and hybrid technologies, it is highly likely that reverse osmosis based processes will continue to be entrenched as the predominate means of desalting water well into the future. This is supported by estimates of the market for RO membranes.

As illustrated in Figure 7, the global market for RO membranes that are used in SWRO and BWRO desalination and water reuse applications is expected to grow from approximately US$400 million currently to almost US$700 million by 2016.

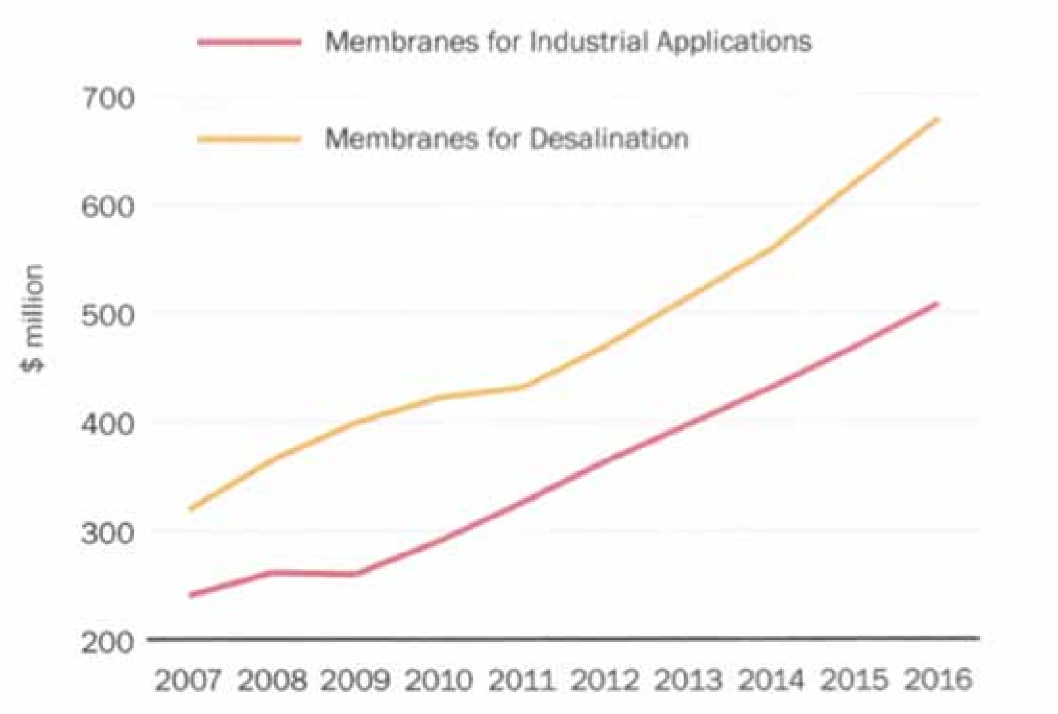


Figure 7: Global RO and NF membrane market forecast (2007-2016)

RO membrane formulations include cellulose acetates, polyamides, polyetheramides and polyethersulfones. However, the most widely used membrane material is a thin-film composite polymer combining a micro-porous polysulfone support layer with a thin polyamide layer (National Academy of Science, 2008). RO membranes have matured significantly over the past few decades resulting in improvement in cost, water flux and permeability, membrane life and salt rejection capability. Indeed inflation-corrected membrane cost declined by a factor of four between 1975 and 1990 and by a further approximate 75% between 1990 and 2002 (Birkett & Truby, as cited in National Academy of Science, 2008).

General issues

Despite being the most efficient means of separating water from salt, RO membranes, in a SWRO and BWRO operating environment, still face a number of challenges that limit their current performance. For SWRO and BWRO membranes, these limitations primarily relate to a specific range of parameters in which a system can operate, including:

- Freshwater productivity (currently limited to a range of 10-20L/m^2/hr);
- Salt rejection (currently limited to a range of 99.0-99.8%);
- Propensity to scale and foul;
- Operating pressure range limitation (maximum of 45 bar for BWRO systems and 75 bar for SWRO systems)
- Maximum operating temperature of 45°C;
- pH tolerance in the range of 4-11;
- Maximum Silt Density Index (SDI) tolerance of approximately 4;
- Maximum turbidity tolerance of less than 1 NTU; and
- Intolerance to oxidants, particularly strong oxidants such as chlorine, ozone, peroxide and bromine, where tolerance is almost zero.

The limited operating range for these variables has a number of implications including requirements for specific quality of feedwater and as such a need for pre-treatment to bring the quality of feedwater within the operating range of the SWRO system, restriction on varying the quality of permeate and general operational efficiency of the SWRO system. However, it is freshwater productivity and fouling propensity that have the greatest impact on plant capital and operational expenditures.

Efforts to improve RO membrane permeability have focused on introducing additives to the production of thin-film membrane polymorphic film, control of membrane surface morphology, the incorporation of inorganic nanoparticles within traditional membrane polymeric film or the development of membranes that consist of a densely packed array of nanotubes (see subsequent section). Most efforts to improve membrane flux result in an undesirable trade-off with salt rejection. Indeed increasing membrane element productivity is limited by a number of factors including the structure of RO membranes, concentration polarisation, enhanced membrane fouling and the increase of osmotic pressure in the membrane feed channel (Karabelas & Karabelas, 2009). Because salt rejection for SWRO and BWRO membranes is currently in the range of 99.6-99.8%, there is limited scope for improving salt rejection. However, additional salt rejection above this range does potentially present economic benefits for SWRO plants by virtue of a decreased need for second pass RO (Cadee, 2010). Furthermore, the fact that historical attempts to improve permeate flux have resulted in a concomitant reduction in salt rejection means that this remains an issue worthy of investigation in relation to increasing membrane flux (Voutchkov, 2009).

It is likely that increasingly stringent water quality restrictions will mean that membranes that have the ability to reject problematic compounds such as boron, arsenic salts, silica, selenium, nitrate, bromide, endocrine disruptors and trace organics will be seen as advantageous, resulting in a reduced requirement for extensive post treatment (Voutchkov, 2009).

Given that as much as 70% of the annual operations and maintenance costs associated with membrane based desalination plants are associated with energy use for membrane separation and membrane placement and cleaning costs, membrane fouling remains a significant issue for the industry. Related to this issue is the fact that thin-film polyamide membranes that are most commonly used in SWRO and BWRO applications are susceptible to anti-fouling oxidants such as chlorine, ozone and peroxide. As such the development of membranes that do not foul or that are tolerant of oxidants such as chlorine would be advantageous to the industry, albeit that continuous chlorination is in any event problematic for SWRO in that it can result in the formation of disinfection by-products (Cadee, 2010).

Issues for the Australian desalination industry

The RO membrane challenges for the Australian desalination industry are largely the same as they are for the global industry – reduction of membrane fouling, chlorine tolerance and improved permeate flux. As mentioned in the discussion on pre-treatment, some Australian inland BWRO operations face significant challenges with achieving recovery rates in excess of 65% because of high silica content in the feedwater. BWRO membranes or processes that could achieve higher recovery rates from silica contaminated feedwater without the need for extensive pre-treatment would be seen as advantageous (West, 2010).

Improvement in membrane effectiveness and efficiency would obviously be beneficial to the Australian desalination industry. However, it should be noted that the development and commercialisation of new membrane chemistry is an expensive exercise, typically requiring tens of millions of dollars. It is also the core focus of the relatively well resourced research programs of large multinational membrane companies such as Dow, Nitto Denko/Hydranautics, Toray and GE. As such, the pursuit of a robust new membrane research program by the NCED would face a considerable challenge unless it was done so under a substantial collaborative arrangement with one of the major membrane companies (Andes, 2010; Cadee, 2010; Campbell, 2010; Crisp, 2010; Dickson, 2010; Findlay, 2010; Herbert, 2010; McCrisken, 2010; Mercer, 2010; Shackleton, 2010; Sibma, 2010; Trousdale, 2010; Windsor, 2010).

Key industry issue
Membrane research

Areas of improvement in membrane performance that would be particularly advantageous to the Australian desalination industry include:

- Development of BWRO membranes that achieve higher levels of recovery from source waters that have high silica concentrations
- Development of more robust low pressure pre-treatment membranes that are tolerant to high levels of magnesium and iron so that they can be used as a pre-treatment option for ground water BWRO in Australia
- Membranes that deliver improved permeate flux
- Development of fouling resistant membranes
- Development of chlorine resistant membranes
- High bromide rejection

Investment in research projects in these areas should only be considered by the NCED where there is substantial collaborative support for the project from a membrane OEM.

Electrodialysis and electrodialysis reversal

Overview

In 2005, electrodialysis accounted for approximately 3% of installed global desalination capacity and approximately 7% of installed desalination capacity in the United States (Global Water Intelligence, as cited in National Academy of Science, 2008). Electrodialysis (ED) and Electrodialysis Reversal (EDR) are desalination processes that use ion-selective membranes and an electrical current to separate ionic species from water. Under an ED process, ionic species are driven through cation and anion specific membranes in response to the electrical potential gradient, while the ion depleted water passes between the membranes.

EDR involves a similar process to ED, with the additional periodic reversal of polarity in order to reduce scaling which in turn results in higher recovery rates (National Academy of Science, 2008).

ED and EDR have a number of potential advantages over RO in specific brackish water desalination applications:

- ED membranes typically require less pre-treatment, with pre-treatment usually confined to pre-filtration to remove suspended solids, some antifouling treatment and the removal of CO_2 to improve efficiency;
- ED and EDR membranes are chlorine resistant, making them more robust for processing feedwaters with higher levels of organic matter that would typically foul RO membranes; and
- ED and EDR are only capable of removing ionic species from a solution and as such fouling from uncharged species such as silica is less severe than it is in the case of RO systems; this is a key advantage for waters high in silica (National Academy of Science, 2008).

General issues

The energy consumption of ED and EDR is approximately 0.5-0.6 kWh/kg of salt removed (Cadee, 2010). As such, the economics of current ED and EDR processes are limited to use on brackish source waters with TDS of up to approximately 7,500 mg/L (Mickley et al, as cited in National Academy of Science, 2008). Therefore, technology that improves the operating economics of ED or EDR such that it can be used on more saline brackish water, or even seawater, may result in the technology having wider application in desalination.

The application of ED and EDR has been limited primarily because there is a single established provider of ED and EDR technology, GE. Greater competition in the ED and EDR marketplace may result in wider use of the technology by utilities and industry.

Issues for the Australian desalination industry

In some applications, EDR has advantages over RO in that it:

- Is a more robust technology (implying less operating and maintenance costs for low salinity waters);
- Uses less energy (particularly when used for waters with TDS levels lower than 2,000 mg/L);
- Has a higher chlorine tolerance and lower bio-fouling potential;
- Recovery is basically unaffected by high levels of silica which can limit RO recovery;
- Allows salt recovery to be varied; and
- In some instances, has a lower associated capital cost.

EDR is particularly relevant to inland desalination applications in Australia where there is a high level of silica in the feedwater, because as silica is not charged, it is not removed and therefore does not negatively affect water recovery (Dickson, 2010).

