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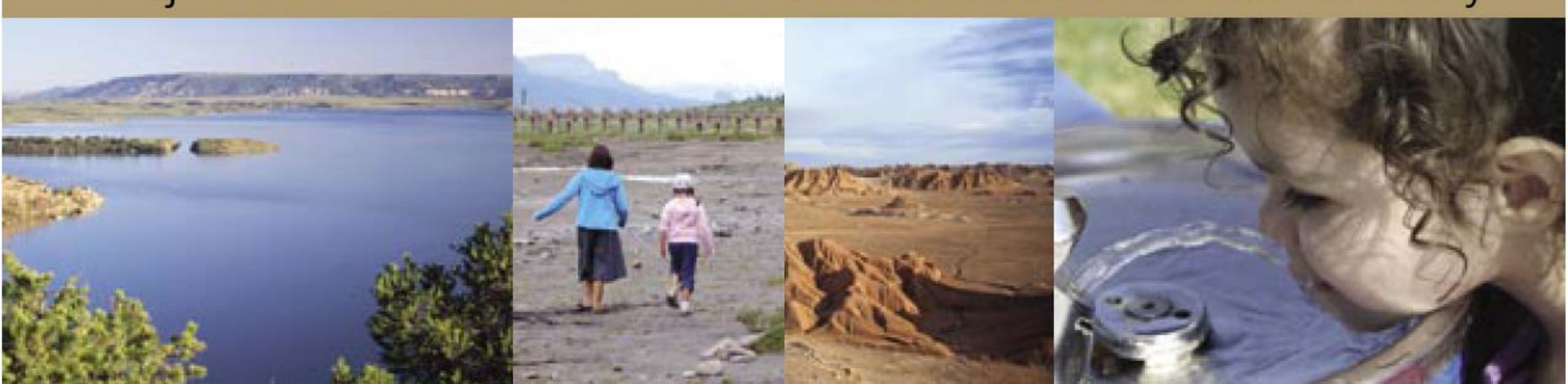
Critical Assessment of Implementing Desalination Technologies

Subject Area: Water Resources and Environmental Sustainability



Critical Assessment of Implementing Desalination Technologies

About the Water Research Foundation

The Water Research Foundation (formerly Awwa Research Foundation or AwwaRF) is a member-supported, international, 501(c)3 nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

The Foundation's mission is to advance the science of water to improve the quality of life. To achieve this mission, the Foundation sponsors studies on all aspects of drinking water, including resources, treatment, distribution, and health effects. Funding for research is provided primarily by subscription payments from close to 1,000 water utilities, consulting firms, and manufacturers in North America and abroad. Additional funding comes from collaborative partnerships with other national and international organizations and the U.S. federal government, allowing for resources to be leveraged, expertise to be shared, and broad-based knowledge to be developed and disseminated.

From its headquarters in Denver, Colorado, the Foundation's staff directs and supports the efforts of more than 800 volunteers who serve on the board of trustees and various committees. These volunteers represent many facets of the water industry, and contribute their expertise to select and monitor research studies that benefit the entire drinking water community.

The results of research are disseminated through a number of channels, including reports, the Web site, Webcasts, conferences, and periodicals.

For its subscribers, the Foundation serves as a cooperative program in which water suppliers unite to pool their resources. By applying Foundation research findings, these water suppliers can save substantial costs and stay on the leading edge of drinking water science and technology. Since its inception, the Foundation has supplied the water community with more than $460 million in applied research value.

More information about the Foundation and how to become a subscriber is available on the Web at **www.WaterResearchFoundation.org**.

Critical Assessment of Implementing Desalination Technologies

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FOREWORD

The Water Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The Foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the Foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The Foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering films. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the Foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The Foundation's trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

In recent decades, the application of desalination has grown substantially. Seawater and brackish water desalination have become viable solutions in addressing safe water supplies in addition to other water management approaches such as water transfer, water reuse, and conservation. The driving forces for implementation of desalination are mainly directed at expanding water source portfolios and resolving water deficits due to (i) drought conditions; (ii) limited availability of conventional freshwater resources; (iii) increase in water demand due to population growth and economic development; and (iv) needs of improving water quality of current impaired water resources.

There are a number of technical, environmental, economic, social, institutional, and political implications associated with the implementation of desalination technologies. These factors are critical to evaluating the feasibility of a desalination project. There may also be regional benefits that emerge as a result of using new water sources; however, there is not a well developed and shared knowledge base on critical issues affecting planning, design, and implementation of desalination technology. This knowledge gap can lead to incompletely scoped projects, underestimated or overestimated costs or benefits, delayed project schedule, and even failure of the project. The Water Research Foundation and the UK Drinking Water Inspectorate (DWI) funded this study to identify the state of implementation and challenges related to implementing desalination technologies. This resultant document provides guidance to water utilities and decision-makers to overcome barriers and to critically assess the implementation of desalination technologies.

RESEARCH OBJECTIVES

The overall objective of the study was to identify and evaluate the full range of water quality, energy, environmental, economic, social, institutional, and regulatory impacts of implementing desalination technologies. This study was designed to focus on seawater and brackish water desalination using membrane-based technologies because of its increasing prevalence as the preferred desalination treatment method in the United States. The key objectives of the study included:

- Documenting and synthesizing the state and challenges of implementing desalination technology
- Developing guidance to mitigate the barriers related to implementing desalination technologies, particularly focusing on intake, water quality, energy use, and concentrate disposal
- Developing a multiple criteria decision support framework for critical assessment of implementing desalination technologies

APPROACH

The project objective was achieved in three phases: data collection, case study analysis, and development of a multiple criteria decision analysis (MCDA) approach for critical assessment of implementing desalination technology. The data collection phase included literature review, international utility surveys, and an expert workshop.

The study was initiated with a comprehensive review of a variety of sources such as grey and peer-reviewed literature as well as reports from government agencies and ongoing desalination projects. Through the literature review, a wide range of information was collected, sorted, and compiled by subject, including technologies, water quality, benefits, costs, energy use, concentrate management, public perception, environmental impacts, permitting and regulatory perspectives. The review also focused on challenges, risks, risk-mitigation strategies, failures and barriers, and unforeseen issues associated with implementation of desalination. Utility surveys on existing and planned water desalination facilities treating various types of impaired waters in coastal and inland regions were conducted. The surveyed desalination facilities cover diverse areas of the U.S., Europe, Asia, and Australia.

Specific issues or problems encountered during the implementation of desalination projects were discussed in-depth through workshop and interviews with stakeholders and utility representatives. Seven case studies were selected, which represent inland and coastal desalination, including Southern California, South Florida, Colorado, Arizona, Australia, UK, and Israel.

The information collected was further used to develop a multiple criteria decision support framework to evaluate the sustainability of desalination.

FINDINGS

Environmental considerations, energy use, carbon footprint, water quality, concentrate disposal, and high cost, were identified as the largest challenges to implementing desalination technologies. Summaries on the major challenges are provided below.

Intake System

Determining the appropriate intake location and type should include a thorough site assessment, a comprehensive environmental evaluation, as well as technical and economic considerations. Subsurface intakes that use sand as a natural slow filter can minimize ecological impacts (i.e., entrainment and impingement of marine life), and yield a highly filtered feed water compared to open water intakes which require extensive and complex pretreatment. The feasibility of subsurface intakes depends largely on the characteristics of the associated site hydrogeology, and often may not be practical for large desalination plants. Subsurface intake systems can be economically justifiable for seawater RO desalination plants because the cost of the wells and conveyance system are often less than the cost of conventional ocean intake and pre-treatment systems. The maximum capacity of such systems depends on the marine aquifer that is tapped by subsurface intake wells. In one case study, a capacity of 15 million gallons per day (mgd) (56,500 m^3/day) has been estimated based on extensive hydrogeological pumping test and groundwater modeling for an alluvial channel of approximately 1,500 feet in width and 180 feet in thickness. Initially, the water quality from a subsurface intake system can be negatively affected by the change of redox conditions in the local groundwater aquifers (e.g., dissolution of manganese and iron), but with extended pumping, the presence of dissolved metals will be significantly reduced once the wellfield inflow reaches equilibrium and is producing mostly seawater.

Impingement and entrainment are the biggest environmental concerns associated with open intake facilities. The adverse environmental effects of intake systems can be reduced through siting of the intake and design features. Co-use of existing power plant cooling water can avoid an additive impact as long as the power plant is operating. Employing advanced screening techniques and other behavior barriers can further decrease the effects of impingement and entrainment. In some cases, off-site mitigation may be required to offset unavoidable adverse impacts from the intake operation.

Pretreatment

Conventional pretreatment, including coagulation, media filtration, and cartridge filtration, is the most commonly used pretreatment method of open intake systems providing feed water to subsequent high-pressure membrane processes. Primary issues of concern associated with these treatment processes include biological activity, mineral scaling, and determining the appropriate controls. This can be accomplished through pilot testing or in some cases during initial start up operations if chemical treatment is deemed sufficient. Microfiltration (MF) and ultrafiltration (UF) have also been used or considered as pretreatment for seawater reverse osmosis (SWRO). The use of membrane pretreatment has been successful in wastewater reclamation. Though this experience is valuable, the feed water quality for wastewater reclamation is significantly different from seawater. The use of MF and UF for SWRO pretreatment still needs to be extensively pilot tested.

For seawater desalination, control of RO membrane fouling is challenging for both membrane and conventional pretreatment using an open intake system. The design of pretreatment processes should consider water quality variations and events associated with extreme water quality changes such as red tide events or oil spills. Chlorination followed by dechlorination was found to contribute to RO fouling occasionally. Chlorination may break down organic material into assimilable organic carbon, which acts as a food source for the re-growth of bacteria on RO membrane surface. Membrane pretreatment can produce a more consistent filtrate quality than sand filters, in particular during challenging source water conditions such as high turbidity and total organic matter concentration. However, during upset events, the MF/UF operation is more challenging than conventional pretreatment due to MF/UF membrane fouling. Because oil spills and red tides are temporary events, one option may be to shut down the operation of a desalination plant.

Subsurface intake facilities have the potential to provide improved feed water quality than those of open intakes, and thus reduce pretreatment requirements. The level of reduced pretreatment depends on the design of the subsurface intake system. Subsurface intakes are protected from shock loading in the open ocean from red tides, oil spills, and algae growths.

Product Water Quality and Post-treatment

Membrane processes produce a product water of high quality by retaining most contaminants and impurities in the concentrate stream. In addition to regular drinking water standards, there are increasing concerns regarding the potential presence of brominated disinfection by-products (DBPs), bio-toxins, boron, and emerging organic contaminants in the product water. However, highly purified water exhibits side effects such as lack of basic micronutrient minerals (e.g., magnesium), high corrosivity and incompatibility problems in blending with other water sources in the distribution system. Common post-treatment processes in desalination plants require one or a combination of recarbonation, remineralization, corrosion control, disinfection, and water quality polishing.

Concentrate Management and Disposal

The typical water recovery of brackish RO is between 60 and 85 percent while the water recovery of SWRO varies between 30 and 60 percent. Approximately 15 to 70 percent of the feed water may be wasted as concentrate. The low product water recovery leads to not only substantial loss of valuable water resource and energy but also to environmental challenges. This water loss also affects permitting of brackish water desalination facilities because raw water withdrawal volumes and concentrate disposal are the key parameters assessed during permitting.

The disposal method of concentrate is determined by its quantity and quality, permitting requirement, geographical and geological availability (e.g., accessibility to ocean or sewer, appropriate geology for deep well injection, availability of land uses), costs, and potential impacts on the receiving water body, soil, or beneficial use.

Surface water discharge and sewer discharge are the most common concentrate disposal practices. The discharge of high salinity and more contaminated concentrate to surface water without appropriate mixing may cause the degradation of quality of receiving water bodies. Although disposal of a small volume of concentrate to sewer is economical, discharging large volume of concentrate with high salinity to sewer systems may have negative impact on the operation of the wastewater treatment plants. Deep well injection (DWI) or subsurface injection involves the disposal of concentrate into a deep geological formation, and is limited by site-specific geological conditions. Evaporation ponds can be a viable solution in relatively warm and dry areas and where land is inexpensive. This method is typically employed only for smaller concentrate flows. Land application depends on the availability and cost of land, irrigation needs, water quality, tolerance of target vegetation to salinity, percolation rates, and the ability to meet ground water quality standards. Zero liquid discharge (ZLD) processes such as brine concentrators, and crystallizers require substantial capital costs and experience high energy consumption, particularly for large concentrate volumes. Although ZLD processes have been used in industrial applications, they have not yet been implemented at large scale in the municipal sector.

Concentrate disposal and the associated environmental concerns represent the largest challenges to inland desalination. Substantial research efforts have been taken to increase desalination water recovery and minimize concentrate volume. The approaches that may help mitigate the disposal challenges include beneficial use of concentrate, technological improvements leading to more efficient ZLD processes, and regional and watershed management for concentrate disposal.

Energy

Because the energy demand of desalination treatment processes is mainly a function of the feed water salinity, energy is of particular concern for seawater desalination than brackish water desalination. Power consumption for desalination of brackish water can range from 2.6 to 7.4 kWh/kgal (0.7 to 1.92 kWh/m^3) while energy demand in large SWRO desalination plants range from 13.2 to 22.7 kWh/kgal (3.50 to 6.0 kWh/m^3). The Affordable Desalination Collaboration (ADC) recently released their two-year data for total energy use of SWRO project:

12.3 kWh/kgal (3.25 kWh/m^3) for a 10 mgd (37,850 m^3/d) plant and 11.3 kWh/kgal (3.0 kWh/m^3) for a 50 mgd (189,250 m^3/d) plant.

The energy required to desalinate water is a function of water quality (salinity and temperature), permeate flux, recovery, membrane resistance, and energy efficiency of the equipment. The energy consumption could be reduced through optimized operational parameters, centralized energy system design, and through development of higher energy efficient membranes, pumps, and energy recovery devices.

Given the high energy demand and utilization of fossil fuels for power generation, the relatively high carbon footprint of desalination as compared to conventional water treatment may render seawater desalination publicly less favorable due to concerns related to greenhouse gas emission and contribution to climate change. However, it is also important to emphasize that conventional treatment methods are unable to create a usable water supply without a fresh water source and water transportation may be necessary. As such, in some regions, energy consumption for seawater desalination may be comparable to that for water importation. Regardless, incorporation of renewable energy sources, such as wind and solar energy, in desalination projects may allow desalination plants to operate in a carbon neutral mode and be more environmentally friendly. Currently, Perth's (Australia) seawater desalination plant is the world largest desalination plant using renewable energy credits. Several other plants have also announced the use of renewable energy, including Perth II and Sydney (Australia), Carlsbad (California), and Thames Water (UK). With the reducing gap between renewable and conventional energy costs, the use of renewable energy in desalination is becoming more feasible.

Co-location and Co-generation

Co-location and co-generation with power plants may be desirable for seawater desalination plants in terms of reducing environmental concerns (such as impingement, entrainment, benthic impact, and concentrate disposal), and with possibly more favorable electricity tariffs. However, there are concerns associated with the co-location with power plants. Electric companies may not see drinking water as an economic commodity. Co-locating a desalination plant next to a power station but farther from major customers may translate to increased conveyance cost and as a result increased distribution system cost and energy cost for pumping. In addition, with the attempt in the United States to phase out once-through-cooling (OTC) loops from adjacent power plants, such benefits may no longer be applicable. However, the power plant's abandonment of OTC may free up intake and outfall systems for use by desalination plants. This offsets the loss of heated desalinated feed water, and dilution benefit of the cooling water discharge flow on the RO concentrate. Additional intake flow may be required to reach an acceptable dilution ratio, which in turn will increase pumping cost. It should also be noted that many of those existing structures were sited before there was thorough understanding of their ongoing environmental impacts, and continued use of the structures may require substantial mitigation, in particular if the desalination plant would take the intake structures and operate as stand-alone facility.

Economics and Financing of Desalination

The determination of actual desalination cost is site specific and varies widely. It depends on a variety of factors such as location, ownership of the facility, feed and product water quality, production capacity, local labor and construction costs, energy costs, as well as hidden costs in subsidies and amortization periods. The desalination cost is often a key consideration in the public's acceptance of a desalination project. On the other hand, desalination also brings a number of external values. These include diversification of water resource portfolios and decreasing stress in water-overdraft situations. Seawater desalination may also provide a "drought-proof" water supply source. By highlighting such values, desalination projects may be presented and perceived as an investment rather than comparing it to equivalent costs of conventional water supplies.

Public utilities are observed to shift towards a partnership with private firms to implement a desalination project. The transfer of services to private sectors would include advantages as transferring risks and responsibilities of asset ownership, operation, maintenance, and replacement to the private sector. Another economic and financing consideration is the flexible approach and strategies of privatized firms in implementing desalination projects. Among a variety of financing approaches, the design-build-own-operate-transfer (DBOOT) approach has the advantages of reducing costs through competition in the private sector. However, public agencies might have the risk of losing control of the treatment process, resulting in unanticipated cost if the selected private entities failed to perform.

Social, Political, and Institutional Aspects

Social, political, and institutional issues are playing a key role in regulatory and associated permitting process, and are often the most significant hurdle in implementing desalination technologies. A better understanding of the issues would help water utilities identify and develop potential options and strategies to address these challenges. High cost, intensive energy use and related carbon footprint, and environmental concerns are the key subjects that affect public perception, political and institutional justification of desalination. These subjects can substantially impact the regulatory and permitting process of a proposed desalination project. However, the level of water crisis (quantity and quality) and long-term climate conditions can considerably change public perception and political decisions regarding the implementation of desalination, such as in Australia and Israel.

Implementation of desalination projects is a multilateral process and requires a collaborative dialogue among communities, regulators, and water agencies. Water agencies should lead a meaningful dialogue with the community and stakeholders that fully addresses the need for water and the alternatives for meeting this need. They should seriously investigate the technologies and strategies to mitigate negative environmental impacts, and collaborate with the community on the appropriate investment in desalination or alternatives.

Concerns over the cost, time, and the uncertainties in regulations and desalination permitting may also be of potential concern. Agencies on the federal, state, and local levels all administer desalination projects with the responsibility over environmental resources, water rights, land use, water use, and supply. Of the regulating agencies, state and local agencies may have variations in regulatory requirements and would have to be addressed on a case by case basis. Regardless of who regulates which operations, it is important that permitting issues be addressed in the early planning stages of project development to ensure proper timing and coordination among agencies.

RECOMMENDATIONS

There are four main recommendations to improve the implementation of desalination:

- Conduct thorough feasibility study and pilot-testing
- Address early and effectively environmental concerns
- Lead a collaborative, open, and transparent dialogue with the general public, special interest groups, political parties, and regulatory agencies
- Develop a multiple criteria decision analysis approach to evaluate the full range of technical/functional, environmental, economic, and social/political aspects of desalination project, and to support the decision making process

Conduct Thorough Feasibility Study and Pilot Testing

Conducting a thorough feasibility study and pilot testing is a key step in planning and implementing a desalination project. The feasibility study includes items such as identifying costs and benefits, financing approaches, potential partners, water quality and quantity goals, siting, handling of residuals, and assessing permitting and other regulatory requirements.

Pilot testing entails (i) selecting processes, (ii) optimizing operations and performance, (iii) demonstrating and certifying technology efficacy such as water quality and energy use, (iv) providing information and comfort to regulators, and (v) offering opportunities for operator training. The pilot testing provides important lessons and data for plant's scalability, complexity, and flexibility. The duration of pilot testing should be long enough to assess the processes performance in site-specific conditions (including variability of source water quality or other factors over time).

Address Early and Effectively Environmental Concerns

It is critical to address early and effectively the environmental concerns of a proposed desalination facility. These concerns comprise a broad spectrum of environmental implications including ecosystem, socio-economic, and public health effects and their cumulative and transboundary implications. The key environmental roadblocks to desalination activities include greenhouse gas emission or carbon footprint, impingement and entrainment of aquatic organisms, concentrate disposal, benthic damage, land use, and aesthetic and noise issues associated with construction and operation of desalination plant. Addressing these issues from the beginning of the project will help identify, evaluate, and develop environmentally sound and sustainable desalination processes. Developing appropriate mitigation measures and alternatives will make the desalination project more acceptable to the regulatory agencies and the affected communities.

Managing Public Dialogue

The most appropriate way to improve the *image* of desalination among the general public and stakeholders is to invest in public education and outreach programs. Desalination may be seen more as an investment in the community to provide a safe and diversified water source rather than a threat to environment, and/or a driver for potential population growth. For the public, it is important to show that desalination is evaluated in a comprehensive water resources planning process and that other more cost effective and environmentally acceptable options are considered before desalination is pursued. The following are the key points that must be considered when managing the public dialogue about desalination:

- The problem and need for investment – clearly articulate the need for more water – how much and by when.
- Options for solving the problem – make a recommendation on the solution and outline the options for investing in new water supplies. Make sure there is a good case for demonstrating strong progress on water-use efficiency and implementation of water reuse.
- Meaningful costs and value – express the cost of desalination (and other options) in terms of their impact on water rates or fees.
- Collaborating with community leaders and other stakeholders – lead a collaborative dialogue with the community members and other stakeholders to which policy makers refer to gauge public opinion. Be flexible, and be willing to alter the course of action based on inputs that are feasible and have strong support.
- Energy consumption – consider launching the project with provisions for using renewable energy or even designing the plant *carbon neutral*.
- Aquatic ecosystem and coastal environment – be prepared to seriously consider intake/outfall structures that reduce the impact on aquatic life and/or consider investing in other environmental mitigation or restoration.
- Technological options – provide information on technological developments such as on concentrate treatment and disposal processes and beneficial use.
- Involve public to identify the nuisances related to truck traffic to/from a desalination facility, transport of chemicals, aesthetics, noise, health and safety issues associated with facility construction and operation. Set acceptable limits and develop neighborhood program.

Multiple Criteria Decision Analysis (MCDA) of Desalination Technology

Evaluation of desalination projects involves large numbers of alternatives and criteria. It is often characterized by uncertainty in permitting, complex interactions, and participation of multiple stakeholders with conflicting interest. It is up to the decision makers to weigh the set of consequences to arrive at a preferred action. However, decision-making is often applied with subjective reasoning and different decision makers may have different values and priorities, and thus different preferred actions. The use of MCDA aims at helping decision makers organize and synthesize such complex and conflicting information; it examines a range of alternative actions and determines the main concerns or criteria of the multiple decision makers. In addition, consulting stakeholders at an early stage, and through the project, makes it less likely that they will oppose the project.

This report presented an overview on MCDA approach and highlights its use as an integrated framework to critically evaluate desalination projects. In general, the MCDA approach for decision support of desalination can be structured in three phases:

Phase 1. Problem Identification and Structuring

- Identification of stakeholders and defining issues
- Identification and screening of alternatives
- Development of evaluation criteria

Phase 2. Perform Detailed Assessment - Building MCDA Model

Phase 3. Development of Action Plan

The purpose of modeling MCDA is to construct a view or perception of decision maker preferences consistent with a certain set of assumptions; therefore, giving coherent guidance to the decision makers in the search for the preferred solution. Ultimately, the goal of MCDA is the implementation of results that translates the analysis into specific plans of actions. It should be emphasized that MCDA does not "solve" the decision problem and should not be viewed only in terms of technical modeling and analytical features. MCDA provides a decision-making framework that gives support and insight to implementation of a project.

FUTURE RESEARCH

This study identified the critical issues associated to implementing desalination technologies. The future research will focus on developing guidelines for planning and implementing desalination projects (Foundation Project #4078). It will provide decision support tools – a useful and accessible compilation of practical experiences, resources, and guidelines – to help water utilities and other water professionals navigating their way through the desalination planning and implementation process. The guidelines will cover the full range of planning and implementation challenges, from feed water acquisition to concentrate disposal, and production water distribution.

This report includes an academic review of MCDA and highlights its use as a potential tool for assessment of desalination projects. However its application to case studies is not fully explored and demonstrated in this project. To make the decision management approach viable and successful, future research work should include:

- Conducting case studies with water agencies. It will help identify how water agencies may handle the multiple stakeholder situation, apply the framework to assist in the decision making process, and validate the MCDA method in a project-specific setting.
- Conducting workshops and one-on-one discussions with project stakeholders to improve the MCDA method. Weighting the evaluation criteria and assessing the performance of alternatives against the criteria are two of the most important and most difficult aspects of applying MCDA methodology. Research work is required to develop approaches to minimize and evaluate the uncertainty in criteria and weight estimation.

CHAPTER 1
INTRODUCTION AND BACKGROUOND

STATUS AND DRIVERS OF DESALINATION

Ensuring a safe, sustainable, affordable, and adequate water supply is vital for maintaining economic development and minimizing future regional and international conflicts (NRC 2004, USBOR and SNL 2003). Solutions to local water scarcity problems often require a combination of approaches, including demand management (e.g., water trading and conservation), improved water storage capacity such as aquifer storage and dam construction, water quality protection, water reuse, and transferring water from other regions (NRC 2004). Desalination of seawater and brackish water offers the potential to significantly add to fresh water supplies in addition to other approaches.

With the advancement of desalination technologies, the application of desalination worldwide has grown substantially over the last two decades. Based on the 19^{th} International Desalination Association's Worldwide Desalting Plant Inventory (GWI 2006), there were approximately 12,300 desalination projects that had a capacity larger than 0.026 million gallons per day (mgd) (100 m^3/d). The cumulative installed capacity reached 10,500 mgd (39.7 million m^3/d) by December 31, 2005. The desalination market for new projects has grown at the rate of 25 percent per year from 2001 to 2005. Desalination plants operate in approximately 155 countries, with seawater and brackish water desalination contributing 65 percent and 15 percent, respectively, of the total worldwide desalination capacity. Due to water scarcity and readily available energy resources, Middle Eastern countries employ almost half of all the world desalination capacity using thermal processes. Desalination in North America accounts for 15.1 percent of the world's total desalination capacity (GWI 2006). More than 2,100 desalination plants operate in the Unites States. Most municipal desalination plants in the U.S. are located in Florida, California, and Texas.

Europe has 13.3 percent of the world desalination capacity, employed mainly in Spain and Italy (GWI 2006). The desalination capacity in Asia was approximately 11 percent in 2002, and it has increased to 12.3 percent by December 2004; with China and India set to enter the large-scale seawater desalination market (GWI 2006). Australia had less than one percent of the world's desalination capacity, mainly in mines and power stations for production of process and boiler feed water or to process effluent to comply with zero liquid discharge. In November 2006, the 38 mgd (144,000 m^3/d, peak capacity) new seawater desalination facility at Kwinana, south of Perth, began supplying 17 percent of the city's water demand (Crisp and Rhodes 2007).

Two main types of technologies are currently being employed for water desalination: membrane based and thermal based processes. Thermal technologies (e.g., multistage flash (MSF) distillation, multiple-effect distillation (MED), and vapor compression (VC) distillation) are more suited for desalination of high-salinity water and/or larger desalination plants because energy requirements are high and almost independent of source water salinity. Thermal desalination technologies are mostly used in the Middle East and are not widely used in the rest of the world, in large part due to their high energy requirement and lack of centralized water and power planning. Water recovery of thermal technologies is generally low, resulting in the generation of large volume of waste stream. Membrane-based technologies, including nanofiltration (NF), reverse osmosis (RO), electrodialysis (ED), and electrodionization (EDI) represent the overwhelming majority of plants outside the Persian Gulf region. Recently constructed desalination facilities (seawater and brackish water) rely almost exclusively on membrane technologies.

In addition to the aforementioned technologies, alternative and emerging technologies are being developed; aiming at improving certain aspects of the performances of existing desalination processes (e.g., higher recoveries, reducing fouling, decreasing energy consumption and capital and operating costs). These new technologies can be classified into three categories: thermal (i.e., Dewvaporation™, membrane distillation), physical (i.e., forward osmosis), and chemical (i.e., capacitive deionization). The potential of these new technologies to supplement or replace existing technologies represents the new frontier of desalination technology.

New hybrid configurations are also being investigated to improve water recovery. These include:

- Physical-chemical or biological treatment of primary RO concentrates, followed by secondary RO or electrodialysis reversal (EDR)
- Double-pass NF-NF process
- Seeded slurry processes to remove scaling compounds in a controlled fashion
- Electromagnetic field for scaling control of RO membrane
- Membrane filtration enhanced by vibratory shear process (VSEP)
- RO/ED or RO/EDR

In recent years, the cost of desalination, especially membrane technologies, has decreased remarkably (NRC 2004, USBOR and SNL 2003) while the cost of conventional water resources development has increased. Desalination is receiving renewed interest as a viable source of water supply in response to water shortages and due to its high product water quality. The status and drivers for desalination in California, South Florida, Arizona, Colorado, Australia, the U.K., and Israel are discussed below to help identify the critical issues in implementing desalination technologies. More details regarding the social, political, and institutional aspects of implementing desalination in these areas are provided in Chapter 8.

Desalination in California

In California, there are five water districts within the Santa Ana watershed operating four brackish groundwater desalters and two ion exchange facilities. These facilities treat and recover about 44 mgd (166,540 m^3/d) of impaired groundwater (California Desalination Planning Handbook 2008). By 2010 it is anticipated that there will be about a dozen desalters and about eight ion exchange operations, increasing the amount of groundwater recovered to 218 mgd (825,130 m^3/d). While most brackish groundwater desalination taking place in Southern California, other facilities exist throughout the Central Valley and Northern California (California Desalination Planning Handbook 2008).

There are sixteen relatively small ocean desalination facilities in operation with individual capacity ranging from 0.002 to 0.6 mgd (7.6 to 2,270 m^3/d) (California Desalination Planning Handbook 2008). There are currently more than 20 proposed large seawater desalination facilities along the California coast (Figure 1.1). These desalination facilities would supply up to 450 mgd (1.7 million m^3/d) of potable water by 2020; accounting for approximately

5.6 percent of California's urban water demand of 8,000 mgd (30.3 million m^3/d) (Voutchkov 2007). Seven of the proposed seawater desalination projects are in Southern California.

Source: Picture courtesy of Nikolay Voutchkov.

Figure 1.1 Planned seawater desalination projects in California

Southern California is a semiarid region with approximately 66 percent of its water coming from the Colorado River and from Northern California through the State Water Project (WBMWD 2007). Questions have been raised about the long-term sustainability of imported water as a reliable water source. Concerns about the dependence of water supply imports have been reinforced by the ordered shutdown and reduced pumping of the California State Water Project through the summer of 2007 to protect the endangered Delta Smelt of the Sacramento-San Joaquin River Delta (DWR News June 8, 2007). Development of a regional integrated water resources program that includes water conservation, water transfers and storage, water recycling, groundwater recovery, and ocean water desalination will help offset losses in imported water supply and will help improve local and regional water supply reliability. Interviews with representatives of water agencies have asserted that an individual community's ability to develop a local water supply will benefit the entire region by promoting water supply independence. The benefit of desalination is that it is virtually immune to dry weather periods and avoids potential disputes over water rights associated with imported water supplies from other areas. Such benefits increase the value of implementing desalination, which provides greater system reliability, particularly in emergency situations.

California Water Plan Update 2005 (DWR 2005) identified 25 strategies to help regions become more self-sufficient with local supplies and minimize conflicts with other resource management efforts. These strategies include water use efficiency, conjunctive management & surface storage, recycling, and desalination. Yet, it is uncertain how much of the new water supply in Southern California will come from desalination. Different water utilities vary in quantity on how desalination will be integrated into their overall water resources. For example, 95 percent of South Orange County's drinking water supply comes from water imports (MWDOC 2005). Because of this heavy dependence on imported water, the Municipal Water District of Orange County (MWDOC) is proposing a 15 mgd (56,800 m^3/d) ocean desalination plant in Dana Point, which would increase its local water resource by 13 percent and improve system reliability for the region (MWDOC 2005). Both West Basin Municipal Water District (WBMWD) and San Diego County Water Authority (SDCWA) have approved desalination in their urban water management plans to a level of 8 percent and 10 percent, respectively, of their water supply (WBMWD 2005, SDCWA 2007). Areas more independent of water importation, such as the Los Angeles Department of Water and Power (LADWP) and the city of Long Beach, may give ocean desalination a lower priority. Nevertheless, LADWP is currently pursuing ocean desalination and is studying the feasibility of constructing a 25 mgd (94,600 m^3/d) plant to increase its local water resources by 2 percent (LADWP 2005). LADWP has put their seawater desalination project on hold until they implement higher priority water recycling and groundwater recovery projects. The city of Long Beach is pilot testing a dual nanofiltration seawater desalination process; a 8.9 mgd (33,700 m^3/d) plant is expected to serve 10 percent of the city's municipal water supply (LBWD 2006).

Besides public desalination projects, privately owned desalination projects are being proposed in Southern California. Poseidon Resources Corporation (Poseidon) has been working with the City of Carlsbad to construct a 50 mgd (189,000 m^3/d) seawater desalination plant at the site of the Encina Power Station. Poseidon has completed pilot tests and obtained the final permit from California State Lands Commission (CCC) in August 2008. The plant is expected to produce drinking water as early as 2010. Similarly, Poseidon proposed to fully fund, build, and operate a 50 mgd (189,000 m^3/d) seawater desalination plant at the Huntington Beach Power Station in Huntington Beach.

Proposals to consider ocean desalination in California have increased the scrutiny on progress in implementing conservation and reuse (Cooley et al. 2006, Desal Response Group website). Opponents of ocean desalination argue that increased conservation and reuse should come first because they may be more cost-effective and have more environmental benefits; including reduction in wastewater discharge. They further reinforce their arguments by highlighting the negative impacts of seawater desalination on marine life.

Water agencies contend that evaluating and planning for ocean desalination do not supersede conservation efforts. In fact, the California Department of Water Resources (DWR) requires that conservation and reuse be an integral element of a balanced water supply portfolio, and water reuse and conservation should be implemented to the maximum extent practicable (Desalination Task Force 2003a). The California Coastal Commission also requires evaluation of other water supply alternatives that may be less environmentally harmful, including conservation and reuse (CCC 2004). For example, in the Santa Ana River Basin, practically all wastewater is currently recycled through direct and indirect groundwater recharge, with the exception of a portion of treated wastewater now discharged to the ocean. Orange County Water District has oversized its recently completed $492 million Groundwater Replenishment System project to recycle up to 130 mgd (492,000 m^3/d). This is considered the maximum feasible level of recycling in the county (Bell 2008).

In summary, the issues that surround desalination in California tend to revolve around the following fundamental questions for a given community:

- How much water is needed, when is it needed, and why is it needed?
- What are the alternatives to desalination and is it the most compelling option now?
- What are the environmental impacts of desalination and what are the best methods for implementing desalination in California?

Consequently, these issues bring about the following challenges to implement ocean desalination in California:

- Develop technologies and strategies to reduce environmental impacts that are associated with feed water intake, concentrate management, and high carbon footprint.
- Overcome the social, political and institutional opposition towards ocean desalination with regards to environmental impact, energy consumption, carbon footprint, costs, and growth inducement.

Desalination in South Florida

The climate in south Florida is primarily humid subtropical, with average yearly rainfall of approximately 53 inches (1,346 mm). Rainfall replenishes the aquifers that supply close to 90 percent of the region's drinking water. But actual rainfall varies widely from season to season, year to year, and location to location. Rainfall can be most scarce when demand is highest; stressing water supplies (SFWMD 2007a).

South Florida is one of the fastest growing regions in the U.S., and its water resources are managed by the South Florida Water Management District (SFWMD), the oldest of the five governmental water management agencies in the state of Florida. The agency's mission is to manage and protect water resources of the region by balancing and improving water quality, flood control, natural systems, and water supply. A key initiative is cleanup and restoration of the Everglades. The SFWMD is not a water utility but has regulatory jurisdiction over the water resources of all or part of 16 counties, from Orlando to the Florida Keys, on behalf of 7.5 million South Floridians. It is the lead agency in restoring America's Everglades -- the largest environmental project in the nation's history.

Population correlates with demand for water. South Florida's population is projected to increase from 7.4 million in 2005 to approximately 10.6 million by 2025. Accordingly, raw water demand is anticipated to increase from 3,124 mgd (11.82 million m^3/d) in 2005 to 4,136 mgd (15.64 million m^3/d) in 2025 (SFWMD 2007b).

Due to population growth and projected water needs, maximized development of traditional fresh water supplies, and meeting the water needs of the environment, the SFWMD is increasing efforts to promote both demand management (i.e., water conservation practices) and supply management (i.e., development of new alternative water sources). As a result of limited availability of additional traditional fresh water sources, future water needs in south Florida will have to be satisfied with increased development of alternative water supplies and increased ethic of conservation (SFWMD 2007b). Alternative water supplies in south Florida include desalinated seawater and brackish water, increased storage through aquifer storage and recovery and above ground impoundments, reclaimed water, and treated storm water. Although some of these water supply options are considered conventional in some areas, they may be alternative water supply options in other areas. For example, the Floridan Aquifer is the primary source of fresh water in the Kissimmee Basin Planning Area (Orlando-Kissimmee). However, in most of the other areas in the District, the Floridan Aquifer is considered an alternative source because its water quality is brackish and requires desalination treatment or blending with a freshwater sources prior to treatment or use. The Floridan Aquifer System (FAS) is the deepest of the aquifers used for water supply in the SFWMD. Water quality in the FAS decreases substantially from Orlando to Miami or Naples with significant increase in hardness and salinity (Figure 1.2).

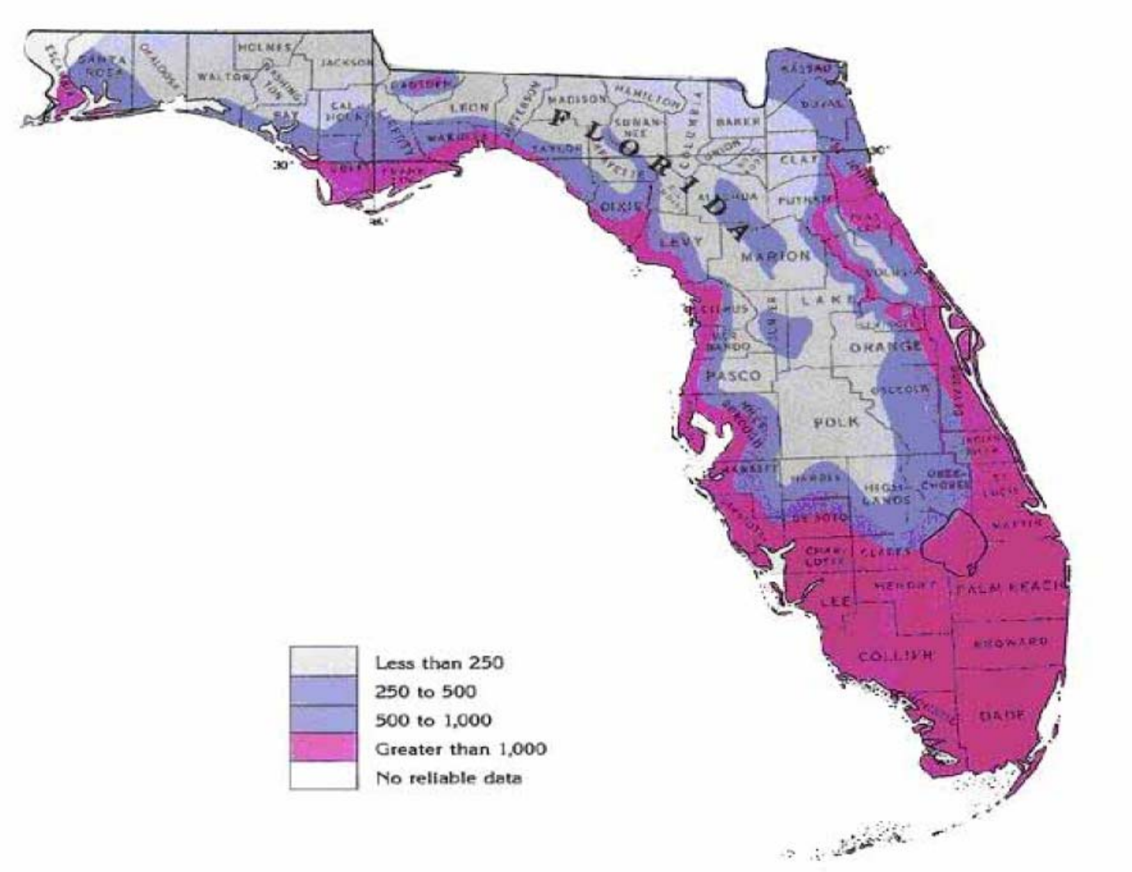
Utilities and other water users will continue to use the Floridan Aquifer to meet future water needs. In 2003, more than 25 water utilities in south Florida were using reverse osmosis to treat brackish water from the Floridan Aquifer to meet potable water demands. Between 2003 and 2008, utilities expanded their supplies from the brackish Floridan Aquifer sources (Figure 1.3). Of the 31 current regional desalination facilities for public water supply, 20 were constructed or are under construction since 2000 (Akpoji 2007). A number of golf courses in south Florida have tapped the Floridan Aquifer including several that installed on-site reverse osmosis plants to meet irrigation needs. The first seawater desalination plant in the US was the Florida Keys Aqueduct Authority's 2 mgd (7,500 m^3/d) peaking plant installed in the early 70s.

It is clear that droughts are part of south Florida and that nine of the 16 counties in the SFWMD have access to abundant coastal water. As a step to understand how this source of water could be utilized, the SFWMD completed a seawater desalination feasibility study, co-sponsored by Florida Power and Light Company (FPL) in 2002. Based on the 2002 study recommendations, a more site-specific feasibility study was done in 2006. Three sites, Fort Myers, Fort Lauderdale, and Port Everglades were recommended as highly desirable electric utility co-location seawater desalination facilities. One site on Virginia Key, near Miami, was recommended for co-locating a seawater facility with a wastewater treatment plant. The SFWMD is continuing to facilitate partnership discussions between FPL and the water utilities in south Florida (Akpoji 2007). More recently, there are additional utilities or consortiums of utilities farther north along the east coast of Florida who are in the planning stages for medium to large capacity surface water desalination facilities, specifically the Coquina Coast and Port St. Lucie projects.

However, the implementation of desalination in Florida is challenged by product water efficiency, cost and environmental concerns. Depending upon water quality, the typical water recovery of brackish RO is between 60 and 85 percent. Approximately 15 to 40 percent of the feed water is wasted as concentrate. This water loss affects permitting of desalination facilities in Florida because raw water withdrawal volumes and concentrate disposal are the key factors in permitting. Due to geological conditions, most desalination plants in Florida employ deep well injection for concentrate disposal. Leakage has been monitored in some Class I injection wells. Regulatory agencies may not renew their disposal permit, and disposal permit will be more difficult to obtain in the future (Akpoji 2007a). In addition, deep well injection is very costly, approximately $5.5 million per well in South Florida.