Furthermore, inland Australia is characterised by a large number of significant sources of very saline ground water. Currently ED and EDR applications are restricted to brackish waters with TDS of approximately 7,500 mg/L. Given the various potential advantages of ED and EDR over RO in remote inland brackish water desalination locations, an ED or EDR system that can desalinate source water with higher TDS concentrations cost effectively would potentially be beneficial.

Key industry issue
Application of ED and EDR to brackish water desalination in Australia

In some desalination application ED and EDR have specific advantages over reverse osmosis in terms of systems robustness, energy use, bio-fouling resistance and lower capital cost. ED and EDR technology is particularly relevant to inland desalination applications in Australia where there is a high level of silica in the feedwater.

Research into Australian inland water resources that could be desalinated using current ED/EDR technology would be a useful input into understanding how this technology could be better deployed in Australia. Additionally, research that leads to the development of ED/EDR technology that is able to cost effectively treat brackish waters with a TDS concentration of greater than 7,500 mg/L may result in wider use of ED and EDR, particularly on the many inland sources of water in Australia that have high silica concentrations and are as such problematic for reverse osmosis.

Emerging physical separation technologies

Hybrid reverse osmosis – electrodialysis systems

Conventional RO systems can be combined with an electrodialysis system to process the concentrate from the RO system thereby increasing overall plant recovery to more than 90%.

Veolia is currently marketing a system known as Zero Discharge Desalination (ZDD) which can be used to minimise or eliminate disposal through more costly (and environmentally unacceptable) options such as deep well injection, large evaporation ponds or waste hauling (see section on waste management). This technology deploys a combination of separation processes that include an electrodialysis device in an ion substitution mode to remove divalent salts from water. A secondary membrane system can then be added to control the silica in the concentrate stream when high silica levels are present. A ZDD system can be added to an existing BWRO to increase potable water recovery from the typical 80% to as high as 97% (Veolia Water Solutions, 2010).

A technology currently under development at Sandia National Laboratories in the United States involves the primary application of the ED component of the system being to remove scaling compounds from the concentrate, thereby reducing the osmotic pressure of the RO feed and decreasing scaling and concentration polarisation effects. Permeate from the ED system is then returned to the feedwater for the RO system for additional recovery.
The brine generated by the ED system can be processed through an evaporator-crystalliser for additional brine volume minimisation. Such a system has potential application in SWRO and BWRO.

Nanostructured membranes

RO membranes that are commonly used in SWRO and BWRO today are dense semi-permeable polymer films of random structure which do not have pores and as such, water molecules are primarily transported through these membrane films by diffusion, travelling on a multi-dimensional, curve-linear path within the randomly structured polymer film matrix. This is inefficient in terms of membrane film volume to surface area and the energy needed to move water molecules through the membrane (Global Water Intelligence, 2009a).

Nanostructured (NST) membranes contain individual straight-line nanometer size channels in the form of nanotubes (pores) that are either embedded into the random polymer matrix or are entirely comprised of clustered nanotubes. (National Academy of Science, 2008).

NST membrane technology has evolved rapidly and it is widely expected that NST membranes will be commercially available in the not too distant future. For example:

- The thin-film composite NST membranes currently being developed by NanoH_2O claim to have demonstrated 60-70% higher productivity than currently available RO membranes (if operated at the same productivity as existing RO membrane technology, this would result in a 10-20% energy saving at the primary RO process);
- A research team at the Livermore National Laboratory in California is developing membranes comprised entirely of a vertically aligned densely packed array of carbon nanotubes;
- A research team at the School of Biology at the Australian National University is developing a silicon nitride membrane that has boron nitrite nanotubes embedded into it, which claims to improve rejection of salts, heavy metals and other contaminants at very high permeability;
- The Australian Advanced Membrane Research Technologies for Water Treatment Research Cluster is developing a membrane based on carbon nanotubes and zeolite TFN membranes; and
- A team at the University of Texas – Austin has developed a membrane based on nanoporous particles in a porous polymer matrix (Funk & Lloyd, 2008).

Forward osmosis

A Forward Osmosis (FO) process can potentially be used for low energy desalination and for the generation of osmotic power (Global Water Intelligence, 2009a). FO is a membrane based separation process that capitalises on an osmotic pressure difference between a concentrated draw solution and a feed solution to drive water across a semi-permeable membrane. Given sufficient difference in osmotic pressure, the magnitude of water flux and degree of salt rejection has the potential to be competitive with RO (National Academy of Science, 2008).

Because the structure of existing thin-film composite RO membranes result in low productivity for FO, the development of a high productivity, low cost FO membrane of a standard size is currently the main constraint in creating a commercially viable FO system (Cath, 2006). A further challenge for FO is the selection of a draw solution so that it can be practically and economically removed (McGinnis and Elimelech, as cited in National Academy of Sciences, 2008).

FO also has the potential to supplement the power requirements of a RO plant, as is discussed in a subsequent section of this paper. Except for brackish and hypersaline sources, the potential to supplement plant energy via a Forward Osmosis process is questionable in Australia because it requires a freshwater supply, which if available, is generally used for customer needs (Herbert & Windsor, 2010).

Membrane distillation

Membrane Distillation involves the transportation of water, in the form of water vapour, between a 'hot' saline stream and a 'cool' freshwater stream across a hydrophobic membrane. To effect the transportation of water vapour across the hydrophobic membrane only a small temperature differential between the two streams is required.

The separation process occurs at normal pressure and could potentially achieve recovery rates that are twice as much as those currently achievable with SWRO. Membrane distillation also has the potential to be a viable means of further concentrating RO brine, which indeed seems its most likely application (Macedonio, 2009). Membrane distillation processes use membranes that are constructed from hydrophobic polymers containing micro-sized pores. The viability of membrane distillation is dependent on the development of a contactor geometry that provides an extremely low pressure drop and on the creation of membranes which have high temperature limits (Khayet & Matsuura, 2010).

Potential advantages of membrane distillation compared to other thermal desalination technologies include a smaller footprint, lower capital costs and the ability to use low-grade heat sources. Possible disadvantages include difficulty in maintaining the hydrophobicity of the membranes over long periods due to fouling and degradation, the large enthalpy of vapourisation required for the phase change of water transported across the membrane and poor rejection of volatile feed stream contaminants (Peng et al, as cited in National Academy of Science, 2008). Another disadvantage is the challenge of finding a suitable site with an available source, close to available heat source, and close to a brine disposal site.

3.4.2 Technologies for phase change separation

Most commercial phase change technologies such as multi-stage flash (MSF) and multi-effect distillation (MED), are only viable where energy costs are very low (such as in certain regions in the Middle East) or where there is a localised supply of waste heat, such as may be the case with a co-located power plant, steel mill, mine processing (e.g. Ravensthorpe Nickel in Western Australia) or refinery. There is a view that the feasibility of co-locating thermal desalination facilities with sources of waste heat has been somewhat overlooked in many western industrial countries, particularly in the United States (National Academy of Science, 2008). However, even where there is a localised supply of waste heat, phase change options need to be carefully compared to the improved efficiency that can be gained from RO processes using heated feedwater, albeit such an option can also exacerbate membrane fouling issues (Voutchkov, 2009). Opportunities for harnessing waste heat from industrial installations around Australia for the purposes of water production should be investigated and where this waste heat can be used to produce water for a ready market, feasibility studies undertaken (Cadee, 2010; National Academy of Science, 2008).

Dewvaporation

Dewvaporation involves an upward flowing stream of air being humidified by a falling film of saline water that wets on one side of a heat transfer surface. At the top of the evaporation tower the air is heated by an external source (solar irradiation or waste heat) and is then forced down the opposite side of the tower where it releases the applied heat and forms dew. This dew is condensed and collected at the bottom of the tower.

Possible advantages of dewvaporation when compared to other thermal methods of desalination include the ability to use low-grade heat or solar energy, small footprint and low capital costs. In comparison to RO it can operate at higher TDS and organic loadings (Findlay & Taylor, 2010). However, similar to other thermal evaporation processes, dewvaporation is only likely to be competitive with RO where free heat (solar irradiation) or waste heat is available (Beckman, 2008). Additional challenges for this technology include the large heat transfer areas that are required, impact of ambient weather and the need for a low-temperature sink to permit condensation (National Academy of Science, 2008).

Gas hydrate (clathrate) desalination

Gas hydrate technology uses clathrate forming compounds such as light hydrocarbons, halocarbon refrigerates and CO_2 and H_2 to form water ice crystals around gas molecules within a temperature range (12-17°C) that is significantly higher than the freezing temperature of water at normal pressure. In the first reactor the clathrate gas and high salinity water are mixed and hydrates (gas-water ice structures) are formed. Since the freezing process naturally excludes the salt from the source water, the hydrate crystals contain fresh water which is then separated in a different vessel from the clathrate former. The clathrate forming substance is then returned to the main reactor for reuse. The key potential benefit of such a process is that it involves a much lower energy input than RO. Sandia Laboratories are currently experimenting with a continuously operated reactor to evaluate the efficiency of salt/ ice separation. The technology is at an early stage of development and is not likely to yield commercially available processes in the near future.

Freeze desalination

Freeze desalination involves changing the phase of water from liquid to solid, capitalising on the fact that as ice crystals form, they exclude salt from their structure enabling the possibility of washing the salt from the crystals. Freeze desalination is theoretically more efficient than evaporation, with the freezing of water at atmospheric conditions requiring 334 kJ/kg of energy compared to 2,326 kJ/kg of energy required to evaporate water at atmospheric conditions. Potential advantages of this technology include improved energy efficiency compared to distillation process because ambient seawater is always closer to its freezing point than to its boiling point. Potential challenges to the practical use of freeze desalination include effective separation and washing of water crystals without prematurely melting them and redissolving the salt, maintenance of relatively complex system components and achieving efficient operation in light of refrigeration requirements (National Academy of Science, 2008).

Advanced vapour compression

This technology is only at a conceptual stage and is based on the benefits derived from the very high heat transfer created by mechanically spinning heat exchange surfaces (Voutchkov, 2009).

3.4.3 Technologies for chemical separation

Electro-desalination

Electro-desalination is at a conceptual stage. Early trials of a continuous electro-desalination technology, being developed by Siemens, have been undertaken at the Singapore Water Hub. The process involves using electrodialysis, exchange softening and a new kind of continuous electro-desalination process based on deionisation to desalinate the water. It consumes 1.5 kWh per cubic meter, which is half the energy required for reverse osmosis (Siemens, 2009).

Capacitive deionisation

Capacitive deionisation utilises ion transport from saline water to electrodes of high ion retention capacity, driven by a small voltage gradient. The saline water is passed through an unrestricted capacitor type capacitive deionisation module consisting of numerous pairs of high-surface area electrodes. Anions and cations contained in saline water are electro-absorbed by the electric field upon polarisation of each electrode pair by a direct current power source. Once the maximum ion retention capacity of the electrode is reached, the deionised water is removed and the salt ions are released from the electrodes by polarity reversal (Farmer, 1996).

The viability of capacitive deionisation as a desalination process is largely determined by the ion retention electrodes. Laurence Livermore National Laboratories have developed a carbon aerogel electrode that will potentially be suitable for low salinity applications, given carbon aerogel contains a very high specific surface area and very low electrical resistivity (Farmer, 1996). Trials suggests that this technology could potentially desalinate brackish water (2,000 ppm feed to 186 ppm permeate) using 0.14 kWh/m^3, assuming 70% recovery of the stored electrical energy (Farmer et al, as cited in National Academy of Science, 2008).