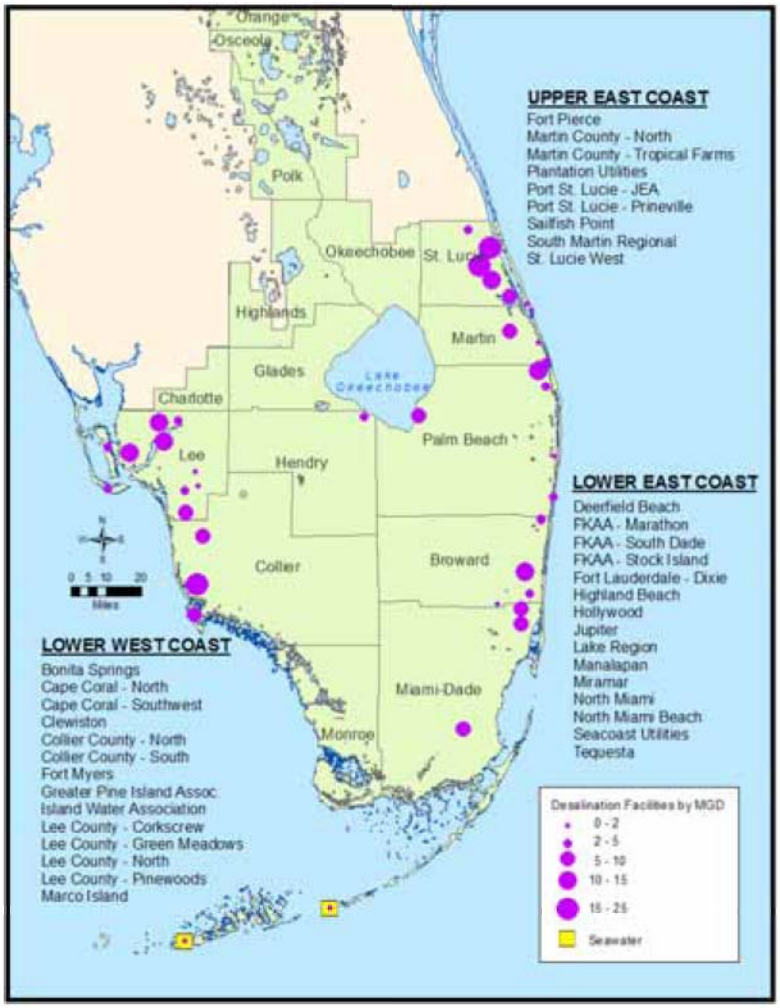
Currently, the cost of desalination is about 50 to 100 percent higher than traditional water sources in South Florida, which makes desalination not as willingly accepted by the public. The major technology issues to desalination are to reduce O&M costs through decreasing energy demand, designing robust membrane systems, and reducing membrane scaling/fouling.

Environmental concerns related to impingement/entrainment, concentrate disposal, energy emission, and costal land use, also need to be addressed in order to gain the support from the pubic, political, special interest groups, and regulatory agencies.



Source: Fernald & Purdum (Ed.) 1998.

Figure 1.2 Brackish water in the Floridan Aquifer System.
Note: Brackish water concentration values in mg/L



Source: Akpoji et al. 2008

Figure 1.3 Potable water desalination plants and capacities in the South Florida Water Management District

Desalination in Colorado

Many water sources in Colorado are characterized by high salinity, mainly due to natural occurrence or because of agricultural uses. Agricultural uses lead to nonpoint source pollution in receiving surface water and groundwater. Impacts include increases in concentration of dissolved solids, nutrients, hardness, and introduction of pesticides and other chemicals to the source water. The specific conductivity of watersheds at U.S. Geological Survey monitoring sites in Colorado is shown in Figure 1.4. There are four communities in Colorado that have installed brackish water reverse osmosis treatment plants to deal with impaired water quality due to high total dissolved solids (TDS), hardness, nitrate, or other contaminants in source waters (Table 1.1 and Figure 1.4).

Table 1.1
Municipal drinking water desalination plants in Colorado

Plant name	Design capacity (mgd)	Start date	Feed TDS (mg/L)	Reason for treatment	Concentrate disposal
Water Treatment Plant, City of Brighton	6.65 mgd ($25,200\ m^3/d$)	1993	605	Nitrate	Surface discharge
RO Water Treatment Plant, Las Animas	1.03 mgd ($3,900\ m^3/d$)	1997	3500	TDS, hardness	Surface discharge
La Junta Water Treatment Plant	6.6 mgd ($25,000\ m^3/d$)	2004	1200-1500	TDS, hardness	Surface discharge
Julesburg Reverse Osmosis Treatment Plant	1.63 mgd ($6,200\ m^3/d$)	2001	-	Nitrate	WW treatment plant

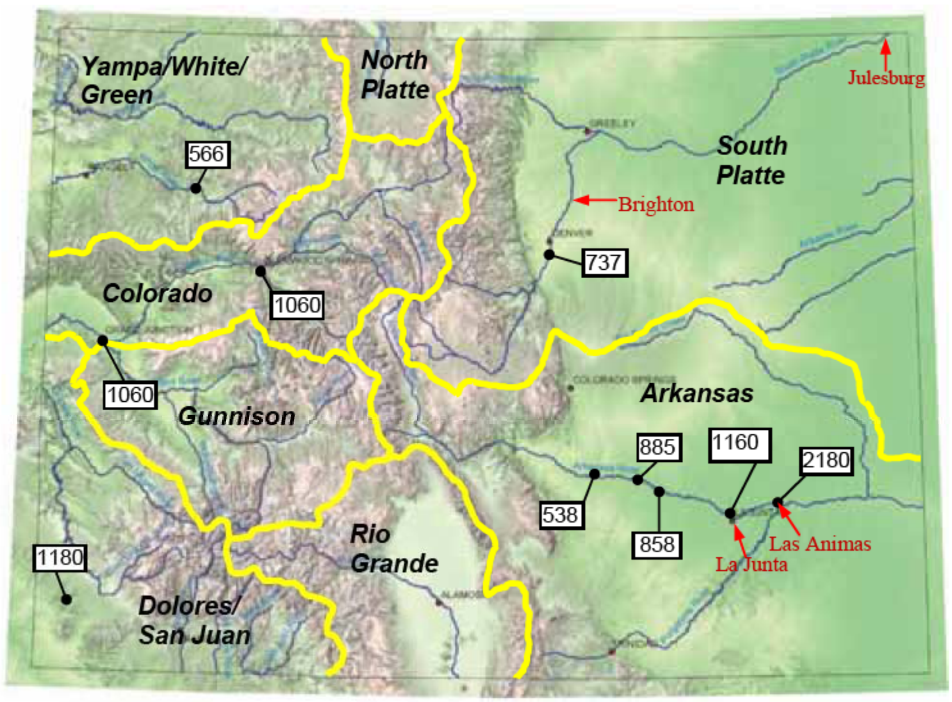


Figure 1.4 Specific conductivity (µS/cm) in Colorado watersheds and location of brackish water desalination plants.
Note: Conductivity data from USGS real-time data on November 6, 2007.

The desalination projects in Colorado are constructed to improve water supply quality to meet USEPA drinking water standards. However, the implementation of desalination projects in Colorado is challenged by more stringent regulations on concentrate discharge permits. The Colorado Water Quality Control Commission (CWQCC) has expressed a concern that if membrane technology is to be viable, it must be implemented responsibly, with residual disposal options that do not adversely impact the environment or beneficial uses of water. The desalination plants in Brighton, Las Animas, and La Junta are requesting permit effluent limits based on assimilative capacity of the receiving stream during times where flows are greater than low flow conditions (CWQCC 2006). The concentration of major contaminants in concentrate such as nitrate, selenium, and uranium will have to be reduced through concentrate post-treatment or dilution.

Desalination in Arizona

Central Arizona is one of the fastest growing regions in the U.S. This region is suffering from serious salt imbalance issues. As concluded by the Central Arizona Salinity Study Phase I Report (2003): "About 1.5 million tons of salts are imported into the region annually, primarily from two major surface water sources (Verde River and Salt River), but also from agricultural fertilizers and salt contributions to wastewater systems, including water softeners and food waste. Since only about 400,000 tons of salts leave the region, more than a million tons are added each year."

Currently there are a number of desalination plants in Arizona including the 102 mgd (386,000 m^3/d) Yuma Desalting Plant treating Colorado River Water, 12 mgd (45,400 m^3/d) Scottsdale Water Campus desalting plant treating reclaimed water for groundwater recharge, and 1.2 mgd (4,500 m^3/d) brackish groundwater RO plant in the City of Goodyear. The Cities of Phoenix and Tucson are also considering brackish water desalination projects to meet its projected water needs. Phoenix's water needs are met through a diverse portfolio of water supplies, including:

- Surface and groundwater supplies delivered through the Salt River Project (SRP) from the Salt and Verde Rivers
- Colorado River water delivered through the Central Arizona Project (CAP)
- Groundwater pumped from SRP and city wells
- Reclaimed water (or treated wastewater effluent)

SRP and CAP surface water supplies are naturally high in salinity due to origin source geology. The salinity of Phoenix surface water sources range from 300 mg/L to approximately 900 mg/L TDS. TDS in the area's groundwater ranges from 1,200 mg/L to more than 2,500 mg/L in the southwest valley (Figure 1.5) (Phoenix Water Resources Plan 2005 Update). The salinity increase in the groundwater aquifers is attributed primarily to the following processes:

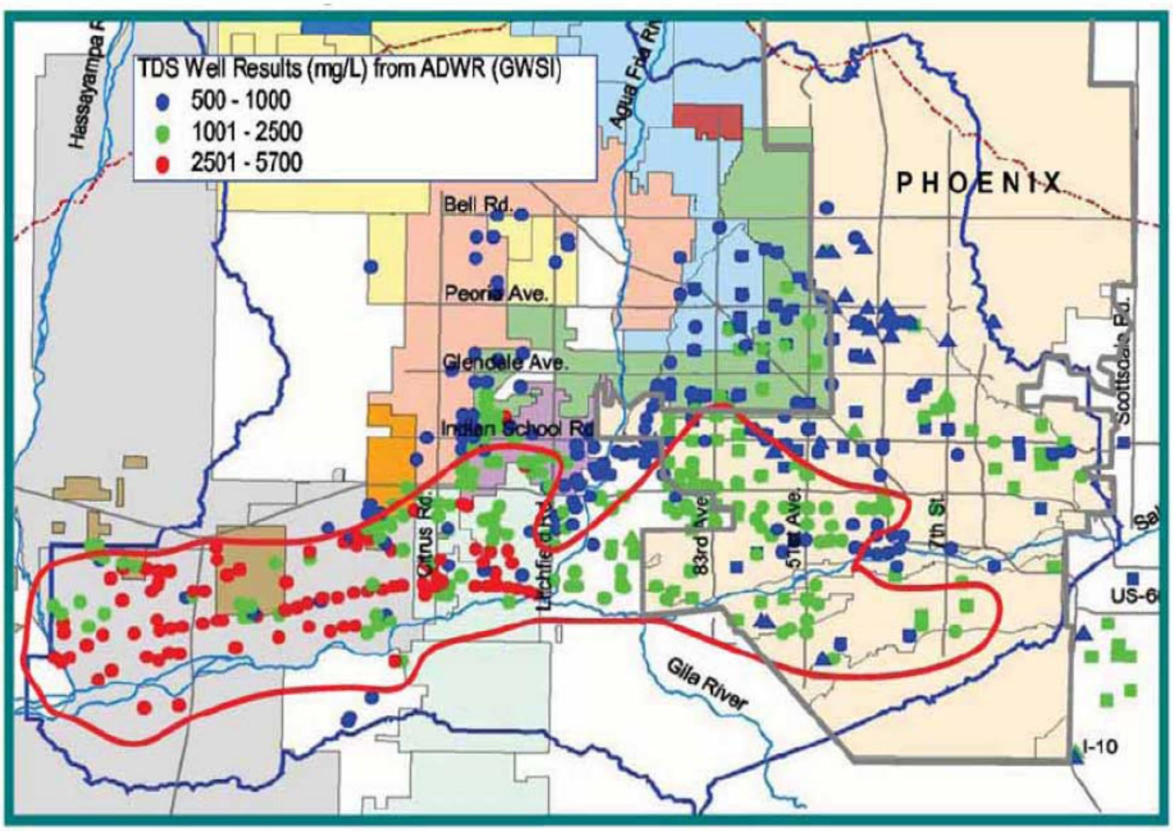
- The use of high salinity surface water (i.e., Colorado River surface water (580-630 mg/L TDS) and Salt River surface water (750-900 mg/L TDS)) introduces significant amounts of salts into the Phoenix area (Phoenix Water Resources Plan 2005 Update).
- Municipal and agricultural irrigation results in high-TDS waters percolating into the water table or discharged to local surface waters that are hydraulically connected to the groundwater.
- Use of reclaimed water for irrigation causes salinity increase in groundwater.

The desalination of impaired water using brackish water RO system, particularly in the West Valley, has been considered an option to meet the local water demands in Phoenix. For the City's long-term planning, the City is considering implementing brackish surface and groundwater desalination facilities in this area.

Tucson's future water quality decisions may also involve brackish water desalination. As increased amounts of CAP water are included in the blend, the salinity of water delivered to customers will increase from 189-498 to 600-650 mg/L TDS (Tucson Water 2007, Tucson Water DecisionH_2O). Tucson is considering desalination to improve the aesthetic of its water.

Concentrate management is the major challenge to implement desalination in Arizona. The primary methods of concentrate management in Arizona are sewer disposal and evaporation ponds (Central Arizona Salinity Study Phase II – Concentrate Management 2006). These two methods are currently the least expensive and/or easiest methods to dispose concentrates of small quantities. With larger quantities the cost of land and cost of lining the evaporation ponds become prohibitive. Meanwhile a wastewater treatment plant receiving the concentrate may not be able to handle the increased salt load. In Arizona, concentrate is expensive to manage considering the limited disposal options, which often require a large capital investment for infrastructure.

Like other inland areas, improving product water recovery is critical to implement desalination in Arizona. Considerable amounts of water would be lost for beneficial use and large amounts of concentrate, if not managed properly, could have environment implications. High concentrations of sparingly salts such as silica in brackish water are a major challenge to RO operation. Membrane scaling in turn results in limited recovery, frequent chemical cleaning, and high energy consumption.

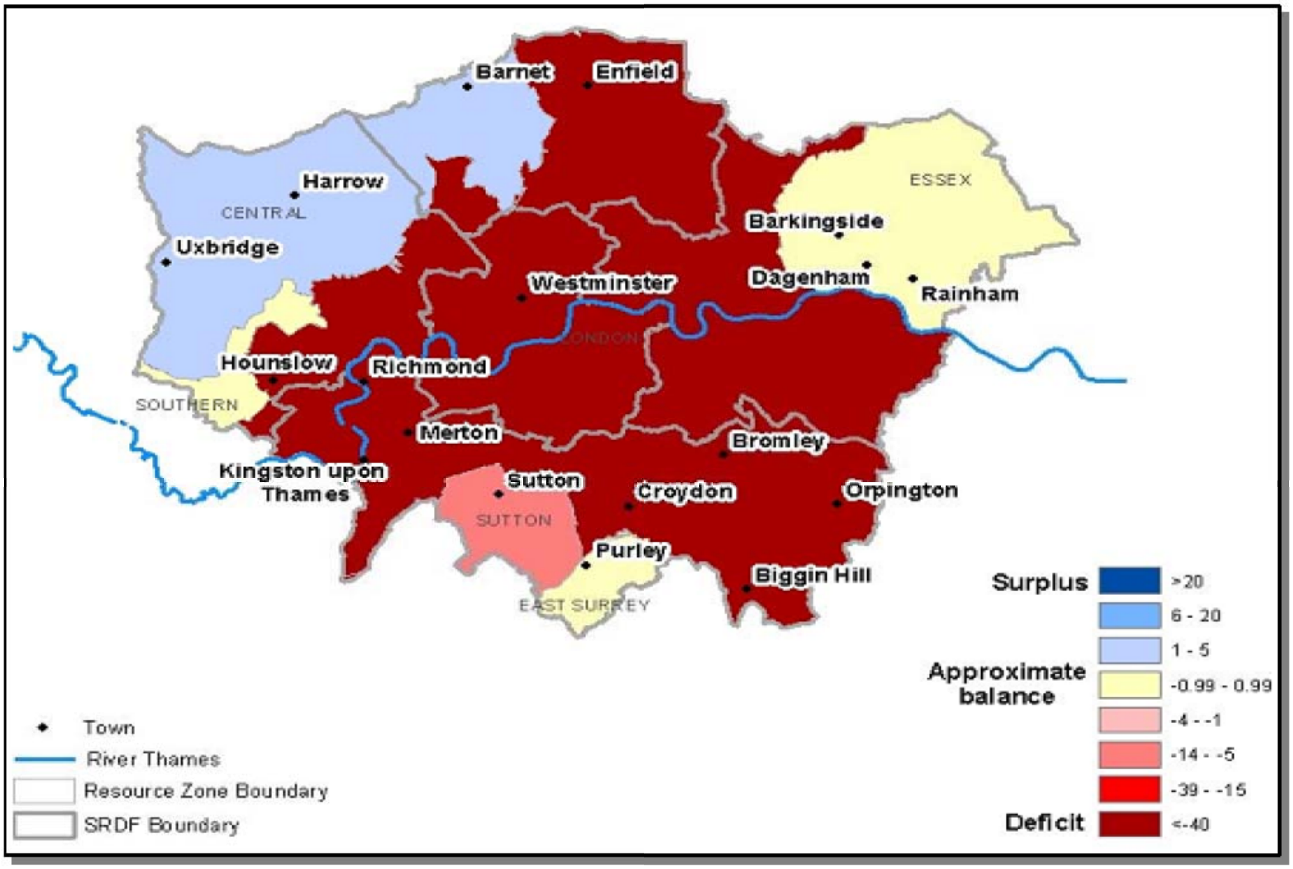


Source: Phoenix Water Resources Plan 2005 Update

Figure 1.5 Groundwater salinity distribution in Phoenix area

Desalination in the United Kingdom

Currently, approximately 80 percent of Greater London's water supply comes from the Thames River and Lee River and 20 percent comes from groundwater use in the summer months (Thames Water Website). However population growth, increase in average water consumption, business demands, and potential reductions in water resources, all contribute to an inadequate water supply to meet projected demand during dry conditions. Following a review of their water supply forecasts in 1999, Thames Water Utilities Limited, the water provider for Greater London, identified a significant supply gap of approximately 39.6 mgd (150,000 m^3/d) for the region (Figure 1.6) (Lyon 2006). Such a supply gap forced Thames Water to seek alternative supplies to decrease the disparity.



Source: GLA 2007.

Figure 1.6 Estimated water supply availability 2005/06 for Greater London

Two main conditions were considered in evaluating provisions for additional water supply in London. One condition was to provide a 39.6 mgd (150,000 m^3/d) capacity of water into their supply system to alleviate the water gap. The other condition required the water to be available and operational in a short term period set by the Office of Water Services (Ofwat) (GLA 2005a). Ofwat, UK's water economic regulatory agency, had initially set short term goals of employing the water supply strategy by 2003/4, back in 1999, when the water needs assessment was originally evaluated (Cascade Consulting 2004). However, due to complexities of introducing a major water management scheme, Ofwat agreed to postpone the deadline to the 2006/07 period. Currently, the deadline for implementation has again been delayed to the year 2010 (Baldwin 2007).

Although identified as water supply strategies, alternative water management options such as mains replacement, repairs, and demand management were not considered for the water supply assessment because they were not considered short-term solutions. Based on a comparative assessment of economic, environmental, and social impacts and the potential to meet target deadlines, brackish water desalination was determined to be the most viable option. Although desalination was not the most economical option in the comparative assessment, it provided the best option as a relatively mature technology, maintained a higher degree of public acceptability, and met capacity demands for Greater London.

The proposed brackish water desalination plant, known as Thames Gateway Water Treatment Plant (TGWTP), is to be sited next to the Beckton Sewage Treatment Works (GLA 2005a). The site lies on the North bank of the Thames River within the London Borough of Newham. The plant is expected to provide 39.6 mgd (150,000 m^3/d) of drinking water and will have a capital cost of approximately £200 million or US$292 million (Baldwin 2007).

The major opposition relating to the TGWTP project is disagreement among what should be employed to reduce the water supply gap, i.e., repairing leakage versus desalination. London's aged water supply infrastructure, in which over half of London's water supply infrastructure is over a hundred years old, has a particularly high leakage rate at approximately 33 percent (London Assembly 2006, Lyon 2006). Opponents maintain that such a high leakage rate is unacceptable, even with harsh soil conditions and dense developed areas. Thames Water acknowledges that leakage reductions are necessary and is the most significant strategy in closing the gap between water supply and demand. However, leak reduction does not close the gap fast enough and the case for building desalination considers the predicted savings from the work in leakage reduction.

Opponents also argue that Thames Water has been poor in promoting water conservation to customers and that a demand side management be fully employed before new water supply side measures are adopted. Similar to leakage repair issue, Thames Water asserts that water conservation is also a long term effort to decrease the water demand. While UK's Environment Agency (EA) and Ofwat both agree that Thames Water's conservation and water efficiency programs can be more assertive, they also both agree with Thames Water that feasible increases in activity in conservation may not be enough to get rid of the supply gap (Lyon 2006).

Another contentious matter in the proposed TGWTP is the energy intensive nature of the desalination plant. The energy consumption of TGWTP is estimated to be 7.44 kWh/kgal (1.92 kWh/m^3) and a predicted carbon output of 20,650 tons of CO_2 per year by using electricity from grid (Lyon 2006). This is significantly higher than traditional treatment works in the surrounding area.

Thames maintains that although the desalination plant will require more energy, it has implemented best management practices to reduce energy consumption including intake within a 3 hour window abstraction during non-tidal period to reduce salinity, use of variable speed drive pumps, and energy recovery turbines (Baldwin 2007). In addition, the TGWTP is not a base load plant and will be used only in times of supply shortages and for replacing regular supplies in emergencies, which will equate to an estimated average of 44 percent plant operational capacity (Baldwin 2007). However opponents argue that use of the plant will be more expensive when implemented in this manner. The cost of desalination at TGWTP at 40 percent capacity is estimated to be approximately 1.18 US$/kgal (0.81 £/m^3) as opposed to 0.51 US$/kgal (0.35 £/m^3) at 100 percent capacity (Lyon 2006).

To further mitigate the CO_2 emissions issues, TGWTP plans to use renewable energy to coincide with the London Plan. The London Plan requires large development projects, such as the desalination plant, to generate a minimum of 10 percent renewable energy onsite (GLA 2005a). A number of on-site and off-site renewable energy options were considered for the desalination plant, including solar photovoltaic cells, tidal and hydro-energy generation, on-site biomass plant, as well as onsite wind energy. All were discounted due to excessive cost, physical or environmental constraints (GLA 2005a). However, Thames Water is still planning to use 100 percent renewable energy source for the desalination plant. Its current plans for renewable energy is to establish an onsite biodiesel combined heat and power (CHP) plant using biogas (methane) from sludge digestion, which may be obtained from the adjacent Becton Sewage Treatment Plant, to power the CHP engines. Heat from the engine is reused to maintain digestion temperatures. In addition, Thames Water is still exploring options in wind energy and also potentially reprocesses locally discarded cooking fat and oil for energy generation (Thames Water website). Because of this commitment, TGWTP is expected to be the first major construction that will be covered 100 percent by renewable energy in the UK (Baldwin 2007). Although actual carbon offset from biodiesel has not yet been established, its use of renewable energy retains a social license with the public.

Although London-Borough/Newham planning authority supported the desalination plan, it received considerable opposition from the Mayor of London at the time. Mayor Ken Livingston, who had direct influence on the planning proposals, overrode Newham Council's decision and directed them to reject the proposed desalination plant on claims that it was "not in line with strategic planning policy which aims to encourage sustainable management of water supply resources" (GLA 2005a). He further argued that "the proposed desalination plant is contrary to this objective as the plant is a highly energy intensive method of producing water." (Lyon 2006). Instead, the Mayor considered leakage repairs to be a more proper method in increasing water supplies in a more cost and energy efficient manner. Thames Water lodged an appeal of the refusal, in which the proposal was re-approved in 2007, two years after the original refusal (Lyon 2006, BBC News June 15, 2007). However, Mayor Livingstone again challenged the decision shortly thereafter and appealed to UK's High Court. The issue was again held up in court for another year until May 2008, in which the appeal was withdrawn under new mayoral leadership of Boris Johnson (BBC News May 12, 2008).

Political opinion proves to be a major challenge for desalination in the case illustrated for the UK. Desalination received more opposition from politicians than from the general public. Although the public and interest groups have influence on the political process, political leaders have a much more direct role on policy such as refusing proposals. Such refusals can lead to costly delays.

Desalination in Australia

Australia is located in a geographic area dominated by subtropical high pressure systems, and as such it is frequently plagued by rainfall deficiencies (ABM 2005). Due to climatic conditions, however, the severity of these deficiencies can be highly variable. Australia at the present time has suffered through an extended period of drought, largely influenced by two recent El Nino phenomena occurring in 2002/2003 and again in 2006. Consequently, Australia finds itself in the situation of having to find new solutions for the water shortages faced because traditional water sources are failing to provide sufficient supply.

Traditionally, water supply management in Australia has focused on "water sharing plans" (NSW Department of Natural Resources 2004), whereby government bodies ensured that sufficient water was available both for the natural and human environments. In terms of the human requirements for water, much of the supply has traditionally been sourced from runoff and sustainable groundwater yield (National Water Commission 2007a). These primary inflows are usually stored for human consumption in large dams, farm dams or in underground aquifers (National Water Commission 2007b). Among these, the majority of water storage occurs in approximately five hundred large dams located throughout the country (Trewin 2006). However, in the five year period between 2001 and 2005, dam levels consistently decreased due to drought conditions (Trewin 2006).

Another traditional Australian approach to water management has been water conservation. This has involved various initiatives, designed to help the Australian population to consume less water in their daily lives. These water conservation initiatives have, on the whole, been a relatively useful response to water shortages. For example, in the Greater Sydney region, water usage has remained constant since 1974 despite population growth of approximately one million people (Sydney Water 2007a).

Australia is currently facing a serious water crisis. Water conservation measures do not reduce water demand sufficiently and traditional water sources are failing. As a consequence, Australia stands at the beginning of a major restructure of national water management strategies, focusing on water recycling for irrigation and industrial purposes and desalination for human consumption.

The developments of the past months and weeks, however, indicate clearly that desalination is perceived as the key to Australian water management with current expenditures nationally being estimated as approaching 26 billion in Australian dollars (AUD) (approximately US$ 23.5 billion) for desalination plants and water infrastructure (Warren 2007). It must also be noted that desalination is not a completely new means of providing a water source for Australia. A number of desalination plants existed in Western Australia more than two decades ago, such as in Coral Bay and Karratha (Water Corporation 2005). In Queensland, 20 small scale desalination plants are supplying water to small inland communities. While desalination has been used for small scale projects in the past, it has not until recently been implemented as a major water source for some of Australia's largest cities. The status of large-scale seawater desalination plants in Australia is summarized in Table 1.2 and their location is illustrated in Figure 1.7.

Individual desalination plants also reveal differences in operation and community response. The seawater desalination plant in Perth, which was Australia's first large-scale desalination scheme supplies 17 percent of the city's daily demand. A second plant for this area, which is in initial stages of planning, has also been announced. Community fears of greenhouse gas emission have been offset to some degree through the declared use of wind-powered energy. However, the environmental impact of seawater desalination concentrate disposal is still a large concern with quality measures and being carefully monitored. An independent report into the environmental impact of the plant has shown that oxygen levels in Cockburn Sound have not been affected by the discharge from the plant (Water Corporation 2007). A documentary film on the adjoining ecosystem near the feed water intake and outfall diffuser has further shed light on the concern. The video shows prolific habitat growth in the area suggesting a healthy ecosystem.

The underwater footage from the Perth Seawater Desalination Plant can be viewed through the website at: http://www.watercorporation.com.au/_files/mmedia/Under_the_Surface_small.wmv.

Other seawater desalination plants in Australia have been planned or in construction but are not operational at this stage. The most common motivation for plant development include increasing drought and climate pressures, combined with increasing demand from the population (as in Sydney, South Eastern Queensland and Victoria). For most proposed plants, operation and maintenance usually come from contract agreements and alliances with private entities.

Plants for the Victoria and Adelaide regions are still in relatively early stages of planning. The Sydney plant is closer to opening, which will supply up to 15 percent of Sydney's drinking water in the summer of 2009-10. Wind power has been identified as the energy source. The proposed plant in South Eastern Queensland (Gold Coast) has had resounding community support. This is due to the careful site selection according to environmental, social and technical criteria, as well as thorough investigation of energy supply options.

However, there is significant local stakeholder opposition to the Sydney desalination plant. In July 2005, the level of Sydney water supply dam dropped to 39.7 percent, and Kurnell was announced as site for the desalination plant to address the water shortage. The severe drought pushed the Sydney desalination plant as a fast tracked and crisis driven project. Some of the groups including the Sutherland Shire Council and the Nature Conservation Council of New South Wales have significant concerns over the impacts of the Kurnell Desalination Plant (Nature Conservation Council of NSW website; Sutherland Shire Council 2006). These concerns relate to potential impacts of the proposal and the lack of detail within the proposal, which does not provide for informed and accurate decision making. There are also general issues related to seawater desalination such as desalination *versus* water reuse and conservation, energy use, impingement and entrainment, and concentrate disposal. In addition, there are specific issues with the construction of Kurnell plant (Nature Conservation Council of NSW website; Sutherland Shire Council 2006):

- The transportation and disposal of spoil resulting from the tunneling of the intake and outtake pipes. Substantial amount of spoil needs to be trucked to appropriate disposal sites resulting in traffic issues and significant greenhouse emissions.
- The disturbance to the threatened sea grass beds of Silver Beach. These sea grass beds are endangered and shown to be very difficult to transplant or rehabilitate. This will have serious ramifications on the ecosystem of the Bay which relies on these sea grasses.
- The dredging of the bed of Botany Bay to lay pipelines will increase turbidity, release toxic matter that has settled and cause the spread of invasive weeds such as Caulerpa Taxifolia.
- Significant noise pollution, construction and disruption as the pipeline infrastructure is constructed through Sydney suburbs. Construction has denied access to some of the surrounding households.

When Sydney's water supply reservoir levels rose back up to above 60 percent in December 2007, the Kurnell desalination plant began to be more widely perceived an unnecessary project that will increase water rates, be enormously energy intensive and have significant impacts on Kurnell and the aquatic ecosystem of Botany Bay.

Table 1.2
Seawater RO desalination status in Australia

City	Size	Status	Energy Source	Capital Cost (AUD$)
Perth I-Kwinana	38 mgd (144,000 m^3/d)	Operated since 2006	Wind farm (via grid)	387 Million
Perth II-Binningup	33-66 mgd (125,000-250,000 m^3/d)	Construction planned in 2009, operate in 2011	Renewable energy	1 Billion
Sydney-Kurnell	66-132 mgd (250,000-500,000 m^3/d)	Construction begun in 2007, operate in 2011	Wind farm (via grid)	1.83 Billion
Gold Coast-Tugun	33 mgd (125,000 m^3/d)	Construction begun in 2006, operate in Nov. 2008	Renewable energy, not announced	1.2 Billion
Melbourne-Wonthaggi	79-159 mgd (300,000-600,000 m^3/d)	Feasibility study	No renewable energy planned	3.1 Billion
Adelaide	>32 mgd (>120,000 m^3/d)	Detailed design	Not announced	2.5 Billion

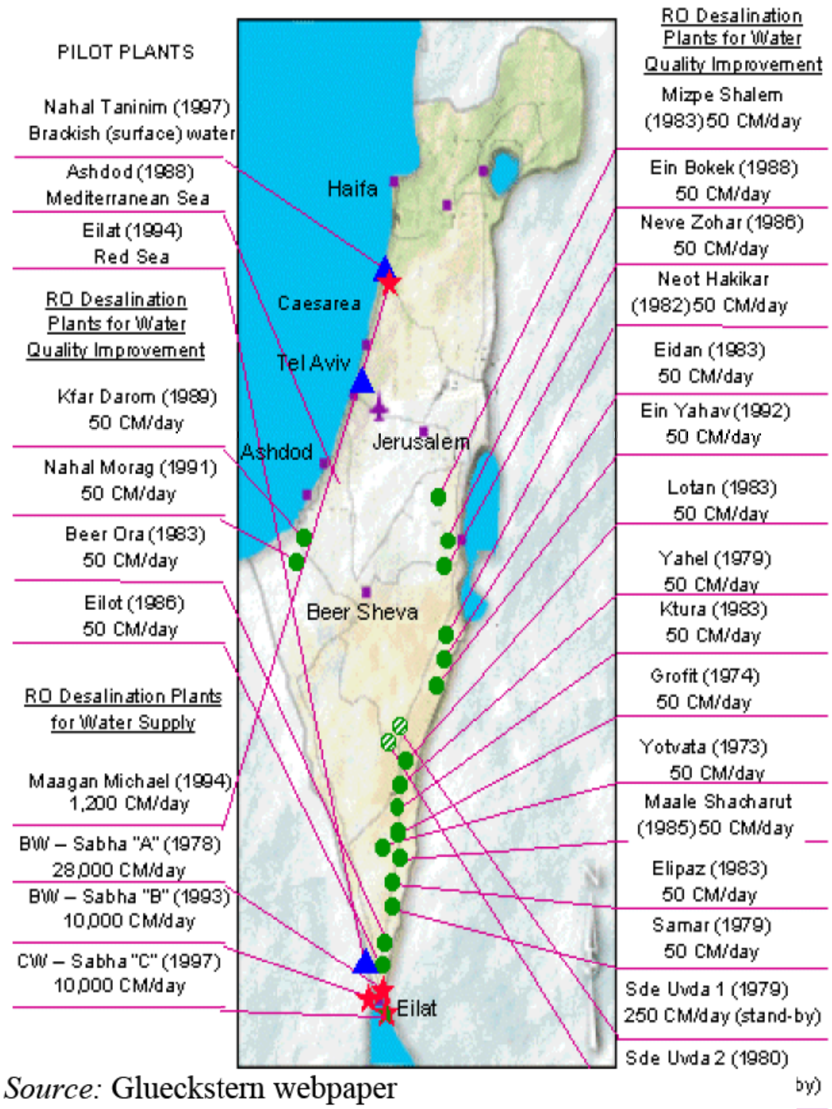
Figure 1.7 Large scale seawater desalination plants in Australia

Desalination in Israel

Similar to other countries in the Middle East, Israel is a semiarid country with a desert occupying more than 50 percent of its land area. Israel obtains approximately 55 percent of its water from the Sea of Galilee and the Coastal Aquifer. Another 20 percent is being extracted from the Western and Northeastern Aquifers of the Mountain Aquifer system. Israel has abundant precipitation in its northern part but land resources are rather limited. On the other hand it has a relative abundance of land in the southern part (the Negev Desert) where precipitation is low. Furthermore, rapid population and economic growth, coupled with frequent drought periods, forced the State of Israel to initiate a massive desalination program. Water resources were always a tense subject in the Middle East and it is anticipated that the current desalination program will mitigate, to some extent, the political conflicts.

A Parliamentary Inquiry Committee was established in Israel to investigate the sources of the water crisis. The committee was charged with finding the sources and acts that led to the severe crisis, and with identifying the immediate actions that must be taken to correct the problem (both short and long-term solutions). Some of the important recommendations of the committee included institutional and organizational restructuring, legislative changes, conservation actions, changes to water rate structure, development of new water resources (including desalination), development of water reservoirs, and water quality and environmental improvements.

By 1999 Israel had close to 30 desalination facilities, mostly in and around the City of Eilat along the shores of the Red



Source: Glueckstern webpaper

Figure 1.8 Distribution of Mekorot's desalination sites - active and reserve installations

Sea (Figure 1.8). A decision to seawater desalinate on a larger scale was taken in 2000 as a result of Israel's growing water scarcity. A 87.2 mgd (330,000 m^3/d) seawater desalination plant at Ashkelon began operations in November 2005, a 26.2 mgd (99,000 m^3/d) seawater desalination facility in Palmahim (ten miles south of Tel Aviv) was inaugurated in September 2007, and an additional 87.2 mgd (330,000 m^3/d) seawater desalination plant in Hadera (midway between Tel Aviv and Haifa) is expected to be operational in 2010 (Israel Ministry of Environmental Protection 2007). Simultaneously, plans and tenders are also being advanced for desalinating saline water and connecting these facilities to the national water system. The potential of brackish water desalination has been estimated to be approximately 174.4 mgd (660,000 m^3/d) based on brackish water sources throughout the country. The projected capacity of desalinated water in Israel is summarized in Table 1.3.

The environmental impact of desalination plants is of concern in Israel. Various measures have been taken to mitigate impingement and entrainment of marine life, concentrate disposal, and protection of coastal land use.

Table 1.3
Seawater desalination within Israel's projected sources of water supply (in average daily capacity)

Year		2005	2010	2015	2020
Potable water					
Natural sources	mgd	1064	1064	1064	1064
	million m^3/d	4.03	4.03	4.03	4.03
Desalinated brackish water	mgd	21.7	36	58	58
	million m^3/d	0.08	0.14	0.22	0.22
Desalinated seawater	mgd	72.4	228	362	470
	million m^3/d	0.27	0.86	1.37	1.78
Sub-total	mgd	1158	1328	1484	1592
	million m^3/d	4.38	5.03	5.62	6.03
Brackish water	mgd	116	101	101	101
	million m^3/d	0.44	0.38	0.38	0.38
Treated wastewater	mgd	217	326	376	434
	million m^3/d	0.82	1.23	1.42	1.64
Total	mgd	1549	1755	1962	2106
	million m^3/d	5.86	6.64	7.42	7.97

Source: Data from Dreizin 2006.

CRITICAL ISSUES ASSOCIATED WITH IMPLEMENTING DESALINATION

Environmental implications, intensive energy demand, limitations of concentrate disposal, high cost, public and political oppositions, and complex and long permitting processes, are common obstacles to implementation of desalination in many parts of the world. In addition to considering technical, engineering, and financial aspects, water agencies have to include social, political, and environmental implications in a desalination feasibility study. Public perceptions of desalination vary widely and the values of different interest groups need to be addressed and understood. The experience of the Thames Water brackish water desalination project implies that desalination projects may face a long and difficult path to implementation if environmental, social, and political implications occur. Although regulatory and permitting processes exist to protect the environment, there may be unique environmental considerations associated with the energy use, intake facilities, and concentrate management that may not have been necessarily considered by utilities. In addition, there are unforeseen problems that may arise in full-scale operation which are not manifested during pilot-scale testing. For example, the 25 mgd (94,600 m^3/d) seawater RO desalination plant built in Tampa Bay, Florida, encountered some serious start-up problems related to pre-treatment of the raw water. As a result, the plant had to be shut down for repair due to the deficiencies in the design and construction of the pretreatment and intake units.

On the other hand, desalination of brackish water and seawater may bring some unrecognized regional benefits like maintaining and restoring stream flows, or freeing up other existing regional resources for other users. An additional benefit that should be recognized is that desalination of higher TDS, hard water supplies that are now being used for potable water will reduce the dependence on household water softeners and help to control the adverse impact of such softeners on the salinity of the communities wastewater effluent. Because of these factors, the actual cost and benefits of developing and operating a desalination plant may be significantly different from the direct cost of the plant itself. Furthermore, an evaluation of desalination should also be based on socio-economic value rather than direct cost. Value will be determined by how the features of the supply (local and drought proof) match the needs of the community. A community with minimal local supplies and no supply diversity will likely value desalination highly rather than comparing its costs to other supplies that are actually not available. Therefore, successful development of new sources of water supply should consider water quality, environmental, economic, and social implications associated with its implementation.

The critical issues associated with decision making in implementation of desalination are summarized in Figure 1.9. These factors are interconnected and cannot be assessed as stand-alone criteria affecting desalination. The problems, barriers, benefits, and challenges encountered in implementing desalination, and mitigation strategies are the focus of this research.

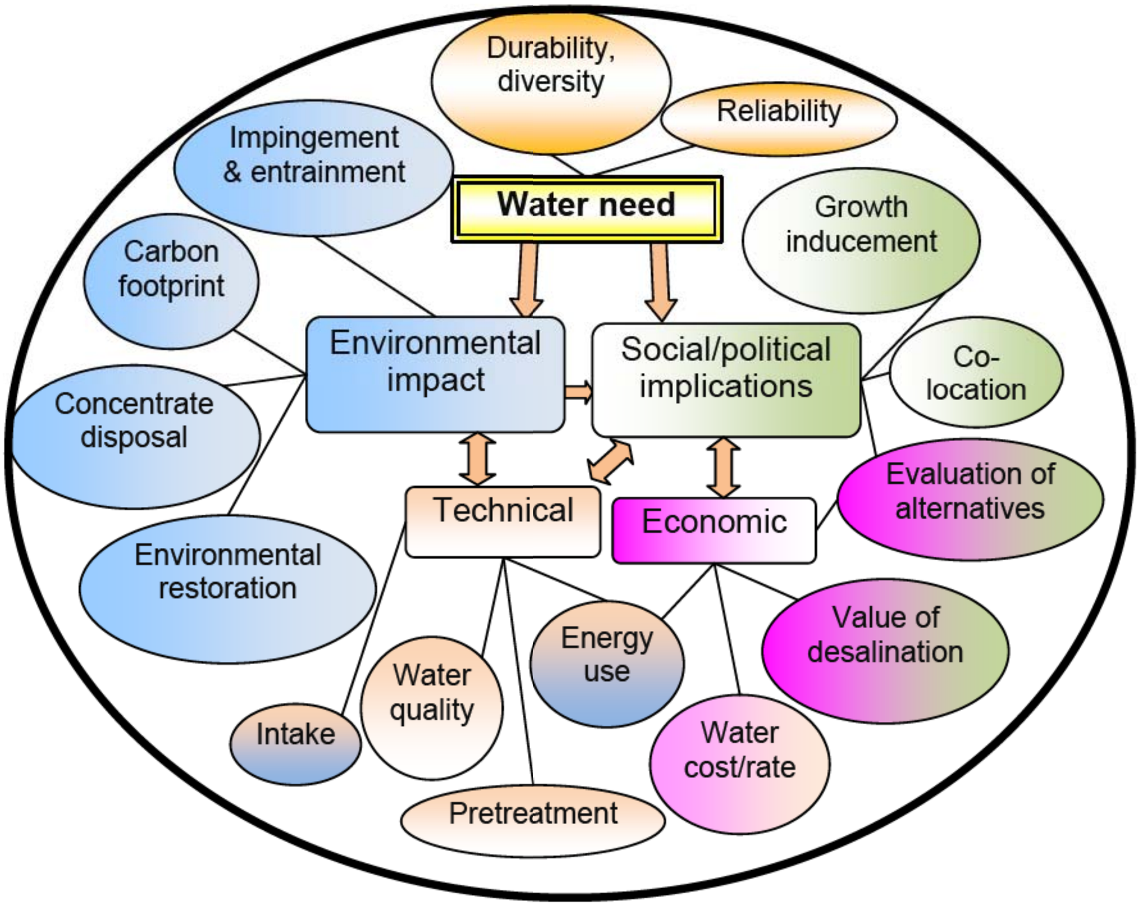


Figure 1.9 Critical issues contributing interactively to the decision-making on implementing desalination technology

OBJECTIVES

The overall objective of the research was to identify and evaluate the full range of water quality, energy, environmental, economic, social, and institutional aspects that may impact the implementation of desalination technologies. This was accomplished through a comprehensive literature review on grey and peer-reviewed literature, a survey of facilities existing and in different planning stages, an expert workshop, case studies and analysis, and the development of a guidance document for the critical assessment of implementing desalination technologies.