The most likely applications of capacitive deionisation are in water polishing or for low salinity brackish water applications as practiced by many water treatment specialists throughout the world in the semi conductor industry.

In-situ crystallisation

Sandia Laboratories has developed inorganic ion exchange materials that can desalinate brackish water. This technology is at a very early stage of development

Ion exchange

Ion exchange is mainly used for water softening and demineralisation and involves water being desalted by passing it through a column of cation exchanger beads in the hydrogen (H+) form. Generally, ion exchange can only be economically justified where there is a small amount of salt to be removed from the source water and as such, its major application has been in the production of ultrapure water or as a polishing stage following another desalination process, (National Academy of Science, 2008) or where specific ion exchange resins are used to selectively remove certain ions.

Biomimetic membranes

Biomimetic membranes are membranes that endeavour to adopt the structure and function of membranes of living organisms, where water molecules are transported through the membrane by a series of low-energy enzymatic reactions, rather than by a process of osmotic pressure. For example, while osmotic pressure driven exchange of water between living cells and their environment is often the key mechanism for water transport, in the cell membranes of many plants and animals are proteins known as aquaporins that regulate the flow of water by selectively conducting water molecules in and out of the cell, while preventing the passage of ions and other solutes. The most unique aspect of this process is its very high selectivity (National Academy of Science, 2008).

Currently researchers in the United States, Singapore, Japan and Australia (National Water Research Institute, 2004) are focusing research on advancing the field of biomimetic membranes. However, any practical developments are not expected in the near future, the main challenge being the formulation of membranes that are scalable.

3.5 Waste product management

3.5.1 Overview

The management of brine concentrate and other liquid wastes that are produced by the desalination process remains one of the major environmental and economic challenges for both SWRO and BWRO desalination and is arguably, the main negative externality associated with reverse osmosis desalination.

Management of concentrate waste streams

The most commonly used methods for concentrate management are:

- Maximising recovery;
- Disposal to surface waters;
- Deep well injection;
- Discharge to a salinity sewer;
- Pond evaporation (evaporation enhancers, enhanced surface areas); and
- Thermal Zero Liquid Discharge.

Disposal of concentrate to surface waters is typically limited to seawater desalination or in inland applications where the concentrate can be disposed to a high salinity aquifer.
In the case of SWRO, brine concentrate can be disposed into a vast ocean. However, for many inland brackish water operations, limited concentrate disposal options in turn limit the number of locations where brackish water desalination plants can be established and the size of those plants.

The most commonly used methods for inland concentrate disposal are either deep well injection or evaporative ponds, both of which are constrained by site availability, geology and disposal capacity and in the case of deep well injection, considerable difficulties in gaining approval in most developed jurisdictions.

Management of non-concentrate waste streams

The key non-concentrate waste streams generated by desalination plants are:

- Spent pre-treatment filters;
- Spent membrane chemical cleaning solutions;
- Residuals (sludge) that are generated from spent backwash water solids; and
- Spent cartridge filters and MF, UF and RO membranes.

The current methods for handling such waste products typically involves transporting them to landfill, which is not a sustainable solution and is one that is also a significant negative impact of desalination. Currently, there is some early commercial activity targeted at regenerating spent membrane elements via cleaning and surface treatment in order to render them satisfactory for reuse.

3.5.2 General issues

With respect to disposing of concentrate and non-concentrate waste streams to surface waters a major obstacle currently exists in that there is typically very limited understanding (generally or on a site specific basis) of how to assess the salinity tolerance of organisms in the local environment or the maximum salinity tolerance of the entire local ecosystem. Existing Whole Effluent Toxicity (WET) testing techniques only provide an indication of toxic type impacts. The absence of an ability to generate such knowledge with an adequate degree of confidence results in very conservative benchmarks being set by regulators, adding significantly to the cost of establishing and operating a desalination facility.

Considerable research has also looked at reusing some of the residual wastes, including concentrate from the desalination process. Concentrate could potentially be reused for the production of products of commercial significance such as gypsum, various metals (such as iron from the ferric coagulant used in many conventional pre-treatment processes) and sodium chloride, as well as other useful salts (Cadee, 2010). However, the economics of creating such products from concentrate is invariably cost-prohibitive when compared to the current economics associated with processes for the industrial production of those products.

Table 8 lists the components of a typical 8" RO membrane cartridge, which collectively weigh approximately 15 kilograms (Shackleton, 2010). In a typical SWRO plant a membrane replacement cost factor of 7% per annum is usually applied to determine the cost of replacing membranes (Dickson, 2010). Currently, spent membrane elements are disposed of in landfill and there is potential for recycling membrane elements.. The recycling of membrane elements potentially proposes a significant economic challenge. Membrane change-over at a plant tends to occur periodically in batches. As such, only a very small number of plants would be sustainable globally as continuously operating concerns. This means that membranes from plants around the world would need to be transported to these few recycling plants and this would most likely result in a carbon footprint that is at least similar to that which results from disposing of membrane elements in landfill (Shackleton, Andes & McCrisken, 2010).

Table 8:
Typical composition of an RO element

Element component	Material
Core Tube	ABS or ABS/Glass
Permeate carrier	Polyester
Feed spacer	Polypropylene
Tape	Polypropylene
Membrane	Polysulfone
Membrane substrate	Polyester
Adhesive	Polyurethane (2 Part)
Hot melt	Polyamide
Seal carriers	ABS
FRP encasement	Epoxy (2 Part)
FRP encasement	"E" Glass Roving
Brine seal	Ethylene Propylene Rubber
O-rings	Ethylene Propylene Rubber
Interconnector	Glass Filled Noryl
Heavy metals	Lead, Mercury, Cadmium or Hexavalent

The volume of water recovered determines both the volume of feedwater required to produce a desired volume of permeate and the volume of concentrate that is produced by the process. For BWRO, recovery rates are typically in the range of 60-80% (Pepperell, French & Srivastava, 2009). In an inland desalination context, the cost effective reduction of concentrate waste to a level of 5-10% of the source water volume (i.e. recoveries of 90%+) are of key importance simply because, unlike the ocean in the case of seawater desalination, inland disposal receptors such as evaporative ponds, high-salinity aquifers, mine voids, oil and gas well injection processes and evaporation crystallisers are very limited in the volume of concentrate that they can store or process.

Currently there are four main commercially available technologies that address recovery issues for inland desalination:

- *High Efficiency Reverse Osmosis (HERO)* was originally developed to produce high quality water for the semiconductor industry but has since been applied to the potable water industry. The process involves multimedia filtration, chemical softening and alkalinity removal in the pre-treatment stage of the RO plant. The PH is then raised to 11 which has the effect of increasing the solubility of scalants (silica) and reducing the extent of biofouling. A 300 kL/day HERO plant was installed in Yalgoo in Western Australia in 2007.

- *Optimised Pre-treatment and Unique Separation Technology (OPUS)* involves multiple pre-treatment steps including degasification, chemical softening, media filtration and ion exchange softening prior to the RO process. OPUS claims to achieve recovery rates in excess of 90%.
- *Electrodialysis Reversal (EDR)* (as discussed in a previous section) is a process that applies an electrical current to permeable membranes to remove salts from water. Some EDR processes claim to achieve recovery rates of 85-90% (Pepperell et al, 2009).
- *Vibratory Shear Enhanced Process (V-SEP)* is a process that uses oscillatory vibration to create a shear at the surface of the membrane, which improves the membranes ability to resist fouling thereby increasing recovery (New Logic Research, 2010).

Membrane Distillation (Duke, Dow, Zhang, Jun-de, Gray & Osteracevic, 2009) and Dewvaporation (Findlay & Taylor, 2010) are technologies still under development that hold promise as a means of further concentrating brine. This technology is discussed in detail in the section on desalting technologies. (Section 3.4).

Evaporative ponds are large shallow reservoirs that are lined with clay or plastic to prevent soil or groundwater contamination. Brine is discharged into the ponds where it is further concentrated through a process of evaporation. The size of evaporation ponds required for brine disposal is governed by the climatic conditions of the area, the capacity of the plant and its recovery efficiency.

Prior to brine being disposed of in mine voids, oil and gas wells or other geological structures, extensive and costly evaluation of the structure needs to be undertaken.

Another highly desirable goal for inland desalination is Zero Liquid Discharge, which is currently primarily limited by its capital costs and the high operating costs associated with thermal evaporation processes that are typically based on vapour compression technology (National Academy of Science, 2008). To put this in context, a large industrial facility with a traditional wastewater treatment facility costing approximately $20 million is capable of recovering and reusing up to 80% of its liquid waste streams. The evaporator and crystalliser system necessary to capture the last 20% can cost double the cost of the treatment facility. Furthermore, energy costs are high, in the range of 20-40 kWh/m^3 (Global Water Intelligence, 2009d). Recently developed non-thermal processes of brine concentration based on precipitating problematic scaling compounds in a post RO reactor and then filtering the supernatant could potentially significantly reduce the operating cost. Indeed use of a membrane crystalliser has shown promise in reducing the cost while allowing selective precipitation (Droili, 2004).

A technology being developed in Israel, the Wind Assisted Evaporative (WAEV) process, claims to have the potential to reduce concentrate to 10% of its volume, meaning that downstream evaporative ponds potentially need only be 10% of the size that would normally be required (Herbert & Windsor, 2010). A disadvantage of this technology is that the salt blows onto the surrounding land. Hanging strips can direct water flow, increasing the surface area and allowing the wind through.

3.5.3 Issues for the Australian desalination industry

A deeper understanding of the salinity tolerance of organisms in the local environment and the maximum salinity tolerance of the entire local ecosystem at existing municipal SWRO sites and potential future sites in Australia could substantially reduce municipal SWRO operating costs and the costs of establishing new municipal SWRO systems.

With respect to SWRO, a major emerging problem is the management of untreated backwash water. In the case of the Kwinana plant, the sludge which is removed from the filter backwash water is captured and transported to landfill and this will be the case for all Australian SWRO plants that incorporate conventional pre-treatment. In the case of the Binningup plant which is using low pressure membrane pre-treatment the backwash is able to be discharged to the sea because it does not contain ferric coagulant (Campbell, 2010). Technologies that facilitate the economic and environmentally friendly management of sludge that contains ferric coagulant would be seen as advantageous to SWRO plants that incorporate conventional pre-treatment processes (Pelekani, 2010).

With respect to concentrate management for inland BWRO plants in Australia, most locations have the advantage that the climate is well suited for effective evaporation pond operation and most regional sites have adequate land availability to the extent that the large footprint required for evaporation ponds is not a major problem (but they are expensive when lined and maintained). The significant capital expenditure that is associated with establishing evaporation ponds, which is often more than the capital expenditure associated with the plant (Cadee, 2010; Herbert, 2010; Windsor, 2010) remains problematic. As such, technologies that provide cost effective means of further reducing the volume of concentrate produced by BWRO plants would be seen as advantageous by the inland BWRO industry in Australia (West, 2010). Achieving higher recovery is one way which also reduces requirements for scarce source water required. Furthermore, as the volume of brine reduces with higher levels of concentration, opportunities may emerge for separating the various types of salt that comprise a specific brine, which may have implications for more cost effective disposal or alternative uses (Dickson, 2010).