This study was designed to focus on seawater and brackish water desalination using membrane-based technologies because of its increasing prevalence as the preferred desalination treatment method in the United States. Membrane technologies, especially RO, are the fastest growing desalination techniques with the largest number of installation around the world. The use of desalination technologies for the purpose of salt, nutrient and TOC removal from wastewater effluents (advanced water reclamation) was not considered in this study.

SIGNIFICANCE OF THE PROJECT

Desalinated water is increasingly being proposed as a potential new water source for communities in coastal and inland regions. There are numerous water quality, environmental, economic, social, and institutional implications associated with implementation of desalination. There may also be regional benefits that emerge as a result of developing a new water source. These factors are crucial to evaluating the feasibility of a desalination project; they are, however, not well documented yet. This knowledge gap can lead to incompletely scoped projects, underestimated/or overestimated costs or benefits, delayed project schedule, and even failure of the project. The findings of the research provide guidance to water utilities and decision-makers to overcome the barriers and to critically assess implementation of desalination technologies.

CHAPTER 2
METHODOLOGIES

The project objective to evaluate the full range of factors relevant for implementing desalination projects was achieved in three phases: data collection, case study analysis, and critical assessment of implementing desalination technologies using a multiple criteria decision analysis approach.

LITERATURE REVIEW

The study was initiated with a comprehensive review of grey and peer-reviewed literature, government documents, and reports on current and proposed desalination projects. Vast information on implementation of desalination was collected on different aspects. The information obtained from the literature review further assisted in selecting representative facilities for additional survey.

SURVEY OF UTILITIES

Surveys were conducted at utilities in various stages of desalination planning and treating different types of impaired water. Twenty-six desalination plants or projects were surveyed in total, and are listed in Table 2.1.

The utilities selected for case study include desalination facilities covering geographically diverse areas of the U.S., Europe, Asia, and Australia. The selected utilities are in different stages of implementation (operating, under construction, pilot or demonstration testing, and proposition); they use different feed water sources (i.e., seawater, brackish groundwater, impaired surface water); they implement major desalination technologies (RO and NF); and they vary in capacities from 0.5 to 87.2 mgd (189 to 330,000 m^3/d). Some are co-located with a power plant and have a variety of concentrate disposal methods. The survey included existing desalination facilities and particularly focused on recently constructed and large-scale facilities. This is because newly-constructed plants often experience more challenges associated with engineering planning and design, permitting, environmental impacts, public perception, and social benefits and values.

An initial database for the survey was built upon the information obtained from the literature review and previous survey conducted by Mickley (2006). Questionnaires were sent to water utilities for information. Some utilities were further contacted to obtain missing or unclear information. Some of the desalination projects, such as those in Southern California, Florida, Colorado, Perth, Ashkelon, and Thames Water, were also included in case studies.

Table 2.1
List of Surveyed Desalination Plants/Projects

	Water Utility	Desalination Plant/Project	Status
Seawater Desalination			
1	VID Desalination Co. Ltd., Kadima, Israel	87.2 mgd Ashkelon SWRO Plant	Operating since 2005
2	Tampa Bay Water, Tampa Bay, FL	25 mgd Tampa Bay SWRO Plant	Operating since 2007
3	Water Corporation of Western Australia, Leaderville, Australia	38 mgd Kiwana SWRO Plant, Perth	Operating since 2006
4	Long Beach Water Department, Long Beach, CA	9 mgd Long Beach Seawater Desalination Project	0.3 mgd Prototype Plant operating since May 2006
5	Marin Municipal Water District, Corte Madera, CA	5-15 mgd MMWD Seawater Desalination Project	Completed pilot testing
6	San Diego County Water Authority, San Diego, CA	50 mgd Seawater Desalination Project at Camp Pendleton	Proposing and feasibility study
7	West Basin Municipal Water District, Carson, CA	20-40 mgd WBMWD Seawater Desalination Project	Pilot testing
8	Poseidon Resources, Stamford, CT	50 mgd Carlsbad Seawater Desalination Project	Final construction permit approved in May 2008
9	Municipal Water District of Orange County, Fountain Valley, CA	26.4 mgd Dana Point Ocean Desalination Project	Proposing Phase 3 pilot-plant testing and water quality testing
10	Texas Water Development Board, Austin, TX / Brownsville Public Utilities Board, Brownsville, TX	25 mgd Brownsville SWRO Desalination Project	Proposing demonstration-scale testing
Brackish Water Desalination			
11 12	Inland Empire Utilities Agency (IEUA) /Chino Basin Desalter Authority, Chino, CA (2 facilities)	14.2 mgd Chino I Desalter 10 mgd Chino II Desalters	Chino I operating since 2000, expanded in 2005; Chino II operating since 2006, plans for expansion by 2010
13 14 15	Eastern Municipal Water District, Perris, CA (3 facilities)	3 mgd Menifee Desalter 4 mgd Perris Desalter 3 mgd Perris II Desalter	Menifee operating since 2003; Perris operating since 2005; Perris II under design
16	City of La Junta, CO	6.6 mgd BWRO	Operating since 2004
17	City of Brighton, CO	6.65 mgd BWRO	Operating since 1993, expanded in 2002 and 2004
18	City of Cape Coral, FL	13 mgd BWRO	Operating since 1977
19	City of Fort Myers, FL	12 mgd BWRO	Operating since 1992
20	City of Pompano Beach, FL	10 mgd BWNF	Operating since 2002
21	City of Dunedin, FL	9.5 mgd BWNF	Operating since 1992
22	City of Hollywood, FL	2 mgd BWRO	Operating since 1999
23	City of Port St. Lucie, FL	9 mgd BWRO	Operating since 2001
24	El Paso Water Utility, El Paso TX	27.5 mgd Fort Bliss/El Paso Water Utility Joint Desalination Facility Project (BWRO)	Operating since July 2007
25	City of Abilene, TX	8 mgd surface water RO Hargesheimer WTP	Operating since 2003
26	Thames Water, London, UK	39.6 mgd Thames Gateway Water Treatment Plant	Final planning permission granted in May 2008

WORKSHOP AND INTERVIEWS WITH STAKEHOLDERS AND UTILITY REPRESENTATIVES

In addition to literature review and surveys, more specific issues on the drivers for desalination and problems encountered during the implementation of desalination projects were discussed in-depth during a workshop and interviews with stakeholders and utility representatives. Seven case studies were selected; representing inland and coastal desalination and including Southern California, South Florida, Colorado, Arizona, Australia, UK, and Israel. The case studies were examined from a regional and national perspective because multiple desalination projects were often proposed or implemented in one region and the selection of one or two projects for a case study would be limiting. Water agencies in the same region may often deal with the same or similar stakeholders and in similar social and political environments. The case studies allowed the comparison of the values of desalination in different social and geographic areas and highlighted the differences in community needs and conditions.

The case study analysis was conducted through a comprehensive literature review on water resources management in the region/country, water utility survey, a workshop, and numerous interviews with stakeholders, including representatives of the public, managers/executives from water agencies, professional engineers, regulatory agencies, and representatives from environmental interest groups. The workshop and interviews covered subjects related to the need for more water, options for augmenting water supplies, environmental impacts of desalination, economics of desalination, risk mitigation strategies (location and option of intake/outfall, and concentrate disposal), technology and water quality, energy use, public perception and politics, and permitting.

MULTIPLE CRITERIA DECISION ANALYSIS FRAMEWORK

Many factors affect the decision to implement desalination, and although some factors are crucial, they are often not taken into consideration in planning and implementing desalination projects. A structural framework was developed for a multi-criteria assessment of implementing desalination.

ORGANIZATION OF REPORT

Chapters 3 through 8 summarize the results from the comprehensive literature review, survey, and case studies. Chapter 9 summarizes the guidelines for public dialogue, and chapter 10 presents the framework for multiple criteria decision analysis.

CHAPTER 3
FEEDWATER INTAKES AND PRETREATMENT

Feedwater intake and pretreatment are key technical components in a desalination plant. Feedwater intake may vary in physical shape and feature depending on the source of water (e.g., seawater, groundwater, or surface water). It plays a major role in controlling the quantity and the quality of the water transferred to the pretreatment and desalination process. A well-designed and constructed intake system guarantees a stable quality and quantity of water supply and is an important factor in improving the desalination process efficiency and the plant's overall reliability (Desalination Task Force 2003a). The intake facility strongly influences the selection of pretreatment process, stability and efficiency of membrane processes, cost of product water, and environmental impacts. This chapter discusses different types of feedwater intake structures and pretreatment systems, their environmental considerations and mitigation strategies.

FEEDWATER INTAKES OF BRACKISH WATER

For brackish groundwater and surface water, the feedwater intake structures are based on several factors including hydrogeology, groundwater flow gradients, and existing infrastructure (Desalination Task Force 2003a). For inland brackish water desalination, feedwater intake is usually groundwater extraction wells. Surface water treatment plants often use open intake structure to divert water from rivers or draw water from reservoirs. For example, the Thames Gateway desalination plant in London proposed to use an open intake structure to draw water from the Thames and pump to salinity buffer tanks. Because entrapment of fish and crustaceans has a significant impact on the ecology of the Thames, wedge wire screening and an acoustic fish deterrent will be incorporated into the design to mitigate the impact of open intake on fish population in the area (GLA 2005a).

FEEDWATER INTAKES OF SEAWATER

The successful operation of seawater desalination plants strongly depends on the intake structure and pre-treatment process. The withdrawal of seawater is critical to downstream processes; it should draw water with reduced suspended solid concentrations, take into consideration variation of seawater temperature and presence of pollutants (particularly oil), and exclude marine creatures from the raw water. All these issues, individually or combined present a great challenge for pre-treatment (Peters and Pinto 2008).

Seawater intakes can be broadly categorized as surface intakes where water is withdrawn from above the seabed or as subsurface intakes where water is collected via beach wells, infiltration galleries, or seabed filtration systems. The most appropriate location and type of the intake can only be determined after a thorough site assessment and careful environmental evaluation (Pankratz 2006). The California Coastal Commission (CCC) requires a site-specific alternatives analysis for each proposed project to determine what types of intakes are feasible and would cause the least environmental damage (Luster 2008).

Open Surface Intake

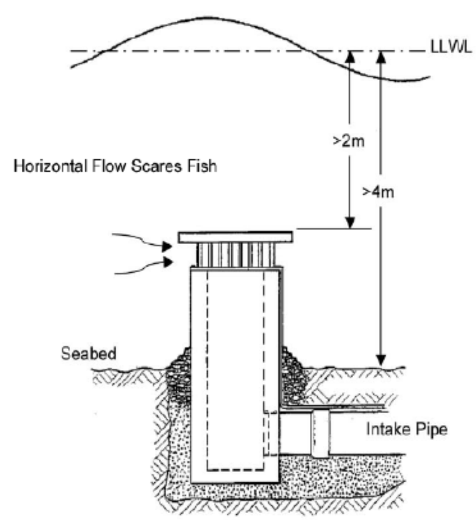
Conventional surface intake systems have been used for decades by most electric power plants to obtain condenser cooling-water from the sea. Water is withdrawn directly from the ocean or sea through offshore intakes, pumps, screens, and pipelines. Generally, it is proposed that the intake be located a minimum of 33 ft (10 m) below the water surface in bays and 49 ft (15 m) below the water surface in the ocean (Melbourne Water 2007). Most desalination plants withdraw water from shallow water areas from a depth of 3.3 to 19.8 ft (1 to 6 m) below the water surface (Gille 2003). However, in these depths, the presence of sand, fish, seaweed, algae, jellyfish, and microorganisms might be a concern (Gille 2003). Better water quality can be obtained from depths greater than 115 ft (35 m) below water surface where debris load is 20 times lower than at the surface (Gille 2003); however, water depths of 115 ft (35 m) are usually not available within 0.31 mile (500 m) from the shoreline. Desalination plants are often designed to take shallow water to avoid the high cost of pipeline or other transmission methods.

Types of Open Intake Screens

Different types of screens can be used in intake structures including traveling water screens, mechanically cleaned bar screens, and passive well screens (Pankratz 2006). Screen chambers are located offshore, onshore, or near shore.

Traveling water screens and mechanically cleaned bar screens are most commonly used in conventional seawater intakes for medium and large sized desalination plants. As long as the water intake is new or well maintained, the intake screens could provide constant water quality and quantity. Experience shows that more debris passes through the screens when these intake facilities become old (Gille 2003). Additionally, intake facilities may have to shut down on an emergency basis if the traveling band screens are blocked by seaweeds, jellyfish, or small fish (Gille 2003). To protect downstream pumps, additional debris filters are often installed in front of the desalination units. Some high performance debris filters can reach ten times the debris load than conventional traveling band screens or drum screens.

The screens can be located onshore, at the end of a channel or forebay that extends out beyond the surf zone. For submerged offshore intake facilities, a vertical velocity cap is often placed over the vertical terminal of the intake pipe (Figure 3.1) (Pankratz 2006). The cover converts vertical flow into horizontal flow at the intake entrance to reduce fish entrainment. It has been noted that fish will avoid rapid changes in horizontal flow and velocity cap intakes have been shown to provide 80-90 percent reduction in fish impingement at two California power stations, and a 50-62 percent impingement reduction versus a conventional intake at two New England power stations (EPA



Source: Pankratz 2006.

Figure 3.1 Velocity cap for seawater intakes

Efficacy of Cooling Water Intake Structures, cited from Pankratz 2006). The relationship of the vertical opening to the length of horizontal entrance can be optimized to create a uniform flow and improve a fish's ability to react. As with all intake configurations, there are many design issues that must be considered, and the performance of a velocity cap may vary in still water *versus* areas subject to tidal cross-flows (Pankratz 2006).

Passive screens are often used for small and medium size desalination plants. The intake screens are attached to a pump pit, or the pumps are connected to the intake screens by long pipelines (Gille 2003). Passive screens are best suited for areas where an ambient cross-flow current is present (Pankratz 2006). Cylindrical wedgewire screens that have openings ranging from 0.5 to 10 mm are usually oriented on a horizontal axis with screens sized to maintain a velocity of less than 15 cm/s (0.5 foot per second) to minimize debris and marine life impingement (Pankratz 2006) (Figure 3.2). Because of debris accumulation, an air backwash system is usually recommended to clear screens and remove debris from the screen surface.

Source: MMWD 2007

Figure 3.2 Wedgewire intake screen

The disadvantage of the cylindrical intake screen is that air backwash unit is often unable to clean the cylinders. It is difficult to clean the entire cylinder because air always goes to the surface through the shortest path. Fibrous debris, like seaweeds, can get entangled on the screen and cannot be backwashed. Figure 3.3 shows a fouled wedgewire intake screen used in the Desalination Pilot Plant of Marin Municipal Water District (MMWD). The intake screen was air-burst-cleaned in the water weekly and cleaned every four to six weeks over the course of the pilot program. The slime that covered the copper-nickel screen appeared to be easily removed by periodic air-burst cleaning and by washing (Figure 3.3). However, barnacles and marine plants were able to attach to the stainless steel components inside of the screen and grow.

The material used for passive screens is stainless steel or copper nickel. Corrosion often develops on the screen and affects the removal efficiency of debris from wedgewire screens (MMWD 2007a, Gille 2003). When the screen is partially blocked, the velocity through the remaining free area can increase substantially and lead to severe erosion-corrosion. Additional fine filters have to be installed before the pump if the particle size cut-off of wedgewire filters is above the required pretreatment process.

Source: MMWD 2007a.

Figure 3.3 Fouled wedgewire intake screen used in the Desalination Pilot Plant of Marin Municipal Water District after manual cleaning (April 2006)

Co-location with Power Plants

Currently large seawater desalination plants almost exclusively use open intake structures. Seawater desalination plants often co-locate with power plants to take advantage of existing power plant intake structures or use the plant cooling water before it is discharged to the ocean (Desalination Task Force 2003a). For example, the Tampa Bay seawater desalination plant uses the once-through-cooling (OTC) water from the adjacent power plant as feed water. Several seawater desalination projects in Southern California have proposed to co-locate with power plants, including West Basin, Carlsbad, Huntington, and Los Angeles projects.

The co-location concept can yield substantial construction cost savings, especially avoidance of construction of a separate ocean intake and outfall for concentrate disposal. This approach can also yield significant environmental benefits associated with the accelerated dissipation of the thermal and saline discharges and the reduction of impact on the marine benthic and seashore habitats by avoiding the construction of new facilities. The discharge into the ocean is also warmer, which can help a salty brine float better; making it more neutrally buoyant which in turn can help protect the benthic environment. Another advantage of using cooling water as membrane feed water is the decreased energy usage associated with an increase in water permeability through membranes due to higher feed temperature. On the other hand, results from pilot testing at West Basin Municipal Water District's (WBMWD) desalination facility showed that the warmer water may promote biological growth, which could cause a higher fouling potential for membrane treatment processes. Additionally, the salinity level of the product water produced from the warm water would be slightly higher than using ambient seawater due to higher salt transport through membranes (Lauri et al. 2007).

The future of OTC systems remains unclear in the United States. The U.S. Environmental Protection Agency (USEPA), which regulates cooling water intake structures under section 316(b) of the Clean Water Act, issued new regulations for existing power plants in 2004. It requires power plants to reduce impingement by 80 to 95 percent and entrainment by 60 to 90 percent. This may influence power plants to shift from OTC systems to closed-cycle cooling systems. As a result, the proposed co-located plants face a large degree of uncertainty about future operations. In addition, power plants are starting to feel that seawater desalination efforts are 'hastening the death' of OTC by shining an unwanted spotlight on this historically contentious issue.

The power plant's abandonment of OTC would free up the intake and outfall systems for use by the desalination plant. This offsets the loss of heated desalinated feed water, and dilution benefit of the cooling water discharge flow on the RO concentrate. Additional intake flow may be required to reach an acceptable dilution rate, which in turn will increase pumping cost, and impingement and entrainment.

A specific consideration should be given to the complexity in matching the operation of desalination plant with that of power plant. The operation of desalination plant may need to be discontinued during periods of maintenance or upgrade of power plant facilities. Because of the complexity to match with the operation of power plant, large desalination plants may require dedicated intake facilities. The operation of desalination plant may also be affected by the operation of power plant because the cooling water discharge is used as source water for the desalination plant. The power plant discharge may contain levels of copper, nickel or iron significantly higher than those of the ambient seawater. These metals may cause severe scaling of the membrane elements. For instance, the Perth and Ashkelon desalination plants co-locate with power plants but have dedicated intake facilities.

Subsurface Intake

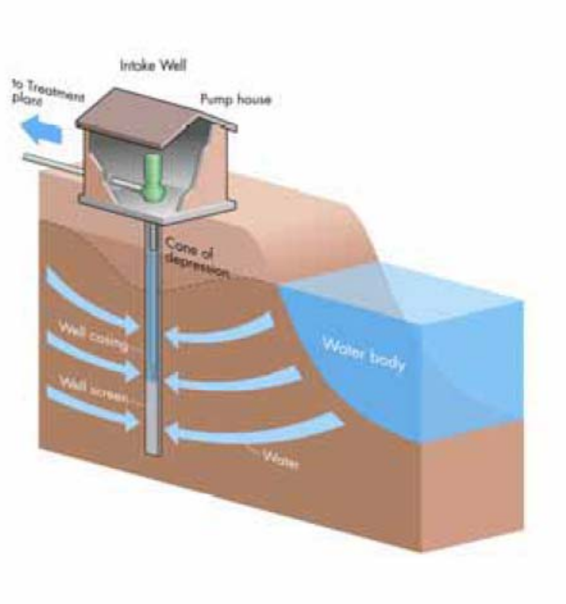
Beach Well

Beach well is the most common subsurface intake structure, where seawater is extracted from the sand below the beach, or below the seabed near the shore. The sand acts as a natural slow filter to minimize ecological impacts (i.e., entrainment and impingement), and to provide stable and constant quality water. Beach wells can yield better quality water than open seawater intakes, including reduced suspended solids, turbidity, and organics, and commonly achieve lower silt density index (SDI).