The disposal of brine concentrate is also an issue from an environmental approvals and public perception point of view. New knowledge that can be used to standardise a process for determining environmental impact as well as educating the public on the true environment impact would be seen as advantageous (Herbert, 2010; Windsor, 2010). However, standardisation is limited by a wide range of site specific factors (Rhodes, 2010).

Key industry issue
Development of technologies and systems for the economic management or recycling of ferric sludge

Australian municipal SWRO plants that either do or will use conventional pre-treatment systems typically use ferric chloride or ferric sulphate as a coagulant to assist in the removal of suspended solids. This coagulant is then recovered as a ferric sludge waste product from the process. Current practice is to dispose of the sludge to landfill. Research that leads to the development of technologies that facilitate the economic and environmentally friendly disposal of recovered ferric, a cost competitive means of recycling the ferric, or an alternative flocculant would reduce operating costs associated with many Australian municipal SWRO plants.

Key industry issue
Detailed understanding of the salinity and toxin tolerance of marine species in the vicinity of SWRO outflows

Globally, there is typically a limited understanding of the salinity tolerance of organisms in the local environment or the maximum salinity tolerance of the entire local ecosystem of each site. Existing Whole Effluent Toxicity (WET) testing techniques only provide an indication of toxic type impacts. The absence of an ability to generate such knowledge with an adequate degree of confidence results in very conservative benchmarks being set by regulators, adding significantly to the cost of establishing and operating a desalination facility. Furthermore, the absence of this knowledge can also result in overly conservative plant shutdowns that disrupt water supply.

A deeper understanding of the salinity tolerance of organisms in the local environment and the maximum salinity tolerance of the entire local ecosystem at existing municipal SWRO sites and potential future sites in Australia could substantially reduce municipals SWRO operating costs and the costs of establishing new municipal SWRO systems.

Key industry issue
Development of technologies and systems for the economic management of concentrate waste produced by inland BWRO plants

The cost effective and environmentally friendly management of brine concentrate associated with inland desalination plants is arguably the most important issue for desalination in Australia. Australia is blessed with an abundance of land and as such, in most locations, the footprint required for evaporation ponds is not a major problem. However, the significant capital costs associated with those evaporation ponds remains an issue.

Additionally, managing the product from the evaporation ponds is also a significant expense, because in many cases it is required to be transported from remote areas. As such, there are opportunities for research that leads to:

- A reduction in the capital costs associated with evaporation ponds or elimination of the need for evaporation ponds;
- Technologies that cost effectively reduce the water content of brine concentrate, thus reducing its disposal cost; or
- The cost competitive recycling of brine concentrate by extracting specific salts or using it as feedstock for the manufacture of products that can be used locally.

3.6 Product water

3.6.1 Overview

Product water from a desalination process will vary in quality depending on the source water, type of desalination technology and the design of the desalination system, but it is typically not immediately suitable for consumption or distribution. RO desalination processes produce permeate in the form of freshwater that is very low in mineral content, highly corrosive and does not contain a final disinfectant. As a result RO permeate is typically conditioned with a range of chemicals designed to add alkalinity and hardness and/or with corrosion inhibitors for protecting the integrity of downstream infrastructure and is disinfected with chlorine, sodium hypochlorite or other disinfectants.

Typical post-treatment will include:

- Stabilisation by addition of carbonate alkalinity;
- Corrosion inhibition;
- Re-mineralisation by blending with high mineral content water;
- Disinfection; and
- Specific water polishing processes for enhanced removal of specific compounds such as boron and silica.

3.6.2 General issues

Key issues associated with product water quality are:

- Public health issues;
- Issues associated with using the product water for horticulture and agriculture; and
- Corrosion issues.

Public health issues

Permeate is typically deficient in key minerals including calcium, magnesium and fluoride and is high in sodium and chloride. This affects taste and also has public health implications. Similarly elevated levels of bromides can result in disinfection by-products and unstable chlorine residuals which are not typical in water supplied from conventional sources (Weinberg, 2002).

Dietary intake of fluoride at a concentration of 1 mg/L is generally recommended for the prevention of skeletal and tooth dental decays. However, exposure to excessive amounts of fluoride increases the risk of dental mottling and crippling flourosis. Concentrations of fluoride above 4 mg/L can cause lesions of the bones and endocrine glands and other organs. High nitrate intake has been associated with methaemoglobinaemia, especially in bottle fed infants and products of nitrate degradation are potentially carcinogenic (Agenson & Schafer, 2009). World Health Organisation Guidelines set recommended maximum fluoride and nitrate concentration limits in drinking water at 1.5 mg/L and 50 mg/L respectively (World Health Organisation, 2004).

Permeate from SWRO plants can contain high levels of boron, which when above a certain level can have significant human health implications. Boron has been shown to cause male reproductive defects or delayed development in the offspring of animals exposed over a relatively long period of time through food or drinking water. It is also detrimental to plants at higher than normal concentrations (Agenson & Shafer, 2009). Current World Health Organisation (WHO) Guidelines set recommended boron levels in drinking water at 0.5 mg/L (World Health Organisation, 2004). However, this level is generally expected to be increased to 2.4 mg/L with the revision of the WHO Guidelines.

The World Health Organisation recently released guidelines relating to desalination product water quality (World Health Organisation, 2007). While these are as yet to be adopted by many countries, they suggest that many current post-treatment processes may be deficient in producing product water quality that meets these guidelines, particularly with respect to recommended levels of calcium and magnesium which are set at 40 mg/L of calcium and 10 mg/L of magnesium.

Horticulture and agriculture issues

With approximately 69% of global water supply being used in irrigation, present freshwater sources that are used by irrigation may soon be insufficient to meet the growing demand for food. SWRO is currently generally considered too expensive to be used for irrigation purposes, with perhaps the exception of irrigation for some high value crops. However, BWRO is widely used for irrigation purposes, particularly in countries like Spain and Israel where freshwater sources are particularly scarce (Yermiyahu, Ben-Gal, Bar-Tal, Tarchitzky & Lahav, 2007). Further, desalinated waters will eventually become waste water and waste water is used for irrigation. As a consequence, contaminants in the SWRO water supply may impact irrigation water.

A number of plant species that are grown for commercial reasons are sensitive to elevated levels of boron, chlorides and sodium in the water used for their irrigation. This raises concerns for commercial horticultural and agricultural industries that are serviced by desalinated water as there is the potential for desalinated water to affect yield and the commercial viability of some crops (Johnson, 2001)

Corrosion issues

Water distribution and household plumbing systems typically contain metallic components. Product water quality issues that can affect chemical reactions that can potentially cause corrosion of those metallic components (World Health Organisation, 2007) are summarised in Table 9.

Table 9:
Water quality chemical reactions and corrosion

Water quality parameter	Corrosion implications
pH	Low pH (less than 7) may increase corrosion rates, whereas high pH (above 8) may reduce corrosion rates.
Alkalinity	Alkalinity provides water stability and prevents variations in pH and may contribute to the deposition of protective films. Highly alkaline water may cause corrosion in lead and copper pipes.
Hardness	Hard water is generally less corrosive than soft water if calcium and carbonate alkalinity concentrations are high and pH conditions are conducive to calcium carbonate disposition. Calcium carbonate does not form on cold lead, copper or galvanised still pipes, but calcium hardness may assist in buffering pH at the metal surface to prevent corrosion.
Chlorides	High concentrations of chlorides may increase corrosion rates in iron, lead and galvanised steel pipes.
Phosphate	Phosphate can react to form protective films.
Temperature	Temperature can impact on the solubility of protective films and rates of corrosion.

Desalinated water is often blended with water from other sources. When this is the case, a potential issue is that the chloraminated desalinated water may destabilise the chlorine residual of the other chloraminated water sources if it contains high levels of bromide. Furthermore, because desalinated water is typically softer than most other water sources with which it is blended in the distribution system, the desalinated water may impact negatively with the overall corrosiveness of the blend. However, this is avoided if the desalinated water is treated appropriately before it is blended (Taylor, 2005).

3.6.3 Issues for the Australian desalination industry

Limited work has been undertaken to understand the effects of the constituents of desalinated seawater and brackish water on key Australian crops (Dickson, 2010).

Key industry issue

Investigation into the effect of the constituents of various desalinated water sources in Australia on key Australian agricultural products

As Australia's desalination capacity expands, it is increasingly likely that more and more water produced from SWRO, and particularly BWRO, will be used for irrigation purposes, albeit that direct use for irrigation is only likely to be economically viable for high value crops in the short to medium term.

There is some evidence that desalinated water can have a negative impact on the yield and commercial viability of some crops. However, to date, limited work has been undertaken to understand the effects of the constituents of desalinated seawater and brackish water on key Australian crops.

3.7 Managing energy usage and carbon footprint

3.7.1 Overview

While the desalination of water is not as energy intensive as many of the world's, or for that matter Australia's, other manufacturing and processing industries, it is nevertheless energy intensive, particularly given the low value commodity that it produces.

In the case of RO, SWRO consumes the most energy primarily by virtue of the much higher pressures that are required at the primary RO process. However, the average energy required to desalinate seawater at the primary RO stage has reduced by a factor of three over the past two decades from approximately 7.5 kWh/m^3 to approximately 2.5 kWh/m^3 (Stover, 2009) at the primary RO membrane. A number of technology developments have contributed to this dramatic improvement and because current energy consumption in the case of SWRO is approaching theoretical limits, future process improvements are not expected to yield significant additional specific energy reductions (Stover, 2009).

The minimum theoretical energy requirement at the thermodynamic restriction at 50% water recovery, being the optimum low energy water recovery rate at the limit of infinitely permeable membranes of finite area (Zhu, Christofides & Cohen, 2009), is 1.83 kWh/m^3 (Stover, 2009). Current generation SWRO plants typically consume between 2.4 kWh/m^3 and 3.2 kWh/m^3 at the primary RO membrane, suggesting that current state-of-the-art SWRO plants are 74% efficient. Emerging nano membranes promise efficiency levels of 85%.

The carbon footprint of a desalination facility needs to be considered in the context of a water supply system's total carbon footprint. For example, in the case of Water Corporation in 2006-07, the transportation of water accounted for 34% of its Greenhouse Gas (GHG) inventory and total water treatment (including wastewater treatment) accounted for 43% of its GHG inventory (Dracup, Nattrass, Down, Huxtable & Luketina, 2009).

3.7.2 General issues

There are three general approaches to bringing SWRO power consumption closer to the theoretical minimum target, namely:

- Reducing energy losses in the system that occur through pumping, water conveyance through the system (friction) and water transport through the membranes;
- Increasing energy recovery from the RO system concentrate stream;
- Use of low energy desalination processes other than RO; and
- Reducing carbon footprint by powering desalination facilities from renewable energy sources or offsetting carbon footprint via sequestration.

Energy reduction issues

Contemporary lowest energy SWRO design was first trialled in Israel and Algeria in 2002 and 2003 and is now more or less the industry standard in design. This generation of SWRO plants involve:

- High permeability membranes;
- High water recovery second pass;
- Large, high pressure pumps that are fed with feed booster pumps;
- High boron and bromide rejection membranes, thus eliminating second pass and recovering more water with less energy and capital equipment; and
- Isobaric energy recovery devices (Stover, 2009).

RO membrane technology, plant equipment and plant design have evolved over the past five to ten years to a point where SWRO is now within 15-20% of the theoretical energy minimum (National Academy of Science, 2008) and as a result, future design and equipment improvements are likely to result in only incremental improvement in energy consumption. For example, the permeability of ultra-low energy membranes is already so high that the associated feed pressure is approaching thermodynamic restriction (a condition where the associated feed pressure is equal to the osmotic pressure of the reject), and as such further significant reductions in feed pressure and therefore energy input at the primary RO process are unlikely (Stover, 2009). However, if salt rejection of these low energy membranes could be improved without a concomitant loss of water permeability, the second pass RO requirement may become redundant resulting in further energy savings (Stover, 2009). Furthermore, the efficiency of the second pass RO process has been improved by systems improvements such as split-permeate takeoff.

Pumps are a well invented device. While there have not been any significant improvements in pump or motor efficiencies specifically for SWRO applications, pump and plant designers have reduced energy consumption with better process designs including the use of larger centrifugal pumps with inherently greater efficiencies and variable frequency drives. Additionally, feed booster pumps have been used to improve high pressure pump efficiency.

Energy recovery issues

Due to the low net recoveries of the highly pressurised feedwater in SWRO, as much as 60% of the applied energy in the process can be lost if the concentrate pressure is discharged to the atmosphere without a process to recover that energy. A main driver of the significant reduction in energy consumption that has been achieved by reverse osmosis desalination has been the result of the development of highly efficient energy recovery devices that capture energy from the concentrate stream (National Academy of Science, 2008). Energy recovery devices have been used to recover energy from the RO membrane reject stream since the late 1980s and have undergone considerable evolution. Initially energy recovery devices took the form of reverse running pumps or Francis Turbines that were coupled to the high pressure pump. Subsequently Pelton Turbines were introduced with higher efficiencies and then hydraulic turbochargers that drove a high pressure impellor that operated in series with the high pressure pump became the norm (Stover, 2009). Table 10 summarises the energy efficiency of various energy recovery technologies (Geisler et al, as cited in National Academy of Science, 2008).

Table 10:
Energy efficiency of energy recovery technologies

Energy recovery system	Efficiency (%)
Francis Turbine	76
Pelton Turbine	87
Turbo Charger	85
Work Exchanger	~96
Pressure Exchanger	~96

Introduced in the early 2000s, existing state-of-the-art isobaric chamber based energy recovery technologies (work exchangers and pressure exchangers) recover energy from the RO concentrate stream at an efficiency of 93-96%, which is very close to the theoretical maximum efficiency that an energy recovery technology can yield of 98% (Voutchkov, 2009).

Table 11 summarises the rapid growth that suppliers of energy recovery technologies have experienced in recent years. With the exception of Calder, all energy recovery OEMS have experienced phenomenal installed capacity growth, demonstrating that state-of-the-art energy recovery is an essential component of any new SWRO installation.

Table 11:
Growth in installed capacity of isobaric energy recovery devices (Global Water Intelligence, 2009b)

Year	FEDCO (m^3/day)	PEI (m^3/day)	Calder (m^3/day)	ERI (m^3/day)	Total (m^3/day)
2005	95,760	87,259	927,763	451,200	1,561,982
2006	143,760	205,878	337,627	771,650	1,458,915
2007	206,760	292,629	798,000	1,432,560	2,729,949
2008	480,840	580,915	748,000	2,094,050	3,903,805
YTD 2009	397,170	722,408	160,000	910,000	2,198,578
Share (05-09)	11.2%	16.0%	25.1%	47.8%	100%
Growth (05-08)	+502%	+666%	-19.4%	+464%	

The main areas where energy recovery devices could potentially be improved include:

- The scaling up of individual equipment units to make them more suitable and cost effective for large applications;
- Improving outstanding secondary performance issues such as reduction of brine mixing, leakage and noise attenuation; and
- Modification and application of energy recovery systems for BWRO as energy recovery can only currently be cost effectively implemented on BWRO plants with more than approximately 100 membranes (Voutchkov, 2009).

Low energy desalination process issues

As discussed in the section on Desalting Technologies, there are a number of emerging technologies for desalination that have the potential for lower energy usage than current RO membrane technologies. Nanostructured membranes are probably the more likely of these technologies to become commercially viable in the not too distant future.

Another emerging technology that holds promise is Forward Osmosis (FO). The mixing of freshwater and seawater where rivers flow into the ocean releases large amounts of energy. The Pressure Retarded Osmosis (PRO) technology being developed by Statkraft and currently being trialled in Norway (Global Water Intelligence, 2010) uses filtered freshwater originating from a river or other freshwater sources near the ocean that is pumped into modules containing FO membranes. Freshwater is conveyed to one side of the FO membrane and pressurised seawater is applied to the other side of the FO membrane. In the FO membrane modules, the freshwater moves through the membrane driven by osmotic pressure towards the pressurised filtered seawater and dilutes it. The flow of diluted and pressurised seawater is then split into two streams where one is depressurised through a hydropower turbine to generate power, while the other stream passes through a pressure exchanger in order to pressurise the incoming seawater. A similar concept could potentially be applied using concentrate from the SWRO or BWRO process instead of ocean seawater, with the concentrate having a benefit of creating a significantly higher osmotic pressure (Voutchkov, 2009).

Issues associated with the use of renewable energy sources and carbon sequestration

Renewable energy technologies and technologies for carbon sequestration are not as yet adequately advanced to a stage where:

- They are able to provide adequate consistent base load power for a continuously operating desalination plant;
- Due to capital and maintenance costs, power generation costs are competitive with conventional fossil fuel power sources and as such will add significantly to the cost of producing water; or
- With the exception perhaps of geothermal energy, they command an adequately small footprint to be collocated with a desalination plant in most instances.

Certainly small plants can have their energy requirements supplemented by more advanced renewable technologies and plants are able to acquire renewable energy credits from established renewable sources such as wind energy. However, the direct coupling of renewable energy sources to large desalination plants to any meaningful effect is unlikely to occur in the near future. To put this in context the United Arab Emirates, a country with considerable installed desalination capacity, is currently evaluating a plan to commission a significant nuclear power installed capacity from 2017, that will largely be used to power its growing desalination capacity (Global Water Intelligence, 2009b).

Plant design optimisation

It is likely that many future gains in capital and operational cost savings and application range will come from the optimisation of plant design and the tailoring of plant design to specific sites, feedwater quality and customer water quality requirements.

RO system designs are optimised for a number of specific factors including:

- Source water quality specifications;
- Product water quality requirements;
- Cost of construction labour and materials;
- Cost of operations and maintenance labour and chemical costs;
- Energy costs;
- Membrane element costs; and
- Plant size, location and type of power supply.

Depending on these site specific factors there are various conceptual approaches to the optimisation of RO system performance.

High recovery plant design

SWRO plants optimised for high recovery are designed to achieve recoveries of between 50 and 65% (depending on salinity and other factors), whereas BWRO plants optimised for high recovery are designed to achieve recoveries of between 85 and 90%. High recovery designs typically have a comparatively lower capital cost, but incur higher operating costs in the form of energy penalties and other additional operating and maintenance costs.

Lower recovery plant design

SWRO plants that are optimised for lower recovery are designed to achieve recoveries of between 35 and 40%, whereas BWRO plants optimised for lower recovery are designed to achieve recoveries between 65 and 70%. These are typically smaller automated plants that are deployed in remote locations as they generally experience lower rates of fouling, requiring less cleaning activities and eliminating a need for permanent plant staff.

Low energy three centre RO plant design

As more municipal SWRO plants and other new sources of water come on stream there will be a need to facilitate variability in supply. Currently in Australia, Adelaide is the most flexible plant in this regard (Pelekani, 2010).

Low Energy Three Centre RO Plant designs are utilised in applications which need to produce frequently varying potable water flows. Because most of the SWRO plants in operation today supply a relatively small portion of urban water supply they are typically designed to operate at near constant production flow all year. However, it is likely that as desalination costs fall, SWRO plants will become a primary, rather than supplementary source of water for many coastal urban centres that have limited alternate sources of water supply. SWRO plants servicing such centres will need to be designed to have the ability to match water supply with potable water demand patterns that fluctuate seasonally and as the result of unpredictable events. This operational flexibility requires a change to the typical SWRO configuration to a configuration that is suitable for cost effective delivery of varying permeate flows.

One such configuration is the Three Centre RO Plant Design that was first commissioned at Ashkelon SWRO plant in Israel. Under such a design, the RO membrane vessels, high pressure pumps and energy recovery equipment are not separated in individual RO trains, but are combined in three functional centres – a high pressure RO feed pumping centre, a membrane centre and an energy recovery centre – that are interconnected through service plumbing. Such a configuration results in the ability to vary water supply from the plant. For example, both the Kwinana and Binningup plants in Western Australia can operate in 1/6 increments of full capacity (Cadee, 2010).

Materials and process flow optimisation

Currently, many elements of SWRO plants are over-engineered when compared to theoretical engineering requirements and even the manufacturer specifications of many of the components. This is largely the result of conservative environment requirements and the highly corrosive environment in which they operate. Currently a level of over-engineering is necessary because there is typically inadequate understanding of the environmental impact of the plant and specific species in the source water that contribute to corrosion.
However, over-engineering adds significantly and potentially unnecessarily to capital and operating costs. A better understanding of the environment and source water make-up may create opportunities for areas of investigation such as materials science to reduce operating and capital expenditure associated with municipal SWRO plants (Cadee, 2010).

There is also potential to incrementally improve the efficiency and performance of municipal SWRO plants by identifying bottlenecks, optimising design and refitting obsolete equipment. Collectively, such improvement might result in overall improvement in plant efficiency and performance of 5-10%. Solutions to bottlenecks may be found in other manufacturing processes (Cadee, 2010).

Simple design for small remote plants

There is estimated to be between 400 and 600 SWRO and BWRO plants operating in regional Australia with capacities of between 50 KL/day and 10 ML/day and the number of small SWRO and BWRO plants in regional Australia is expected to increase. Furthermore, these plants are likely to be located in increasingly remote regions. This presents water utilities and municipalities with increasing operations and maintenance logistical challenges and expenses. In this context the development of simple desalination systems for remote communities is desirable (West, 2010; Cadee, 2010; Taylor, 2010; Herbert, 2010).

The capital expenditure associated with small BWRO and SWRO plants is usually dependent on location and site specific pre-treatment requirements and is usually within the range of \$2,000 to \$4,000 per m^3 for BWRO and approximately \$5,000 per m^3 for small SWRO plants. Similarly operational expenditure associated with small plants is highly variable depending largely on remoteness (West, 2010).

Most water utilities award small plant construction contracts on the basis of lowest capital expenditure (West, 2010).