The construction of beach wells requires appropriate geological conditions including permeable sand formation with adequate transmissivity and depth extending (Voutchkov 2005a). Shallow beaches that contain a substantial amount of mud/alluvial deposits, and have limited natural flushing, do not provide favorable conditions for beach well operations. Natural wave motions near the ocean floor provide the energy to dissipate the separated solids from the beach well source water out into the ocean. If the bay area is not well flushed, and the naturally occurring movement is inadequate to transport the solids away from the beach well collection area, the solids would begin to accumulate on the ocean floor. It will ultimately reduce the well capacity and source water quality (Voutchkov 2005a).

The feasibility assessment for the use of beach-well intake should include a subsurface geological investigation, including source water aquifer, flushing and solids dissipation capacity of the tidal action, and currents in the vicinity of the beach well intake area. The impact of beach well operations on an adjacent fresh water aquifer should be evaluated. Well yield may diminish because of naturally occurring scaling of the well collectors caused by chemical precipitation and bacteria growth. Beach wells can also be affected by the dynamic action of the sea such as from natural catastrophes as well as shoreline erosion.

Vertical beach wells consist of water collectors that are drilled vertically into a coastal aquifer (Figure 3.4). Each well consists of a nonmetallic casing, well screen, and submersible vertical turbine pump (Wright and Missimer 1997). The well casing diameter is 8 inches (20 cm), the well depth is usually not greater than 250 feet (76 m), and the maximum yield of each individual well is assumed to be 0.5 mgd (1,900 m^3/d) (Wright and Missimer 1997).

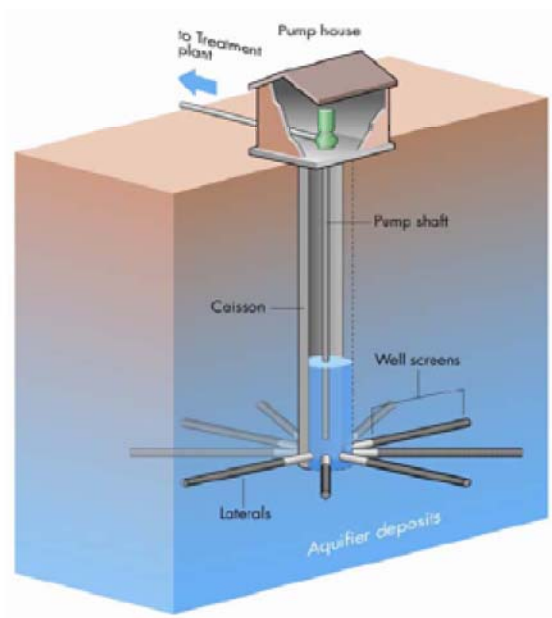


Source: Picture courtesy of Nikolay Voutchkov

Figure 3.4 Vertical beach well intake system

Vertical beach wells are generally used for smaller desalination systems. At present the largest seawater reverse osmosis (SWRO) facility with vertical beach wells is the 14.3 mgd (54,000 m^3/d) Pembroke plant in Malta. This plant has been in operation since 1991. The 11.1 mgd (42,000 m^3/d) Bay of Palma plant in Mallorca, Spain, has 16 vertical wells with unit capacity of 1.48 mgd (5,600 m^3/d) per well. The third largest plant is the 6.34 mgd (24,000 m^3/d) Ghar Lapsi SWRO in Malta. Source water for this facility is supplied by 15 vertical beach wells with unit capacity of 1 mgd (3,875 m^3/d).

Horizontal wells are variations of vertical beach wells that have multiple horizontal collection arms that extend into the coastal aquifer from a central collection caisson where seawater is collected (Figure 3.5) (Poseidon Resources 2005). Individual horizontal wells can be drilled or well screens can be hydraulically jacked out from the bottom of the caisson using a direct-jack or pull-back process. Caissons may be 9 to 20 ft (2.75 to 6 m) in diameter and 30 to 148 ft (9 to 45 m) deep, and radial arms are usually 8 to 12 in (200 to 300 mm) in diameter. The caisson can be completed with a flush-grade top slab or in a buried concrete vault and backfilled with 3 ft (0.9 m) of beach sand to reduce visual impact (Pankratz 2006). The intake capacity could reach 2.5 mgd (9,500 m^3/d) per 12 in (300 mm) diameter well (Poseidon Resources 2005).



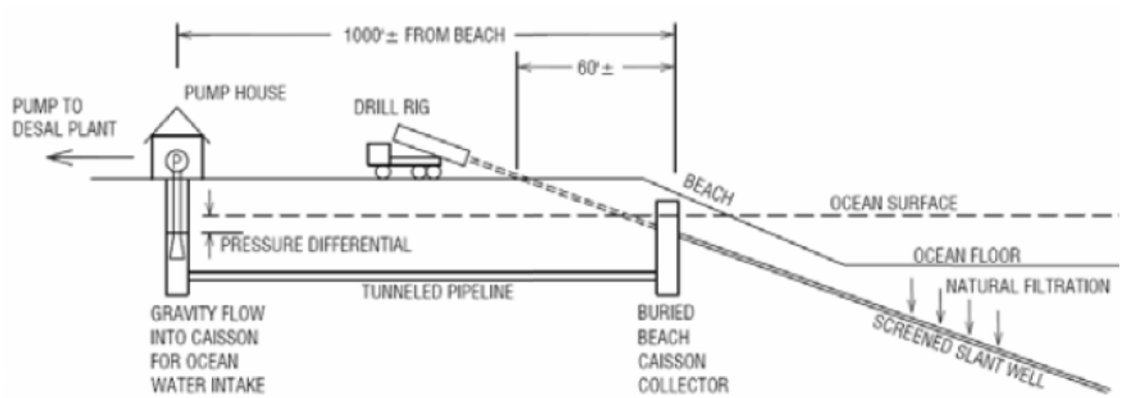
Source: WHO 2007

Figure 3.5 Horizontal beach well intake system

Slant well (or horizontal directional drilling) is a variation of vertical and horizontal well intake structures (Figure 3.6). Slant wells are subsurface intake wells drilled at an angle between 20° and 25° and extending under the seabed to maximize the collection of seawater (Poseidon Resources 2005, Pankratz 2006). The slant well intake system has the advantages of:

- Protection from shock loads
- No ocean construction impacts
- No permanent visual impacts.

MWDOC conducted a two-phased, two years hydrogeological study to investigate the feasibility of developing a full-scale seawater intake system using slant well technology for the proposed 15 mgd (56,775 m^3/d) Dana Point desalination plant (MWDOC 2007). The test slant well was drilled and constructed at an angle of 23° below horizontal, using a dual rotary drilling rig. The extensive groundwater modeling of alternative intake system capacities showed that nine slant wells (seven wells would be operational with two in rotational mode for system reliability) could provide a total volume of 30 mgd (113,550 m^3/d) (MWDOC 2007).



Source: MWDOC presentation

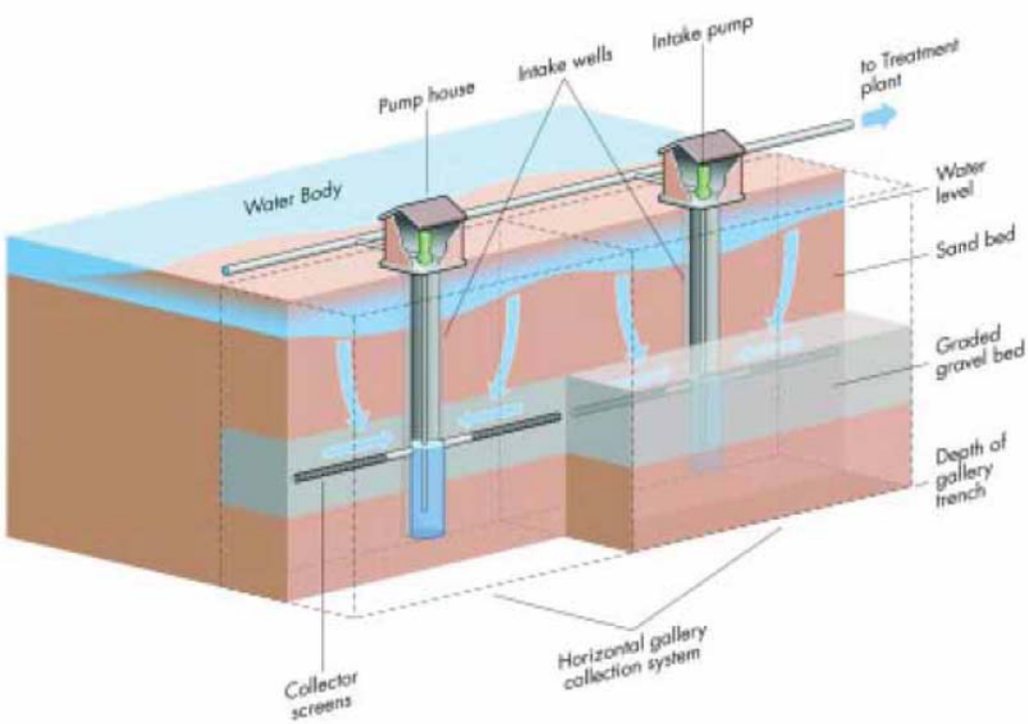
Figure 3.6 Slant well intake system

One specific type of slant well, known as Neodren technology, is based on horizontal drains consisting of patented special porous filter pipes acting as wells. They are installed in bore holes drilled by the horizontal directional drilling method in the stratum below the seabed, and are set a few meters below the ocean floor and they are several hundred meters in length. Seawater is extracted indirectly through the sub-seabed area that acts as a natural filter. The extremely low filtering velocities have negligible influence on marine flora and fauna; thus eliminating impingement and entrainment of aquatic organisms. Even during construction and installation, negative impact on the benthic environment is expected to be minimal because the working area is limited to two points with reduced space; one point is located onshore behind the beach area or further away from the coastline for the drilling rig and peripheral machinery and the second point is offshore, in the seabed, at the end of the drain (Peters and Pinto 2008, Farinãs and López 2007). The Neodren technology can be operated in sandy and karstic seabeds as an ecological and economical alternative for conventional open seawater intake systems. The first unit was in operation since 1996, and there are ten Neodren installations with a total capacity of nearly 79 mgd (300,000 m^3/d) in operation (Peters and Pinto 2008).

Slant wells may allow for larger plant capacities due to its grouping of drains, and allow for the construction of intakes at places with limited beach construction access. Its construction may also be advantageous in areas with poor seawater quality (such as at port basins, dredging areas and other permanent or seasonal problematic seawater conditions).

Infiltration Galleries

An infiltration gallery intake is a variation of the radial collector well arrangement and is used where geologic conditions are relatively impermeable or have insufficient thickness and depth to support groundwater extraction (Pankratz 2006). In these locations, it is necessary to install the radial arms and screens in a trench that is then backfilled with a gravel pack and/or selected filter materials after the screens are installed (Figure 3.7). Usually subsurface seawater intake installations consist of a submerged slow sand media filtration system located at the bottom of the ocean in the near-shore surf zone, which is connected to a series of intake wells located on the shore. The ocean floor has to be excavated to install the intake piping of the wells. Sized and configured using the same criteria as slow sand filters, these systems are constructed using several layers, including crushed stone, gravel, replaced sand, and original sand.



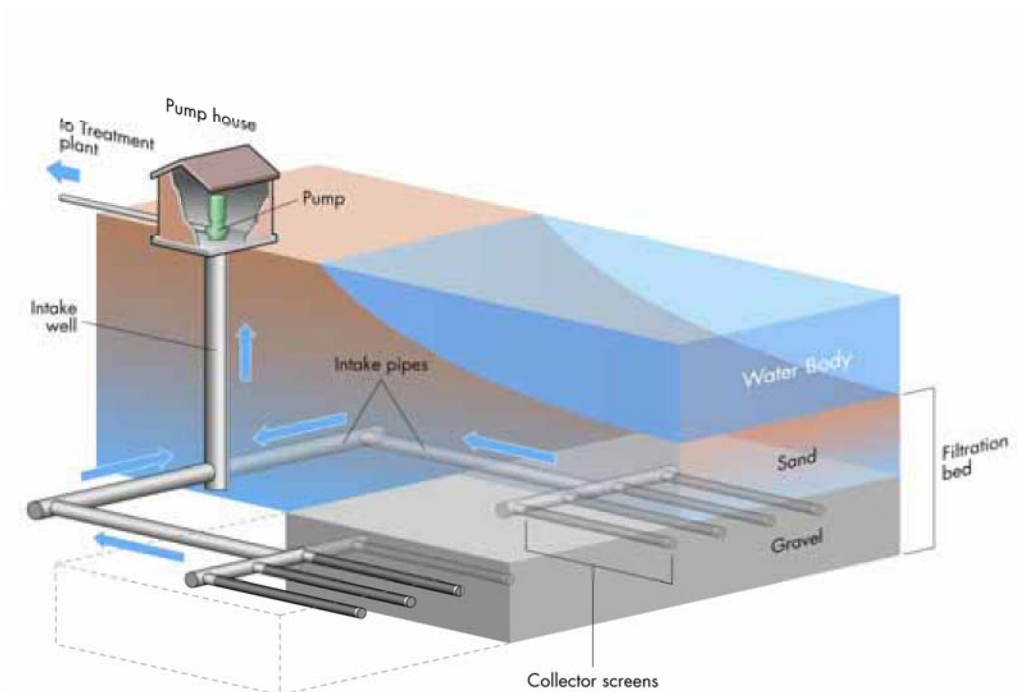
Source: Picture courtesy of Nikolay Voutchkov.

Figure 3.7 Infiltration gallery intake system

Because subsurface systems require appropriate hydrogeological conditions, a synthetic infiltration galley was developed to install seawater intakes in all coastal types (Jones 2008). It incorporates directional drilling and microtunneling, utilizing geotextiles fabrics, and relocating the subsurface reservoir onshore. In addition to the removal of suspended solids, the offshore filter media is designed to foster an environment for microbial communities to remove biologically available nutrients such as phosphorus and nitrogen compounds as well as assimilated organic carbon. The surface area of sachets is 4.9-7.4 kgal/d/ft^2 (200-300 m^3/d/m^2). The system can be backwashed by isolating sections and flushing with up to twice the infiltration rate.

Seabed Filtration Intake

Seabed filtration intake systems consist of a submerged slow sand media filtration system (filtration bed) located in the near-shore surf zone of the ocean floor (Figure 3.8). The filtration bed is connected to a series of intake wells located on the shore via tunnels or horizontal collector pipes (Figure 3.8). The filtration bed is sized and configured using the similar design criteria as these applied for slow sand water treatment plant filters. The surface filtration matt is often removed from the surface of the filtration bed by naturally occurring seasonal scouring events, such as waves and tides (Voutchkov 2005c). When the matt is removed and some of the filtration bed sand is lost over time, the sand media have to be replaced to its original depth in order to maintain filtration bed's performance efficiency. The largest seawater desalination plant with a seabed intake system currently in operation is the 13.2 mgd (50,000 m^3/d) Fukuoka District RO facility in Japan (Matsumoto et al. 2001).



Source: Picture courtesy of Nikolay Voutchkov

Figure 3.8. Seabed infiltration gallery

Long Beach Water District (LBWD) is conducting a demonstration scale testing of the seabed filtration intake system: "Under Ocean Floor Seawater Intake and Discharge Demonstration System" designed by LBWD and the U.S. Bureau of Reclamation (LBWD website). The filtration system is located just below the seabed and is designed to draw seawater for desalination feedwater through beach sand over a large enough area that the intake velocity can be low, thereby eliminating impingement and entrainment impacts that are a concern with open ocean intakes. In addition, the slow sand filtration (loading rate of less than 0.1 gallons per day per square-foot) effectively reduces organic and suspended solids in the feedwater without the use of pre-treatment chemicals. Thus, the process functions as both an intake and pretreatment system. The same sand filtering concept applies to the discharge of the brine concentrate stream, minimizing the environmental impacts of the brine plume as well. Another advantage of this "sandbox" approach is that flow rates and system operation are not affected by waves and tides. In fact, the action of waves and tides functions as a natural cleaning agent for the beach sand. The system is essentially maintenance-free system, requiring no backwashing, cleaning, treatment, recharging, and/or rehabilitation, so there are no operating and maintenance costs.

A large seabed area is required for seabed filtration because of slow filtration rate. It may result in substantial negative impact on the benthic marine communities by digging large seabed area.

Cost Comparison of Seawater Intake Types

The construction costs of subsurface intakes are site specific. Wright and Missimer (1997) compared the costs of various seawater intake and pretreatment systems serving RO desalination plants (Table 3.1). The cost relationship indicates that a beach well system is the least expensive among the alternatives, and seabed infiltration gallery is the most expensive for small desalination system. Surface water intakes are expensive because of high requirement on pretreatment (Wright and Missimer 1997). However, the feasibility of subsurface intakes depends largely on the characteristics of the associated hydrogeology and substrates, and often may not be practical for large desalination plants. Subsurface intake systems have been proven economically justifiable for seawater RO desalination plants with a capacity of up to 13 mgd (49,000 m^3/d) (Desalination Task Force 2003a). Recently, the engineering feasibility study of Dana Point desalination project estimated the construction cost for the slant wells (capacity 30 mgd, 134,000m^3/d) would be between \$19,000,000 and \$25,000,000 (MWDOC 2007).

Summary of Intake Facilities

The challenges and considerations of the two widely used types of seawater collection facilities – open and subsurface (beach well) intakes are summarized in Table 3.2.

Table 3.1
Cost comparisons of intake types serving SWRO desalination plants

Intake System		Water Supply System Capacity				
	m^3/d	2,000	4,000	7,500	15,000	30,000
	mgd	0.5	1	2	4	8
Beach Wells:						
Capital Cost Unit		1.00	1.00	1.00	1.00	1.00
O&M Cost Unit		1.00	1.00	1.00	1.00	1.00
Infiltration Gallery:						
Capital Cost Unit		1.14	1.16	1.18	1.18	1.19
O&M Cost Unit		1.00	1.00	1.00	1.00	1.00
Seabed Filtration:						
Capital Cost Unit		2.30	1.99	1.74	1.34	1.17
O&M Cost Unit		2.13	1.33	1.19	1.31	1.28
Surface Water*:						
Capital Cost Unit		1.99	1.92	1.81	1.67	1.68
O&M Cost Unit		2.00	1.29	1.14	1.27	1.21

Source: Wright and Missimer 1997.
Note: * Including pretreatment 100 μm self-cleaning filter, and mixed-media, high rate, pressure filter.

ENVIRONMENTAL CONSIDERATIONS OF FEEDWATER INTAKES AND MITIGATION STRATEGIES

Desalination intake facilities can have adverse effects on aquatic organisms. The intake system can cause various levels of impingement and entrainment that can degrade the local or regional marine ecosystem. In addition, the construction and operation of seawater intake facilities by drilling through the seafloor can have adverse impacts on benthic organisms. These adverse effects can be avoided or minimized through proper design, siting, and operation. The environmental impact of feedwater intakes on ecological environment and mitigation strategies are discussed below.

Impingement and Entrainment

Impingement is a process in which marine organisms are pulled into an intake system where they cannot escape due to high water velocities and are eventually trapped against a fish screen; this force will cause death or injury to marine organisms. Location of the intake and the water velocity greatly affect the amount of impingement that occurs. Impingement can substantially change the aquatic ecosystem (CCC 2004). Entrainment is a process in which marine organisms are killed or injured because they are too small to be filtered out of the intake screen and they proceed into the desalination process. Organisms are then killed by the high pressure and/or temperatures of the desalination process. All open intakes have some level of entrainment (CCC 2004).

Estimating the Level of Impingement and Entrainment

Estimating the ecological impacts of intake structures on fish population and other aquatic life is a complex undertaking. The impact on entrainment and impingement depends on a number of intake factors (e.g., location, design, capacity and operation) as well as factors related to the characteristics of the aquatic species themselves and the surrounding environment. In addition to obtaining reliable estimates of entrainment and impingement, there is a lack of understanding of aquatic life and fish population dynamics (Desalination Task Force 2003a).

A number of methods are used for estimating the ecological impacts due to entrainment and impingement. These methods try to forecast the consequences of losses of early life stages (larvae, juveniles) for the adult population. Methods of estimation of ecological effects due to entrainment include: the Empirical Transport Model, Fecundity Hindcast method, the Adult Equivalent Loss method, and the Proportional Mortality method (Poseidon Resources 2007b; Desalination Task Force 2003a).

The Empirical Transport Model (ETM) has been proposed by the U.S. Fish and Wildlife Service to estimate mortality rates resulting from cooling water withdrawals by power plants. It has also been the main method used in California for the past decade or so. The ETM model provides an estimate of incremental mortality (a conditional estimate in absence of other mortality imposed on local larval populations by using an empirical measure of proportional entrainment rather than relying solely on demographic calculations. The ETM permits the estimation of conditional mortality due to entrainment while accounting for the spatial and temporal variability in distribution and vulnerability of each life stage to intake withdrawals (Poseidon Resources 2007).