Capital cost optimisation

Theoretical models of the relationship between the size of a SWRO plant and its capital cost suggest that as the size of a plant increases the capital cost per unit of capacity should decrease exponentially. For example, the cost calculator model developed by John Tonner of Water Consultants International (Global Water Intelligence, 2008) suggests that capital costs of approximately US\$1,600 per m^3 per day associated with a plant scale of 20,000 m^3 per day should reduce to approximately US\$1,100 per m^3 per day for a plant scale of 180,000 m^3 per day. However, as illustrated in Figure 8, Australian municipal SWRO projects have defied this cost curve, demonstrating escalating capital costs. A number of factors have been cited as contributing to the escalating capital cost of Australian municipal SWRO plants including:

- The emergency response nature of most Australian municipal SWRO projects has resulted in 'crisis prices' having being paid for the construction of those plants;
- The political imperative to offset at least part of the carbon footprint by acquiring Renewable Energy Credits equivalent to the power consumption of the plant has often involved additional capital expenditure;
- Increased capital costs associated with intakes and outlets in order to minimise environmental and social impacts (Global Water Intelligence, 2009b). For example, the Adelaide plant incorporates 1.5 kilometre intake tunnel that is 30 meters below the seabed (Pelekani, 2010); and
- Relatively high wage rates for desalination project construction workers in Australia (Schneiders, 2009).

It has also been noted that water utility procurements have resulted in extensive use of offshore water engineering companies in the design and construction of Australian municipal SWRO plants which may also add to the capital cost (Palmer, 2010).

Plant design, piloting, systems integration, procurement, contracting and commissioning initiatives designed to circumvent further escalating capital costs for reverse osmosis desalination plants will benefit future installations (Butler, 2010; Palmer, 2010) and have potential benefits for infrastructure projects in other water sectors such as reuse. Additionally, the production of independent analysis of the environmental and carbon footprint performance of desalination would go some way to alleviating public concerns, creating greater opportunity for desalination and desalination cost reduction (Butler, 2010).

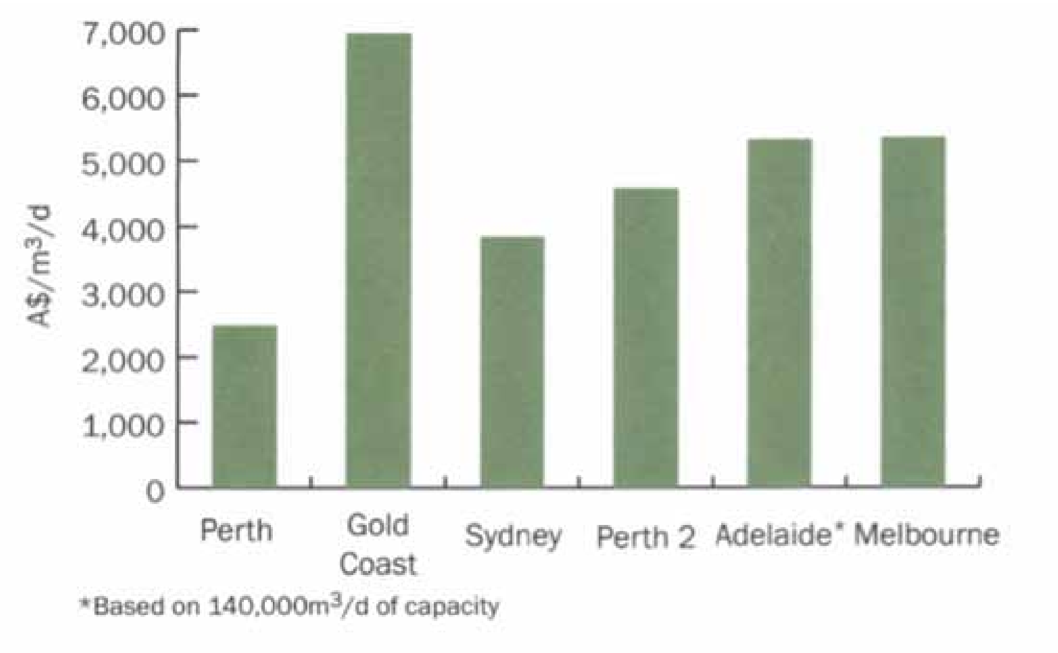


Figure 8:
Capital cost of Australian desalination plants

3.7.3 Issues for the Australian desalination industry

In an attempt to reduce Greenhouse Gas (GHG) emissions, the Australian government is anticipating implementing a Carbon Pollution Reduction Scheme (CPRS). Additionally, most of Australia's major water utilities have also set voluntary GHG emission reduction targets. For example:

- Water Corporation has set a target of zero net GHG emissions by 2030;
- Sydney Water has set a target of carbon neutrality for energy and electricity by 2020;
- SA Water is aiming to achieve GHG emissions that are 40% of 1990 levels by 2050; and
- Melbourne Water has set a target of zero net GHG emissions by 2018 (Dracup et al, 2009).

This analysis assumes an electricity cost of $0.10/kWh, a desalination energy efficiency of 5 kWh/kL, and a carbon intensity of 0.873 kg CO_2/kWh

Table 12:
Estimated annual carbon footprint of the Australian municipal SWRO industry

Desalination Plant	kL/day	Annual Power Usage (GWh)	Annual CO_2 Emmisions (t)
Kwinana	140,000	256	223,052
Binningup	125,000	228	199,153
Adelaide	275,000	502	438,137
Melbourne	410,000	748	653,222
Sydney	250,000	456	398,306
Gold Coast	133,000	243	211,899
Total	**1,333,000**	**2,433**	**2,123,769**

As a result of their contemporary design, all municipal SWRO plants in Australia are designed for energy consumption minimisation and incorporate state-of-the-art energy recovery. BWRO plants operate at lower pressures than SWRO (approximately 14-18 atms) and they are typically much smaller plants. Both per unit energy cost (approximately 2-2.5 kWh/m^3) and total energy consumption is less in the case of BWRO. Furthermore, because the concentrate stream is smaller and running at much lower pressure, there is limited scope for energy recovery. Therefore, the economic viability of energy recovery devices on small BWRO plants is questionable. While there are energy recovery devices available for BWRO plants, they tend to only be used on larger BWRO plants (West, 2010). In the case of small scale SWRO plants, energy recovery tends to only be cost effective in plants larger than 200 kL/day in capacity (Herbert, 2010; Windsor, 2010).

The potential to supplement plant energy via a Forward Osmosis process is questionable in Australia because it requires a freshwater supply, which if available is generally used for customer needs (Herbert, 2010; Windsor, 2010).

The direct coupling of solar or wind technology to supplement power requirements for small inland BWRO plants in Australia is a possibility, as is the direct coupling of solar, wind, wave and geothermal energy to supplement the power requirements for small scale SWRO plants. However, the viability of direct coupling is site specific, adds complexity to the plant and hence undesirable operations and maintenance issues (which is particularly problematic for plants in remote locations) and for the foreseeable future will still require connection to diesel power generation or the grid in order to ensure reliable supply. Direct coupling of renewable energy sources adds significantly to the capital costs of the plant and thus the whole of plant life cost of the water it produces. It should be noted that diesel generators used to power small SWRO and BWRO plants can use biodiesel as the feedstock.

With these limitations in mind the economics of direct coupling of any desalination facility need to be carefully examined. The most likely use of geothermal energy is to increase the temperature of the RO feedwater via a heat exchange process, improving the efficiency of the RO process, albeit that this can exacerbate membrane fouling issues (Cadee, 2010).

It is likely that future shorter term improvements in plant efficiency will come from improvements in module design that enable operation at higher fluxes that reduce operating costs of desalination because the capital costs and energy costs per cubic meter of permeate produced would simultaneously be reduced (National Academy of Science, 2008).

Key industry issue
Optimisation of municipal SWRO design, construction and contracting to reduce capital and operating expenditure associated with municipal SWRO plants

It is widely acknowledged that compared with many other countries, the capital costs associated with Australian municipal SWRO plants are relatively high. It would appear that those costs are escalating. The reasons for this are articulated in a previous section of this report.

There is an opportunity for research into the application of materials science or new design concepts with the goal of reducing capital expenditure associated with new future municipal SWRO plants in Australia. Similarly a review of the tendering, contracting and construction arrangements pursued by Australian water utilities with respect to the construction and operation of municipal SWRO plants with a view to identifying mechanisms that could be used to reduce construction and operating expenses may benefit future municipal SWRO plants in Australia.

Critical analysis of existing SWRO plants with the aim of identifying operational 'bottlenecks', optimising design and refitting obsolete equipment, perhaps borrowing process concepts from other manufacturing industries, would also be a useful contribution to the Australian municipal SWRO sector.

Key industry issue
Plant simplification and operations and maintenance simplicity for remote plants

Operations and maintenance expenditure associated with remote desalination plants in Australia is considerable as a result of their isolation from maintenance services. Similarly, this isolation creates systems monitoring challenges. Research that leads to simplified designs for small plants that are used in remote locations as well as improved remote monitoring, diagnostic and control systems would be advantageous to the Australian authorities and companies that manage remote desalination facilities.

Key industry issue
Development of simple, low maintenance renewable energy systems that can supplement power supply for small desalination facilities

Despite desalination being less energy intensive than many other Australian manufacturing and processing industries, it is relatively energy intensive. Therefore, there is an imperative to reduce the energy intensity of the Australian desalination industry. For municipal SWRO plants the only practical and economic option that is currently available is the purchase of Renewable Energy Credits (RECs) to offset the carbon footprint, which a number of Australian municipal SWRO plants either currently do or plan to do in the near future.

Renewable energy technologies are not as yet adequately advanced to a stage where they can provide consistent base load power for a continuously operating desalination plant or provide that power at a cost that is competitive with fossil fuel sources of energy. The need for a continuous supply of power is particularly problematic for reverse osmosis as unmanaged downtime causes damage to the reverse osmosis membranes.

Additionally, the capital expenditure and footprint currently required to provide even intermittent renewable energy directly to a large-scale desalination plant is prohibitive.

The most likely application of renewable energy sources to desalination in the near to medium term is either:

- The application of renewable sources to supplement conventional energy supply on small scale plants;
- The application of renewable energy sources to small scale non-membrane based desalination systems that do not require continuous operation; or
- The development of desalination technologies that are specifically suited to the variable and intermittent nature of most renewable energy sources.

Additionally, there is a requirement for remote plants to be simplistic and easily repairable in order to manage the operations and maintenance expenditure associated with those plants. Any renewable resource applied to a remote plant must be simple and not pose additional operations and maintenance challenges. Given the reduction in the carbon footprint of the Australian desalination industry is a prescribed objective of the NCED, the development of desalination technologies capable of directly receiving various renewable energy sources (e.g. DC, wild AC, heat, and kinetic) or technologies that optimise the transfer of renewable energy are an opportunity to respond to the likely need for carbon reduction.

Key industry issue

Audit of opportunities in Australia for the harnessing of waste heat for desalination purposes and development of suitable technologies

An improved understanding of the location, nature and quality of waste heat sources in Australia together with local water markets would be a useful input into identifying possible opportunities to use waste heat to either render thermal methods of desalination viable for those local water markets or improve the efficiency of reverse osmosis desalination for those local water markets. Feasibility studies could then be undertaken to determine if desalination is a cost competitive source of water for those local water markets. The outputs of such an exercise would make a valuable contribution toward the development of future Australian water strategies.