Poseidon Resources conducted a one-year study from June 2004 to May 2005 to assess the entrainment and impingement impact of the Carlsbad Desalination Plant (Poseidon Resources 2007a). The ETM was used to estimate the average proportional entrainment mortality of the most entrained larval fish living in Aqua Hedionda Lagoon. The average proportional entrainment mortality was estimated 12.2 percent based on the average flow of 304 mgd (104 mgd for production of 50 mgd drinking water, and 200 mgd for concentrate dilution). The total daily weight of the impinged marine organisms of the Carlsbad Desalination plant, operating on a stand-alone basis at 304 mgd is estimated at 1.92 lbs/day (0.96 kg/day). This represents 0.0000001 percent of the total volume of material flowing through the intake. The amount of impinged organisms generally varies with the amount of flow. Poseidon has proposed to install variable frequency drives (VFDs) on the intake pumps of the desalination plant intake pump station. These VFDs will allow to closely match the flow that enters into the desalination plant with the fluctuations of the drinking water demand to minimize the ecological effect of stand-alone operations of the desalination plant (Poseidon Resources 2007).

Table 3.2
Brief summary of challenges and considerations of seawater intake facilities

		Open intake	Subsurface intake
Source water quality	TDS	High and constant TDS level (vary <10% for ocean, and highly variable for estuary)	Lower TDS due to replenishment by in-land fresh and brackish water; In general TDS level is constant, but may vary in exceeding 30% of the average influenced by fresh water inflow to the coastal aquifer.
	Overall quality	Poor	Because water is pretreated via slow filtration through subsurface sand/ocean floor, water quality is better in terms of solids, silt, oil and grease, natural organic contamination, and aquatic microorganisms
	Difficult-to-treat contaminants	Typical free of endocrine disrupting and carcinogenic compounds	May contain these compounds if under the influence of contaminated groundwater
	Temperature		2 to 5°C colder than ambient ocean water, which may result in higher power demand, and elevated costs as compared to open ocean intake
	Dissolved oxygen	5-8 mg/L	<2 mg/L. RO concentrate needs reaeration to increase DO to 4-5 mg/L to meet USEPA discharge requirement to an open water body (ocean or river).
Pre-treatment		Always required	Typically simple. May require chemical conditioning and sand filtration if iron and manganese contained in intake water.
Capacity		Flexible	Based on site conditions
Site conditions		No specific requirement	Suitability is determined by the transmissivity/productivity of the off-shore and on-shore geological formations; and the thickness and configuration of the beach deposits. Beaches of shallow bays that contain significant amounts of mud/alluvial deposits and have limited natural flushing do not favor the use of beach wells.

(continued)

Table 3.2 (Continued)
Brief summary of challenges and considerations of seawater intake facilities

Environmental impact	Marine organisms	Negative impact due to entrainment and impingement, and can be minimized through appropriate siting and employing more advanced screens.	Entrainment of marine organisms is minimized. Benthic impact needs to be avoided.
	Adjacent wetlands	No impact to wetlands	If seawater intake well site is in the vicinity of existing coastal wetlands, the operation of large intake wells may result in a substantial drawdown of the groundwater table and could ultimately drain or impair the wetlands and cause significant environmental damage.
	Impacted seashore size	Less impacted (<2 acres for a 10 mgd plant)	Significantly impacted (4.2 acres might be needed for a 10 mgd plant)
	Visual impacts	Low profile structures that may blend better with the coastal environment and surroundings.	Limited visual and aesthetic appeal due to the above ground concrete structures of well collectors, pumps and service equipment. At some sites subsurface intakes can be located entirely underground or blend architecture to minimize their visual impacts
Intake useful life		30-50 years	15-20 years without major refurbishment. Beach well yield may diminish because of naturally occurring scaling of the well collectors caused by chemical precipitates or/and bacterial growth. Beach erosion may damage the well collectors and impact the useful life of the wells.
Experienced problems		Clogging and corrosion of intake screens	Improper design, faulty construction, inappropriate geological setting, particulate plugging of the overlying sediments, and geochemical plugging of the laterals.

Benthic Considerations

Another environmental consideration of feedwater intake structures is the habitat loss of the benthic organisms, which may occur due to digging trenches for intake, and the placement of intake pipelines. The excavation and installation of collecting wells, pipes, tunnels or seabed filter may result in substantial impact on the area's marine flora and fauna and on the surrounding environment including the beach. Additionally, the impact of cleaning and changing sand layers after a few years of operation on the ecosystem should be considered. Although the subsurface intake facilities can minimize impingement and entrainment, the benthic impact due to construction and operation must be assessed.

Visual and Aesthetic Concerns on Coastal Environment

As compared to open intake structure, beach well intake structures for large seawater desalination plants could have a visual and aesthetic impact on the shore line on which they are located. Typically, beach wells are often constructed as large-diameter caissons and are tall aboveground concrete structures. Pumps and service equipment are located above the wet-well of the caisson. Because beach wells are usually located close to the ocean, the well intake pumps have to be installed at an elevation that assures the protection of the pumps and associated auxiliary equipment from flooding. Therefore, the height of the structures of large intake wells with above-grade pump houses may exceed ten feet (three meters) above beach ground level. The design and construction of intake structures should minimize visual impacts, such as being located entirely underground, or blend architecture to harmonize with the coastal environment and landscape (Desalination Task Force 2003a).

Strategies for Minimization of Adverse Ecological Impacts

The adverse ecological impact of intake facilities can be minimized through appropriate location selection, improved technologies, and restoration approaches.

Location Selection

The first step to minimize adverse ecological impacts is to choose a location with relatively low conservation significance. It is proposed to use environmental assessments for site selection to avoid high-risk ecologically sensitive areas. Designers and operators want to avoid marine life as much as possible as it causes operational difficulties for the plant, so these two objectives are complementary.

Selecting and locating desalination plants where intake and outfall structures already exist for other purposes, such as power plant sites, can minimize the construction cost and environmental impact associated with construction. However, many of those existing structures were sited before there was thorough understanding of their ongoing environmental impacts, and continued use of the structures may require substantial mitigation.

Improved Technologies

Employing more advanced screening techniques and other behavior barriers can decrease the effects of impingement and entrainment of open intake facilities. The potential impingement and entrainment minimization of different technologies is summarized in Table 3.3.

Table 3.3
Potential reduction in impingement and entrainment of different technologies

Technology	Impact reduction potential	
	Impingement	Entrainment
Traveling screen with fish return	Yes	No
Fine mesh traveling screen	Yes	Yes
Fine mesh screen	Yes	Yes
Cylindrical wedge-wire screen with fine slot width	Yes	Yes
Fish barrier net	Yes	No
Aquatic filter barrier	Yes	Yes
Fine mesh dual flow screens	Yes	Yes
Modular inclined screens	Yes	No
Behavior barriers (e.g. light, sound, bubble curtain)	Maybe	No
Variable speed drives	Yes	Yes

Source: Data from Poseidon Resources 2007a.

Restoration Approaches

In addition to the technological methods to minimize the adverse impact of desalination plants on the ecosystem, environmental restoration approaches can be employed to offset unavoidable impingement and entrainment. The restoration approaches are site specific, and can include enhancement of fish hatchery, sediment restoration, and land acquisition to create conservation.

Currently, the Carlsbad desalination project is proposed to be located adjacent to the Encina Power Station, and use the power plant cooling water system as source water. If the power plant operations are discontinued or the plant intake flow is lower than the minimum flow of the desalination plant needed, the desalination plant will withdraw seawater through the existing intake and result in incremental impingement and entrainment. Based on the identified entrainment impacts, the California Coastal Commission required Poseidon Resources to restore up to 55.4 acres of estuarine wetlands to mitigate for the losses of marine organisms (Luster 2008). Poseidon has proposed restoration program that would provide additional coastal wetland to restore the habitat loss as a result of stand-alone intake facility (Poseidon Resources 2007b).

Water Quality Aspects of Open Seawater Intakes

Large desalination plants are often constructed close to large coastal cities in order to reduce the cost of pumping and long-distance transmission of treated water. In North America, the primary water quality issues for open intakes that have been encountered are algal blooms and biogrowth. Algal brooms have affected significantly the pilot testing of Carlsbad, West Basin and Affordable Desalination Corporation (ADC) SWRO projects. With the Tampa Bay

SWRO project, the proliferation of Asian green mollusks was a problem during initial operation. West Basin SWRO pilot-scale plant experienced issues with passage of larval forms of shell forming macroinvertebrates that colonized low pressure membrane systems and caused integrity issues.

Open ocean intakes are also susceptible to increased pollution loads due to urban wastewater effluents, presence of adjacent commercial harbors and ports, presence of estuaries, uncontrolled discharge, and accidental pollution from marine traffic. For example, Las Palmas Seawater Desalination Plant in the Canary Islands was commissioned in 1987 and has operated since 1989 (Farinas et al. 2005). The discharge from a co-located power plant caused clogging and elevated water temperatures in the intake basin. The discharge of untreated urban wastewater from remote residential areas contributed nutrients to the seawater catchment, resulting in total organic carbon (TOC) concentration commonly above 5 mg/L. The combined effects of sunlight, elevated temperature, and high nutrient concentrations resulted in biological and algal growth in the feed water intake. This in turn caused membrane biofouling and required frequent membrane cleanings. To control biological growth on the membranes, maintaining a residual free chlorine concentration of 1.5 mg/L was required in the intake basin. However, the highly chlorinated seawater caused severe corrosion on the steel reinforced tank and resulted in high concentration of iron in the pre-treated water. Moreover, the plant was also affected by oil spills from ships. This example indicates that unforeseen but rather common problems should be considered during plant design.

Water Quality Aspects of Subsurface Seawater Intake

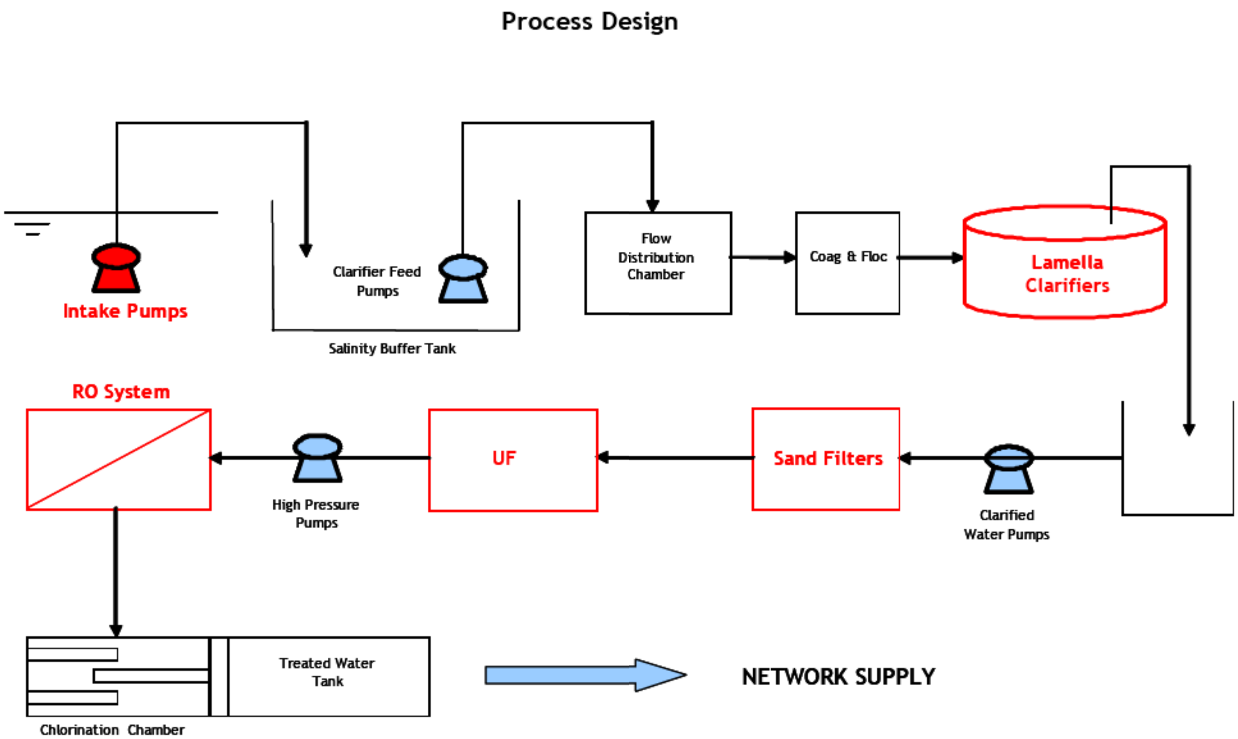
The quality of water from subsurface intakes is often superior to open intakes by reducing suspended solids, turbidity, SDI, and marine organisms. In some areas, the water quality from a subsurface intake system can however, be affected by the adjacent groundwater aquifers. For example, water abstracted from beach wells for seawater desalination in Morro Bay and in Salne Cruz, Mexico, exhibits high concentrations of manganese and/or iron caused by water contributed by adjacent aquifers (Voutchkov 2005a). The Morro Bay facility was originally designed without pre-treatment filters, which resulted in plugging of the pretreatment cartridge filters within less than an hour of starting operation in 1996. The high-iron concentration problem was resolved by the installation of a pretreatment filter. Higher concentrations of dissolved iron (1,180 to 3,800 µg/L) and manganese (1,200 to 2,100 µg/L) were also reported in the Dana Point Desalination Plant feasibility study (MWDOC 2007) during its slant well pumping test. Hydrogeological modeling showed that with extended pumping the presence of dissolved metals will be significantly reduced once the wellfield inflow reaches equilibrium and is producing mostly seawater.

PRETREATMENT OF BRACKISH WATER DESALINATION

Pre-treatment is often one of the most difficult challenges in the design and operation of a desalination facility. Most inland salt waters are enriched with calcium and depleted of sodium relative to seawater. Silica levels are often higher in inland waters. Unlike seawater, the dominant anions in inland waters tend to be sulfate and carbonate as opposed to chloride (Brady et al. 2005). The presence of trace metals such as iron, manganese, copper, aluminum, and barium can also accelerate membrane scaling (Gabelich et al. 2002a, 2006). This water chemistry implies that water recovery for inland brackish water is limited by the scaling potential of the source water.

For brackish water desalination, the selection of pretreatment processes is site specific. They may vary from minimal or no pretreatment for low turbidity and low fouling and scaling groundwater, to complex treatment trains for surface water including coagulation, flocculation, filtration, and chemical addition to prevent membrane fouling and scaling. Sixty percent of the surveyed plants use 5-micron cartridge filters to remove particles, and add acids and antiscalants to prevent membrane fouling/scaling. For groundwater with high concentrations of silica, iron, and manganese, and for surface water desalination, coagulation, flocculation, and filtration is required. Surface water desalination plants often include membrane for pretreatment, such as the Hargesheimer RO Water Treatment Plant in City of Abilene in Texas, and Thames Gateway Water Treatment Plant in UK. The schematic of the Thames Gateway desalination plant is illustrated in Figure 3.9.

The most reported problems associated with brackish water desalination are membrane scaling and fouling. Most desalination plants clean membrane annually or bi-annually triggered by increases in operating pressure. Proper pretreatment can reduce membrane-cleaning frequency and extend membrane life. General membrane lifetime for brackish water desalination is approximately five years. The Brighton desalination plant in Colorado has been operating for 16 years without replacing RO membranes. In contrast, some RO membranes lasted less than three years or experienced unacceptable scaling after installation (Alhajjy 2005, Survey Results), due to the brackish groundwater quality and inadequate pretreatment.



Source: Baldwin 2007

Figure 3.9 Schematic of the proposed Thames Gateway desalination plant

PRETREATMENT OF SEAWATER DESALINATION

Pretreatment of Subsurface Intake Water

Pretreatment for seawater desalination depends on the type of intake structures and raw water quality. The quality of water from subsurface intakes is generally better than open intakes by reducing suspended solids, turbidity and SDI, and may require minimum pretreatment. This may include simply cartridge filtration or microfiltration (MF) or ultrafiltration (UF) treatment, with pH adjustment and antiscalant addition (Figure 3.10). Water qualities from different subsurface intake systems may vary substantially, and is subject to the influence of adjacent groundwater sources. The SDI values of water from beach well were found to be very low and could meet the RO membrane SDI requirement of less than three. Feed water SDI measurements at Dana Point's test slant well were found to be below 0.58 (MWDOC 2007). Likewise, the Al-Birk SWRO plant in Saudi Arabia using vertical beach well intakes had SDI measurements below one (Jamaluddin et al. 2005). All the SWRO plants in Malta utilize beach wells for seawater intake, and cartridge filters or microfiltration for pretreatment (Jamaluddin et al. 2005, Lamendola and Tua 1995).

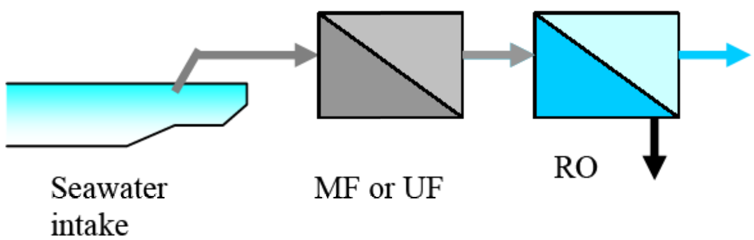


Figure 3.10 MF/UF RO pretreatment process

However, the elevated concentration of dissolved iron and manganese in subsurface intake water can complicate the selection of pretreatment. Dissolved iron and manganese can cause RO membrane scaling that is difficult to be removed, particularly if the water is exposed to any oxidizer, such as air. Permanent membrane damage can be caused by residual oxidants that might be used for iron/manganese oxidation (e.g., chlorine). A common approach for the removal of iron and manganese is oxidation followed by granular media filtration. Membrane technology using MF/UF to remove oxidized iron and manganese is also capable of providing consistent quality water to RO. Membrane technology is more operationally intensive, and has relatively higher capital and O&M costs than conventional greensand filtration (MWDOC 2007).

A seabed filtration gallery can provide consistent water quality and quantity to RO systems; however, the water quality seems inferior to beach wells. The experience of the 13.2 mgd (50,000 m^3/d) Fukuoka SWRO plant in Japan showed an SDI reduction of 1.0 to 2.5 due to its seabed filtration gallery intake; decreasing from 4.5-6.0 in its raw seawater to 3.0-4.5 in its infiltrated seawater. This SDI value was further decreased to two or less through UF treatment prior to feeding to RO units (Matsumoto et al. 2001).

Pretreatment of Open Intake Water

Conventional pretreatment is the most commonly used method for the treatment of open intake water prior to RO units. The large existing seawater desalination plants, such as Tampa Bay, Perth, and Ashkelon, employ almost exclusively conventional pre-treatment processes including coagulation with ferric chloride ($FeCl_3$) and polymer, media filtration, and cartridge filtration (Figure 3.11). The 36 mgd (136,380 m^3/d) Tuas SWRO plant in Singapore use dissolved air flotation process to enhance coagulation and improve TOC removal (Huijbregsen et al. 2005).

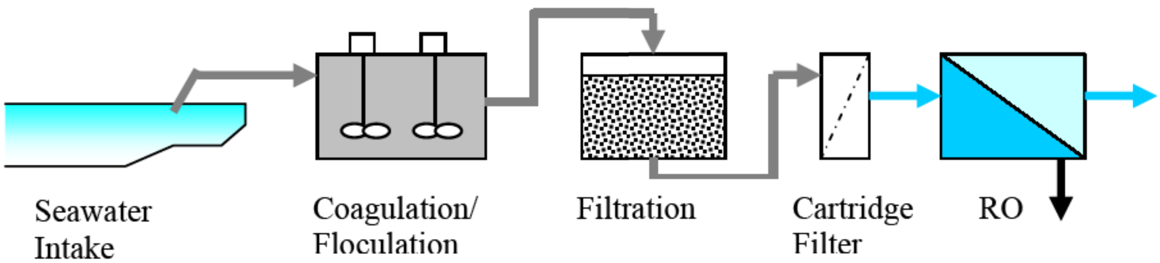


Figure 3.11 A conventional RO pretreatment process

Currently, MF or UF processes (Figure 3.10) is being tested as alternatives to conventional pretreatment for RO at several treatment plants. VanderVenter et al. (2005) compared four pretreatment options in a feasibility study for the Corpus Christi, Texas Seawater RO (SWRO) Desalination Demonstration Project. The conventional treatment process of ocean water from open intakes using rapid mixing, 2-stage flocculation, and dissolved air floatation-filtration, was ranked the highest of the four alternatives. This process provided an ease of implementation with high reliability and moderate costs. Although UF was determined to be highly reliable in terms of water quantity and quality, the high costs made this option less attractive (VanderVenter et al. 2005). In contrast, a one-year pilot study conducted by MMWD demonstrated that a MF/UF pretreatment system was better suited for treating the San Francisco Bay water compared to conventional pretreatment system. The MMWD study found the MF/UF pretreatment provided more consistent and better water quality, and reduced fouling on the SWRO membranes. Moreover, the project capital costs and O&M costs of MF/UF pretreatment are lower than conventional pretreatment (MMWD 2007a).

Membrane pretreatment has been successfully used to treat secondary effluent prior to RO for wastewater reuse at several treatment plants, including West Basin Water Recycling Plant, Orange County Water District Groundwater Replenishment System, and Scottsdale Water Campus. Although the experiences of using MF/UF in water reuse are valuable, they might not be applicable to seawater desalination directly because of differences in feedwater chemistry and composition.