3.8 Conclusions

The goal of all applied research is technology transfer, that is, adoption of research outputs by an end user. In the case of the NCED, this end user is in the first instance, the Australian desalination industry and in the second instance the global desalination industry and other allied industries. In most instances the end customers are water utilities of various shapes and forms.

Many water utilities, but certainly not all, are often reluctant to try new technologies. This is due to a number of factors:

- Conservative cultures;
- A recent history of not having to manufacture water and as such, a lack of familiarity with manufacturing technology issues; and
- The fact that most water utilities are municipally owned with water tariffs set below the level that would provide a return on capital deployed to produce that water.

This last point is important in assessing adoption challenges as it implies that investing in new technology brings additional risk to the utility, without significant commercial rewards. Furthermore, when compared to other utilities, water utilities have some unique characteristics. Firstly, water has been and will most likely continue to be a much cheaper commodity compared to electricity and gas. Secondly, automatic metering in the water sector is 5%, versus an average of 10% for electricity or gas utilities. Thirdly, 70% of the costs of a water system reside in the networks of pipes required to transport water to and from users and potential for significant innovation in pipes is limited. As such, the technology market in the water industry is characterised by a multitude of small innovations with restricted market potential (Global Water Intelligence, 2009a).

Adoption in the SWRO market place is more readily facilitated where solutions are simple and can be implemented in the existing infrastructure (Dickson, 2010). Nevertheless, adoption of technologies for large scale municipal SWRO desalination will require protracted periods of piloting, simply because of the scale of capital, significance of supply volume and the quantum of project value that the new technology is placing at risk. In the case of municipal SWRO plants, most utilities will require any new technology that has the potential to disrupt supply if it does not perform to be demonstrated on a pilot or small system for a period of between 10 and 20 years (Cadee, 2010). Related to this issue is the fact that major breakthrough innovation in the municipal SWRO market is the core focus of well-funded research programs of multinational companies like Veolia, Acciona Agua, Degremont, Dow and GE and these companies have well established channels to trial technologies and achieve adoption.

While there is a larger number of competitors in the BWRO industry, there is a much wider range of desalting technology options (ED, CDI, EDR, HERO, etc), which has resulted in research and development investment being dispersed over a broader range of technology areas. This has resulted in a wider scope for improvements. The other advantage of the BWRO space is that scale up from piloting is much shorter than is the case for SWRO and technology adoption risk is much less because of the typically smaller scale of BWRO plants (Cadee, 2010; Herbert, 2010; Windsor, 2010). Furthermore, it is likely that only a small number of new municipals SWRO plants will be constructed in Australia over the next decade, whereas it is estimated that at least a dozen new BWRO plants are commissioned in Australia every year (Cadee, 2010; Herbert, 2010; Windsor, 2010).

4

Priority Research Themes

4.1 Purpose

The roadmap process identified potential technology improvement opportunities for the Centre to pursue. This task was the focus of collaborative effort in a roadmapping workshop, where opportunities were identified by small groups and subsequently validated by industry experts and the Roadmap Advisory Group.

Improvement opportunities are grouped into thematic research focus areas where strategy, benefit, and prerequisite are described.

4.2 Priority research themes by technology area

4.2.1 Pre-treatment

Pre-treatment plays a significant role in maximising the efficiency of the preferred desalting technology. The Centre is interested in funding research that improves understanding of the relationship between pre-treatment and treatment, and how novel pre-treatment technologies and improvements can reduce fouling and/or scaling of the coupled treatment process.
The Centre has identified the following improvement opportunities in pre-treatment:

Priority research themes:
Pre-treatment

1.1 Preheating using waste heat or renewable energy and the use of lower-pressure membranes
1.2 Optimal use of chemicals
1.3 Specific issues for pre-treatment in rural and remote areas relating to seasonal and location variability in feedwater composition
1.4 Characterisation of groundwater and seawater sources and mapping those to best fit desalination technologies

4.2.2 Reverse osmosis desalting

Enormous advances in membrane technology have resulted in the maturation of brackish water and seawater reverse osmosis (BWRO and SWRO) to the point where it is considered the benchmark method for the industry. The Centre has identified the following improvement opportunities in RO desalting:

Priority research themes:
Reverse osmosis desalting

2.1 Anti-fouling technologies and membranes and oxidant-resistant membranes
2.2 New membrane materials that reduce operating pressure while maintaining or increasing flux rates and maintaining ion rejection
2.3 Contaminant removal without the need for second-pass RO
2.4 Direct use of renewable energy via kinetic, electrical, or thermal means
2.5 Real-time monitoring and classification of potential foulants
2.6 Operational optimisation

4.2.3 Novel desalting

Novel desalting can exploit the unique properties of water and saline solutions. The Centre is particularly interested in identifying and piloting novel technologies for Australia's rural and remote needs, against a benchmark of BWRO. The Centre has identified the following improvement opportunities in novel desalting:

Priority research themes:
Novel desalting

3.1 Novel technologies including those for direct agricultural use
3.2 Low-maintenance, reliable evaporative technologies using waste heat or renewable energy
3.3 Coupling water production with renewable energy
3.4 Piloting in real-world situations breakthrough near-commercial desalination technology

4.2.4 Concentrate management

Concentrate management represents the most pressing challenge of all desalination technologies with regard to disposal in a non-ocean environment, and is a key barrier to inland deployment. The Centre seeks to remove this barrier to desalination for inland Australia through effective reuse or disposal. The Centre has identified the following improvement opportunities in concentrate management:

Priority research themes:
Concentrate management

4.1 Novel zero liquid discharge processes
4.2 Waste minimisation based on value adding
4.3 New materials for lower-cost corrosion management
4.4 Extraction of desalted water at source or concentrate injection

4.2.5 Social, environmental and economic issues

Desalination is still a relatively controversial public issue. Most of this controversy revolves around the energy intensity of desalination and concerns over the environmental impacts of brine concentrate and other waste products. The production of data and the application of scientific rigour that provides an independent analysis and assessment of controversial issues associated with desalination would go a long way toward addressing public concerns in a constructive manner. There is an opportunity for research that assists the development of a scientifically informed public awareness program.

Widespread deployment of desalination, while dependent on improvements in critical system requirements, will also require attention to environmental impact, social concerns, economic policy, and other non-technical barriers. The Centre has identified the following opportunities:

Priority research themes:
Social, environmental and economic issues

5.1 Appropriate disposal or reuse of spent membrane cartridges
5.2 Total life cycle analysis and sustainability assessment of desalination against other water sources
5.3 Public perception analysis and improvement through education and communication
5.4 Policy development to better understand energy-water interdependence
5.5 Centralised understanding of national desalination deployment, performance, and lessons learnt
5.6 Detailed understanding of the salinity and toxin tolerance of marine species in the vicinity of SWRO outflows
5.7 Management of entrainment of small marine organisms in SWRO intakes

4.2.6 Summary of improvement opportunities

Table 13 summarises the improvement opportunities described above, indicates the likely horizon for commercialisation outcomes – short term (ST, may be commercialised within 5 years), medium term (MT, 5-10 years), or long term (LT, beyond 10 years) – and links each improvement opportunity to the three elements of the Australian Government Funding research mandate: Australia's unique circumstances (AUC), Rural and remote areas (RRA), and Reduced carbon footprint (RCF).

Table 13:
Summary of priority research themes

Technology areas and research themes		Horizon	Research mandate		
			AUC	RRA	RCF
1.	**Pre-treatment**				
1.1	Preheating using waste heat or renewable energy and the use of lower-pressure membranes	MT			✓
1.2	Optimal use of chemicals	MT		✓	✓
1.3	Specific issues for pre-treatment in rural and remote areas relating to seasonal and location variability in feedwater composition	ST	✓	✓	
1.4	Characterisation of groundwater and seawater sources and mapping those to best fit desalination technologies	ST	✓	✓	✓
2.	**Reverse osmosis desalting**				
2.1	Anti-fouling technologies and membranes and oxidant-resistant membranes	MT	✓	✓	✓
2.2	New membrane materials that reduce operating pressure while maintaining or increasing flux rates and maintaining ion rejection	LT			✓
2.3	Contaminant removal without the need for second-pass RO	LT			✓
2.4	Direct use of renewable energy via kinetic, electrical, or thermal means	MT			✓
2.5	Real-time monitoring and classification of potential foulants	ST	✓	✓	✓
2.6	Operational optimisation	ST		✓	✓
3.	**Novel desalting**				
3.1	Novel technologies including those for direct agricultural use	MT		✓	
3.2	Low-maintenance, reliable evaporative technologies using waste heat or renewable energy	MT		✓	✓
3.3	Coupling water production with renewable energy	MT			✓
3.4	Piloting in real-world situations breakthrough near-commercial desalination technology	ST		✓	✓
4.	**Concentrate management**				
4.1	Novel zero liquid discharge processes	MT		✓	
4.2	Waste minimisation based on value adding	ST	✓	✓	✓
4.3	New materials for lower-cost corrosion management	LT			✓
4.4	Extraction of desalted water at source or concentrate injection	ST	✓	✓	
5.	**Social, environmental and economic issues**				
5.1	Appropriate disposal or reuse of spent membrane cartridges	ST			✓
5.2	Total life cycle analysis and sustainability assessment of desalination against other water sources	ST	✓		✓
5.3	Public perception analysis and improvement through education and communication	ST	✓		
5.4	Policy development to better understand energy-water interdependence	MT	✓	✓	✓
5.5	Centralised understanding of national desalination deployment, performance, and lessons learnt	ST	✓		
5.6	Detailed understanding of the salinity and toxin tolerance of marine species in the vicinity of SWRO outflows	ST	✓		
5.7	Management of entrainment of small marine organisms in SWRO intakes	ST	✓		

4.3 Details of priority research themes

Table 14 provides further details of the identified priority research themes. Within each technology area, improvement opportunities are identified by:

- **Research theme ("what")** – The research theme encapsulates the general objective for technology performance. This improvement also has an associated horizon (defined as the time taken for the improvement to reach the market – either short-term, medium-term, or long-term) and maps to specific needs and elements of the research mandate in the framework (see Table 13 for these associations). By collecting strategies together in a research theme, we seek to understand points of pain and opportunity in the industry and set objectives for improvement;
- **Strategies ("how")** – For each potential improvement opportunity, there may be a range of strategies or research projects that will achieve the stated objective;
- **Benefits ("why")** – The potential benefits from the realisation of each objective, in terms of reducing cost or other criteria; and
- **Prerequisites ("but first")** – The prerequisites to the research strategies, any follow-up research that would be required, or any other barriers that must be overcome to achieve the objective.

Table 14:
Improvement opportunities and their strategies, benefits, and prerequisites

	Research theme	Strategies	Benefits	Prerequisites
1.	**Pre-treatment**			
1.1	Preheating using waste heat or renewable energy and the use of lower-pressure membranes *(Around 5 years to commercialisation including prerequisites)*	Solar energy input to pre-treatment in remote locations. Geothermal energy to provide feedwater heating prior to RO, suitable for large scale.	Improved efficiency of the desalination process. Reduced environmental impact and low energy requirement, associated reduced carbon footprint. Reduced injection pressure for pre-treatment. Higher temperature also means lower capex due to higher flux.	Need to quantify the site-specific yield, waste heat enthalpy and economic viability in feasibility studies. Cost gains from pressure reduction must be quantified and compared to heat delivery costs for economic benefit.
1.2	Optimal use of chemicals *(5 years)*	Optimisation of chemicals will limit chemical discharge in concentrate disposal stream. Limit phosphorus and nitrogen in feedwater. Application of various types of UF into Australian desalination plants. Economic management or recycling of ferric sludge or development of an alternative flocculant or coagulant.	Higher public acceptance. Improved safety and environmental disposal in ocean and inland applications. Reduced biofouling. Reduced operating cost.	Develop optimisation function for chemical pre-treatment including chemical cost, operating cost and site specific environmental costs.
1.3	Identifying specific issues for pre-treatment in rural and remote areas relating to seasonal and location variability in feedwater composition *(3 years)*	Process water at smaller plants closer to the source and use. Need to address issues in supplying water to niche areas: Ground water vs surface water; organics in surface water, recent experiences of membrane pre-treatment, combining treatment and pre-treatment in hybrid process. Source management, blending, or optimising to improve feedwater quality from a range of sources. Systems to cost-effectively remove iron, arsenic, magnesium and silica.	More specific understanding of local issues and needs for pre-treatment at small scale. Provide knowledge of parameters and issues to remove this barrier to local, decentralised desalination facilities.	Identification of specific water quality and quantity traits which need to be characterised and controlled. Will need real time monitoring methods to provide input data for online monitoring and response.

	Research theme	Strategies	Benefits	Prerequisites
1.4	Characterisation of groundwater and seawater sources and mapping those to best fit desalination technologies *(3 years)*	Develop parameters for seawater inlet and outlet water and treatment parameters in a national database. Match water characteristics to potential pre-treatment technology. Measuring seawater changes over time as what works best may change over time. Develop ground water database with same parameters.	National database will aid knowledge and inform treatment of plant issues, including a learned history of common failures and technical issues. Understanding of seawater characteristics at different locations and related to seasonal data.	Overcome commercial sensitivity. Review all available fouling indices (e.g. SDI, turbidity, MFI (modified fouling index, Fane), particle count, etc) and establish their efficacy and relative importance.
2.	**Reverse osmosis desalting**			
2.1	Anti-fouling technologies and membranes and oxidant-resistant membranes *(5 years)*	Membrane surface, structure, or configuration modification, perhaps using nanotechnology. Novel chemical treatments for biofouling or scaling. Feedwater treatment to limit propensity for fouling. Incorporation of disinfectant or antimicrobial features into membrane. Chlorine tolerant membranes.	Reduced fouling, pre-treatment costs, flux loss, and membrane degradation.	Document state-of-the-art technology in membrane surface, structure, or configuration modification for the purpose of improving anti-fouling characteristics. Use state-of-the-art technology to guide future research.
2.2	New membrane materials that reduce operating pressure while maintaining or increasing flux rates and maintaining ion rejection *(10 years)*	Increase membrane permeability while controlling salt rejection.	Lower operating pressures will reduce operating costs.	Document state-of-the-art in high flux membranes to determine performance goals.
2.3	Contaminant removal without the need for second-pass RO *(5 years)*	Integrated treatment for desalination-specific contaminants (boron (B), bromine (Br), N-Nitrosodimethylamine (NDMA), disinfection by-products (DBP), and other organics).	Adherence to water quality regulation. Membrane life improvement. Fewer water treatment stages. Reduced energy costs. Reduced plant complexity.	Determine need for bromine rejection over and above first pass. Requires membrane or treatment modifications that are less costly than second pass.

	Research theme	Strategies	Benefits	Prerequisites
2.4	Direct use of renewable energy via kinetic, electrical, or thermal means *(5 years)*	Wave power for desalination process energy. DC input from photovoltaic to water splitting or ionisation. Direct heating using geothermal or solar thermal. Develop variable operating rate capability desalination to allow direct use of renewable energy.	Improved efficiencies through avoidance of storage or transfer technologies.	Intermittent nature of most renewable energy sources are not best fit for steady-state desalination processes. Requires demonstration of viability of non-steady operation.
2.5	Real-time monitoring and classification of potential foulants *(5 years)*	Examine wider array of water contaminants to characterise fouling potential. Monitoring and reporting as getting the info in a timely manner is crucial.	Reduces over pre-treatment through knowledge from an optimised suite of online sensing parameters. Better online sensors and instrumentation will warn of variability in feedwater organic levels. Development of fouling indices and monitoring process will allow optimum membranes (for viability of alternative, cheaper membranes).	Substantial state-of-the-art study to determine methods currently being tried.
3.	**Novel desalting**			
2.6	Operational optimisation *(3 years)*	Optimising design and understanding obsolescence and improvement technologies. Plant simplification and operations and maintenance simplicity for remote plants. Standardisation of modular components.	Economies of scale achievable in smaller plants. Lower barriers to adoption. Sustained performance improvement over time.	

	Research theme	Strategies	Benefits	Prerequisites
3.1	Novel technologies including those for direct agricultural use *(5 years)*	Humidification technology. Combine options to reduce energy requirements, taking advantage of improved thermal recovery where possible. Add heat from solar thermal collectors. Floating humidification plants and floating water capture technologies. Hybrid systems – RO/ED/EDR/IX. Capacitive deionisation (CDI) with particular emphasis on development of more efficient electrode materials. Membrane distillation. Forward osmosis. Biological desalination. Salinity gradient desalination methods.	Cheaper water in remote areas. Higher efficiencies. Direct agricultural use. Economic growth from new agricultural opportunities. Reduced energy cost compared to RO benchmark. Improving commercial viability of alternative technologies. Reduced or eliminated concentrate stream.	Economic projections need to be developed using thermodynamic efficiencies and process estimation techniques. For biological studies basic research is needed on biology and how the concentrate is processed as well as stabilising the biology over time.
3.2	Low-maintenance, reliable evaporative technologies using waste heat or renewable energy *(3 years)*	Couple MED with low cost waste heat. Improve on the technology – can get 20% improved yield from conventional MED.	Cost reductions from large scale synergies through energy management in coupling with large industrial plant. Reduction in volume of concentrate stream. Improvement of recovery if vapour can be captured.	Need to obtain performance data. MED suppliers and real plant to demonstrate the option.
4.	**Concentrate management**			
3.3	Coupling water production with renewable energy *(5 years)*	Convert renewable energy to a carrier (e.g. solar power to hydrogen), then run an electrolysis cell to produce water as a by-product.	Buffering out intermittency of renewables. Can be deployed in remote communities.	Perform systems study to estimate cost of water / power produced by this method. Photocatalytic developments. Examine electrolysis of salty water.
3.4	Piloting in real-world situations breakthrough near-commercial desalination technology *(1-2 years)*	Apply potentially commercialisable bench-scale developments to pilot testing at the Centre.	Brings commercialisation opportunities to the Centre.	Technical bench scale testing successful. Economic argument clearly understood.

	Research theme	Strategies	Benefits	Prerequisites
4.1	Improved feedwater recovery in the limit achieving novel zero liquid discharge *(10 years)*	Options for achieving zero liquid discharge include using forward osmosis as a concentration method; thermal desalination using supercritical water; application of renewable energy. Development of new thermal methods or use of waste heat. Energy minimisation. Enhanced evaporation. Silica treatment.	Reduced or eliminated concentrate volume and associated environmental benefits. Greater feedwater recovery, especially for brackish water desalination. Greater potential for widespread deployment.	Perform systems study to estimate the cost of these methods. Use results to determine where gains are required. If RO is used, the limitations of scaling must be understood.
4.2	Waste minimisation based on value adding or beneficial use *(8 years)*	Grow halophylic organisms in concentrate solution for biofuels and bioproducts. Partial concentration of brine with cultivation uses at each step of concentration. Understanding crop yields with various concentrates. Selective contaminant removal. Recreational or environmental use of concentrates and resulting impact on aquatic life. Understanding additive fate and transport.	Products that can be used by local industry, and associated local economic development.	In all cases, product needs to be identified and economic benefit must be defined. Identifying halophylic organisms that are economically valuable.
5.	**Social, environmental and economic issues**			
4.3	New materials and techniques for lower-cost corrosion management *(8 years)*	Since many concentrate management options rely on thermal treatment, corrosion-resistant coatings for inexpensive metals rather than expensive duplex alloys. Non-metallic non-corrosive materials.	Reduced capital cost. Reduced maintenance cost.	Identification of the main contributors to corrosion for specific water composition.
4.4	Extraction of desalted water at source or concentrate injection *(3 years)*	Understanding hydrogeology occurring on specific sites. Exploration for paleo-channels which are slowly flowing to ocean and are suitable for concentrate injection.	Minimised environmental footprint. Lower-cost concentrate management.	National or state policy or approval.

	Research theme	Strategies	Benefits	Prerequisites
5.1	Appropriate disposal or reuse of spent membrane cartridges *(2 years)*	Responsible disposal of non-biodegradable membrane material. Recycle or reuse membrane materials through new recycling process design. Reuse of support layers for pre-treatment. Use of membrane bulk as filler or structural material.	Reduced waste. Emergence of new recycling markets and resulting lower operating cost.	
5.2	Total life cycle cost analysis and sustainability assessment of desalination against other water sources *(2 years)*	Triple bottom line and life cycle cost analysis of different sources, transparent publication of results and options.	Better understanding of water availability and its true cost. Value water more highly overall, and understand the infrastructure better.	
5.3	Public perception analysis and improvement through education and communication *(1 year)*	Community education for visitors at Centre. Community outreach and in-community trialling via working collaborations. Education and training for desalination professionals for integrated water resource management.	Increased acceptance of desalination. Promotion of desalination industry and skills development.	
5.4	Policy development to better understand energy-water interdependence *(2 years)*	Decision support tools for energy and water deployment planning. System analysis approaches for co-location of energy and water facilities. Understand water implications for power generation and power implications for water treatment.	Reduced overall cost of national or state infrastructure.	

	Research theme	Strategies	Benefits	Prerequisites
5.5	Centralised understanding of national desalination deployment, performance, and lessons learnt *(3 years)*	Licence or develop desalination performance database; Resell database access to Centre clients and give access to Members. Standardising data including the scope for measures of salinity, thermodynamic equation of seawater, adoption of new definition of Absolute Salinity instead of practical salinity scale. Identify and map shared resources and infrastructure for dealing with drought, flood, and emergencies.	Benchmarking national desalination performance. Widespread understanding of lessons learnt. Reduced duplication in research and development.	Theoretical and practical validation of Absolute Salinity as a measure in the Australian context.
5.6	Detailed understanding of the salinity and toxin tolerance of marine species in the vicinity of SWRO outflows *(3 years)*	Longitudinal and aggregated studies of Australian SWRO outflows and environmental impact.	Optimisation of salinity and toxin tolerances reducing shutdown events.	Negotiate sharing of information.
5.7	Management of entrainment of small marine organisms in SWRO intakes *(3 years)*	Intake design to eliminate organism lodgement. Minimally disruptive cleaning methods.	Reduced maintenance costs and plant shutdowns.	

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