Municipal wastewater effluent often exhibits high concentration of organic substances and high microbial activity. As compared to wastewater effluent, the concentration of organic substances in brackish water and seawater is much lower. However, the presence of salts in feed water decreases the stability of organic matter and bacteria, which results in deposition and adsorption of organic substances and bacteria to membrane surface. Although natural organic matter (NOM) molecules are more refractory than effluent organic matter (EfOM), the strong chemical oxidants that many utilities use as a pretreatment to membrane processing can decompose the NOM substances to biodegradable molecules, resulting in increased biofouling potential. It has been found on occasions where addition of chlorine in membrane feedwater worsened the biofouling potential for seawater and brackish water desalination (Baker and Dudley, year unknown; Winters 1997). These findings indicate the importance of defining pretreatment and biofouling strategies for seawater desalination, and extensive pilot-scale testing is required.

Pretreatment process design often relies on average source water quality taking into account the variation over several years. Unexpected events, such as the abnormal red tide event in California during the summer of 2005, can challenge and cause a complete failure of the desalination process. The Affordable Desalination Collaboration's (ADC) demonstration-scale SWRO plant (up to 0.075 mgd or 2,830 m^3/d permeate) was designed to include in-line coagulation and media filtration to produce water with turbidity and SDI values acceptable for a SWRO system (Seacord et al. 2006). The design relied on more than ten years of experience treating Pacific Ocean water from the Naval Facilities Engineering Command desalination test facility in Port Hueneme, California. Shortly after the ADC's plant was commissioned in May 2005, a red tide event occurred that was substantially worse (i.e., regarding both water quality and duration of the event) than any previously occurred event. As a result, the ADC's media filtration pretreatment was challenged to produce qualified water for its SWRO system, and the media filter differential pressure increased rapidly over the course of only two days. This made operating the SWRO equipment impractical and the ADC's equipment remained shut down until October 2005, when the red tide event ended (Seacord et al. 2006).

During the pilot testing for the proposed Carlsbad seawater desalination project, Franks et al. (2007) compared the performance of three pretreatment processes: sand filter, MF, and UF. The performance of SWRO under various conditions was evaluated using the filtrate from three pretreatment systems. During the periods of high biological activity in the raw water, heavy rain and/or algae blooms, membrane biofouling was observed regardless of pretreatment used. Though the MF membrane pretreatment produced a more consistent filtrate quality than the sand filter during challenging source water conditions when turbidity was greater than 5 NTU and TOC was greater than 2.5 mg/L, actual operation of the MF during the upsets proved more challenging due to fouling of the MF fibers (Franks et al. 2007).

Control of RO membrane biofouling is challenging for both membrane and conventional pretreatment using an open intake system. Severe membrane biofouling was observed in the 12 mgd (45,500 m^3/d) AdDur SWRO plant in Bahrain (Alawadhi et al. 2005). UF was installed after its single media filter to improve SDI of the seawater collected from open intake facility. No coagulants such as ferric chloride and polyelectrolyte were used in pretreatment. The UF pretreatment had poor removal of natural organic matter in raw seawater and the assimilable organic carbon provided substrate for biological activities on the RO membranes. Pilot testing results in parallel with the existing full-scale treatment train showed that replacing existing polyamide RO membranes with cellulose tri-acetate hollow fiber RO membranes with injection of chlorine would be one of the most effective solutions to prevent bio-fouling in RO processes under harsh seawater conditions having high biological potential (Alawadhi et al. 2005).

Severe biofouling also troubled a SWRO plant collecting water from the Red Sea using an open intake system (Jamaluddin et al. 2005). The conventional pretreatment using coarse filter, dual media filter and micro cartridge filters could not prevent membrane fouling. A sharp rise in differential pressure across membranes required frequent chemical cleaning of the membrane, and a biweekly replacement of micron cartridge filters. A beach well intake was introduced as an alternative to the open intake system. Performance and biological evaluation of the beach well showed the SDI on an average of < 1 and no biofilm formation. The change from an open intake to a beach well saved the SWRO plant from chronic fouling problems (Jamaluddin et al. 2005).

ENVIRONMENTAL CONSIDERATIONS OF PRETREATMENT AND MITIGATION STRATEGIES

Pretreatment is a major component of desalination plants. There are a number of environmental considerations associated with pretreatment. These environmental considerations are also applicable to desalination process and post-treatment.

Land Use

The land use of a desalination plant is site specific. The area required for SWRO plants is estimated approximately 2.5 acres (10,000 m^2) for 1.3-2.6 mgd (5,000 to 10,000 m^3/d) product water (UNEP 2008). Co-located desalination plants may have relatively lower land use than stand-alone desalination plants by sharing certain facilities, buildings and roads. For example, the 50 mgd (189,000 m^3/d) Carlsbad Desalination Plant will be constructed within the 95 acre Encina Power Station site. The desalination plant would occupy an approximately 4-acre parcel in the area, of which about one quarter would be required for the desalination facility and another quarter for the pretreatment area (Poseidon Resources 2005).

Construction Activities, Aesthetic Impacts and Transportation

Construction generally comprises the initial earthwork activities (site grading, excavation), the laying of foundations, construction of facilities, and landscaping measures (e.g. pavings, planting with trees, grass etc.) (UNEP 2008). The area affected depends on the size, design, and location of the facility.

Construction activities will typically involve all kinds of heavy machinery, including several bull-dozers, excavators, graders, compactors, cranes, etc., as well as forklifts, loaders, and trucks for hauling away debris and excavated soils, and delivering construction materials and plant components. It is estimated that construction of the 50 mgd (189,000 m^3/d) Carlsbad Desalination Plant will require a 24 month period when the desalination facility, the pump station, and the intake and discharge pipe-lines are constructed simultaneously (Poseidon Resources 2005). Construction activities can temporarily impair the aesthetic landscape properties and the natural scenery in the construction site and nearby areas within visual and acoustic range. Construction activities can also cause an increased volume of traffic or transportation. The impacts will vary in terms of intensity and duration depending on construction phases (day and night differences, working week *versus* weekend, busy and more quiet construction periods). The annoyance may be caused by the movements of construction machinery and increased traffic on roadways, the emissions of dust, exhaust fumes and noise, or the stockpiling of soil, debris, equipment and materials if exposed to public views (UNEP 2008).

To minimize the impacts on environment and neighboring area, the project proposer and contractor should work with the stakeholders affected by the construction to determine and implement the best management during construction. The management practices may include collaborating with city's construction inspector; avoiding all concrete washing; dumping spoils in a designated location; covering construction stockpiles to prevent blow-off or runoff during weather events; and developing a pollution control plan.

A traffic control plan should be prepared for approval by each jurisdiction within which the project is proposed to be located (Poseidon Resources 2005). The traffic associated with desalination plant and pipeline construction, including hauling of excavated soils to disposal sites, should not result in unacceptable Levels of Service during peak hour periods on affected roadways.

Chemicals Use

Considerable amount of chemicals are used in pretreatment and desalination process such as coagulation and flocculation, biogrowth control (usually by chlorination, and dechlorination with sodium bisulfate), scaling control (acid addition to lower the pH of the incoming seawater, and/or dosing of antiscalant chemicals), and membrane cleaning. Accidental spills of chemicals or the leakage of these substances may occur during delivering, handling, or from storage tanks. This may cause safety issue and contamination of local soil.

Guidance for chemical handling and safety should be developed with regard to the proper handling of chemical deliveries, security concerns, operational concerns, safety issues, and understanding of Material Safety Date Sheet. Another important consideration is the use of chemicals and formulations for pretreatment and cleaning that possess little or no environmental risk. If possible, hazardous substances that are toxic, persistent, that tend to bioaccumulate or have other adverse properties should be avoided or substituted by chemicals and pretreatment systems that minimize impacts on environment. If feasible, treatment of residual chemicals should be considered before discharge into the environment (UNEP 2008).

Waste Disposal

The wastes generated from pretreatment require proper disposal to avoid potential environmental pollution. The disposal of chemical solutions from cleaning of low pressure membranes and wash water resulting from the backwashing process is discussed in Chapter 5.
For conventional pretreatment system, the sludge (usually containing coagulant $FeCl_3$) removed through media filter beds needs to be collected and processed for landfill disposal. If cartridge filters are used in pretreatment, the spent cartridge filters need to be disposed of at a sanitary landfill.

SUMMARY

Subsurface intakes that use sand as a natural slow filter can minimize ecological impacts as a result of impingement and entrainment, and yield a highly filtered feed water compared to open water intakes. Subsurface intakes are protected from shock loading in the open ocean from red tides, oil spills, and algae growths. Subsurface intake facilities can thus reduce pretreatment requirements. The level of reduced pretreatment depends on the design of the subsurface intake system.

The feasibility of subsurface intakes however, depends largely on the characteristics of the associated site hydrogeology, and is often cost competitive only to small and medium size desalination plants. Construction of subsurface intake facilities, digging trenches and placing intake pipelines can result in substantial impact on benthic organisms. Sediment restoration may be required.

The adverse environmental effects of open intake systems can be reduced through appropriate siting of the intake, installation of variable speed drives, employing advanced screening technologies and other behavior barriers. Co-location with existing power plant and use of cooling water as feed water can avoid an additive environmental impact as long as the power plant is operating. Off-site mitigation may be required to offset unavoidable adverse impacts from the intake operation, such as fish hatchery, sediment restoration, and land acquisition to create conservation

In recent years, the use of membrane pretreatment (MF or UF) has emerged as an alternative to conventional pretreatment, including coagulation, media filtration, and cartridge filtration. In North America, the primary water quality issues for open intakes that have been encountered are algal blooms and biogrowth, which challenge the design and operation of both conventional and membrane pretreatment.

The project proposer and constructor need to coordinate with stakeholders and affected communities to develop strategies to minimize the environmental impacts associated with land use, construction activities, noise, transportation, and develop safety guidance for chemical handling and deliveries. The wastes generated from pretreatment require appropriate disposal.

CHAPTER 4
PRODUCT WATER QUALITY AND POST-TREATMENT

Membrane processes produce high quality water by removing most contaminants and impurities from the feed water. Besides regular water standards, there are increasing concerns regarding the potential presence of brominated disinfection by-products (DBPs), boron, emerging organic contaminants in product water, and side effects of highly purified water. This chapter overviews the issues related to desalinated water quality, and post-treatment needed to safeguard water quality for human health and irrigation, and integrity of distribution system.

DESALINATED WATER QUALITY

Disinfection By-products (DBPs)

Due to elevated levels of bromide in seawater, the distribution of DBPs is dominated by brominated species. Hypobromous acid (HOBr) formed during chlorination reacts with ammonia to form bromamines, which unlike chloramines, react with TOC when desalinated water is blended with surface water. It results in brominated DBPs formation and depletion of disinfectant residual. If the blending conventional water supplies contain a chloramines residual, bromide in desalinated seawater may form bromamines resulting in loss of disinfectant residual.

Due to the high molecular weight of bromide, the USEPA regulations of 0.080 mg/L for total trihalomethanes and 0.060 mg/L for five haloacetic acids in drinking water might be exceeded. The presence of iodide in seawater also exhibits a similar propensity of iodinated DBP formation as bromide. Since the TOC found in seawater could be different from TOC in conventional waters, it is probable that there would be some differences in the chemistry of the byproduct formation reactions that could lead to some different byproducts or different distributions of byproducts (WHO 2007).

Boron

Boron is a contaminant of concern for desalination of seawater and groundwater. The concentrations of boron in seawater may reach 4-5 mg/L and groundwater sources may have substantially higher concentrations than seawater. The USEPA included boron in the second Drinking Water Contaminant Candidate List, while the California Department of Public Health proposed 1 mg/L boron concentration as the action level to provide guidance to drinking water systems for unregulated contaminants (DWR 2003a). The European Union has regulated boron with a 1 mg/L guideline value in the Drinking Water Directive (Weinthal et al. 2005). The World Health Organization (WHO) guidelines for Drinking Water Quality proposed a 0.3 mg/L, later revised to 0.5 mg/L standard for boron (WHO 2006).

In addition to the impact of boron toward human health, boron is also highly toxic toward crops (Yermiyahu et al. 2007). Boron concentration above 2 mg/L is found to be toxic for all but the most tolerant crops. Orchards in Eilat, Israel observed toxic symptoms after irrigation with effluent originating from desalinated municipal water with boron concentration of approximately 1.2 mg/L. Reductions in yield in peanuts and tomatoes were observed with irrigation water containing boron concentration of 2 mg/L (Yermiyahu et al. 2007). For domestic and irrigation usage, a boron concentration of 0.2-0.3 mg/L is recommended in Israel (Yermiyahu et al. 2007).

Previous studies have shown that boron rejection by membrane processes is affected by water chemistry, including pH, TDS, temperature, membrane type, and operating conditions (e.g., recovery, permeate flux) (Busch et al. 2003, Seacord et al. 2006). Within general acidic operating conditions, boric acid exists primarily in an un-dissociated state (H_3BO_3), which results in low rejection by RO membranes. Blending RO product water with water having low boron concentrations is one option to meet acceptable boron concentrations. To achieve additional boron removal by RO or NF, several strategies are commonly employed:

- Double-pass membrane system. The permeate from the first RO/NF stage is treated by a second stage RO/NF, with or without pH adjustment, to enhance boron removal. Membrane scaling associated with high pH operation is avoided and the operating pressure is low due to purer feed water quality treated by the second pass. Currently, this is the most common practice to meet boron water quality specifications (Kabay et al. 2004, Nadav 1999, Pastor et al. 2001, Wilf and Bartels 2005, Sauvet-Goichon 2007, Gorenflo et al. 2007, MMWD 2007a). Seawater desalination plants, such as Ashkelon, employ partial double-pass RO to reduce boron in product water.
- Increasing pH to above 9.5 (optimal at 10.5). Under these conditions, most thin film composite membranes can effectively remove boron. However, at this pH, membrane scaling will be severe and frequent acid cleaning will be required. This will increase operating cost and shorten membrane lifetime.
- Using new commercial RO membranes, which are effective at boron removal. An example is the Hydranautics SWC4 RO membrane, which can meet the WHO requirement in a single pass. However, this is a very tight membrane and rejects boron by size exclusion (Redondo et al. 2003, Taniguchi et al. 2004). Therefore, this membrane requires high operating pressures.
- Using post-treatment by ion-exchange resin. This method is reported to be rather expensive (Bick and Oron 2005).

Recently the Group on Guidelines for Desalination recommended that the WHO guideline for boron in the 4th Edition be reconsidered as boron levels are quite high in seawater, and boron removal is difficult (WHO 2007a). Due to the current assessment on boron toxicity, the proposed WHO guideline value of 0.5 mg/L for drinking water will likely increase. The guideline value will remain provisional on the basis of treatment. The USEPA does not plan to regulate boron in drinking-water. A health reference level of 1.4 mg/L was calculated based on a reference dose of 0.2 mg/kg body weight per day and 20 percent relative source contribution from drinking water (WHO 2007a). As a result of new boron standard, second pass RO would not be necessary. Where desalinated water is used for agricultural, low boron product water will still be required.

Sodium Adsorption Ratio (SAR)

The application of membrane treated water for agricultural irrigation needs to consider the concentrations of sodium, calcium, and magnesium ions. Due to the greater rejection of divalent ions than monovalent ions, RO/NF permeate usually has a high sodium-to-calcium and magnesium ratio. High sodium concentrations reduce the clay-bearing soil's permeability and adversely affect the soil structure. To estimate the degree in which sodium will be adsorbed by a soil from a given source of water, the sodium adsorption ratio (SAR) is calculated (Equation 4.1)

$$SAR = \frac{Na^{+}(meq/L)}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})(meq/L)}{2}}} \qquad \text{(Equation 4.1)}$$

For sensitive fruits, the tolerance limit of SAR for irrigation water is approximately 4. For general crops, SAR of 8 to 18 is considered an acceptable level (Rowe and Abdel-Magid 1995). Without addition of hardness, membrane permeates would not be suitable for crop irrigation.

Calcium, Magnesium, and Sulfate

The side effects of highly purified water generated by desalination also include the removal of basic ions that are essential to human body and plant growth. Current Israeli drinking water standards set a minimum calcium level of 20 mg/L. The World Health Organization (WHO) recommends the following levels of calcium, magnesium, and water hardness in drinking water (WHO 2005):

- For calcium, a minimum of 20 mg/L and an optimum of about 50 (40-80) mg/L
- For magnesium, a minimum of 10 mg/L and an optimum of about 20-30 mg/L
- For total water hardness, the sum of calcium and magnesium should be 2 to 4 mmol/L.

Lacking ions such as calcium, magnesium and sulfate in irrigation water can cause deficiency symptoms in crops and may need remediation by fertilization. For example, the water from Israel's national water carrier typically contains dissolved Mg^{2+} levels of 20 to 25 mg/L, while the product water from the Ashkelon desalination plant has no Mg^{2+}. After farmers used the desalinated seawater, Mg^{2+} deficiency symptoms appeared in crops, including tomatoes, basil, and flowers, and had to be remedied by fertilization (Yermiyahu et al. 2007). Besides Ca^{2+} and Mg^{2+}, SO_4^{2-} is removed completely during the desalination process. In intensive horticulture, the average recommended SO_4^{2-} concentration in irrigation water is 58 mg/L as sulfur. Minimum concentrations are recommended even higher for tomatoes at 141 mg/L as sulfur (Yermiyahu et al. 2007).

Because desalinated water is often blending with other water sources, the concentrations of these basic ions in the final water delivered to farmers may be highly variable. If the missing ions required for agriculture are not added during the post-treatment of desalination plant, farmers will need sophisticated, independent control systems to cope with the variable water quality. Such systems can be intensive in capital investment and operation costs (Yermiyahu et al. 2007).

Based on recent Israeli experiences, Yermiyahu et al. (2007) recommend expanding water-quality parameters in desalination facilities that may supply water to farmers including: calcium 32-48 mg/L, magnesium 12-18 mg/L, and sulfate >30 mg/L as sulfur. The proposed standards are based on lessons learned during the initial operation of the Ashkelon plant and water quality guidelines that were subsequently recommended, as well as the actual agronomic consequences for local farmers (Yermiyahu et al. 2007). It should be noted that the Israeli standards are relevant for dry land regions but will probably not be cost-effective for areas where agriculture does not rely heavily on irrigation.

Algae Toxins

Coastal areas subject to algal blooms or red tides can experience algae toxins in the feed water. During algal blooms, natural toxins are produced inside the algae cells and when the cells die and decompose, the toxins are released into the water. During algal blooms, toxin levels can greatly exceed 1 µg/L (ppb). Freshwater and marine algae produce many toxins, but not all of them are of concern in drinking water. To prioritize toxins, the USEPA identified microcystin-LR, LA, RR, and YR, cylindrospermopsin, and anatoxin-a as the most important algal toxins (USEPA Website). Currently, there is no drinking water standard in the U.S. for microcystins. The USEPA's drinking water Contaminant Candidate List (2005) currently considers algae and their toxins (Cyanobacteria (blue-green algae), other freshwater algae, and their toxins) for possible future regulation (69 FR 17406). Canada, Australia, and the UK have developed a guideline value level of 1 µg/L toxin.

The removal of marine bio-toxins by SWRO was examined during the desalination pilot plant testing at the WBMWD. The testing results showed a high rejection of domoic acid from concentrations observed during the algae blooms events. Other known species observed in the Pacific Ocean including saxitoxin and anatoxin should also observe high rejection by SWRO because of their similar surface functional groups, molecular size, and charge moieties (Loveland et al. 2007).

Emerging Organic Contaminants

Source water subjected to wastewater discharge and contaminated surface run-off, may contain trace concentrations of organic contaminants including endocrine disrupting compounds, pharmaceutically active compounds, personal care products, and various industrial or household chemicals (Castle et al. 2005). The public has increasing concerns regarding the treatment efficiencies of removing these emerging compounds from drinking water. San Francisco Bay is known to contain trace levels of emerging organic contaminants (Castle et al. 2005). In the Morro Bay desalination plant, the beach well intake water was found to contain a gasoline additive, methyl tert-butyl ether (MTBE), caused by contamination from an underground gasoline tank spill (Voutchov 2005a). Similar problems were observed at the Santa Catalina Island's 0.13 mgd seawater desalination plant (Voutchov 2005a).

Recent research showed that hydrophilic ionic compounds (e.g., acidic drug residues) were efficiently removed with membranes by steric and electrostatic exclusion (Xu et al. 2005 and 2006, Drewes et al. 2005). Although there was no evidence that hydrophobic solutes such as steroid hormones partition into permeates (Drewes et al. 2005, Bellona and Drewes 2007, MMWD 2007a), the rejection of small molecular weight compounds, such as disinfection byproducts N-nitrosodimethylamine (NDMA) and chloroform, is moderate to poor (Drewes et al. 2008). Remaining concentrations of potential compounds breaching the membrane, such as NDMA, can be further treated by a number of available technologies, including activated carbon filtration, medium-pressure ultraviolet irradiation, ozonation, or advanced oxidation processes.

Corrosion Indices

Desalinated water is often corrosive and can react with household plumbing and metal fixtures; resulting in deteriorated pipes and increased metal content in the water. This reaction could result in aesthetic problems, such as bitter or flat water-taste, stains around basins/sinks, and in many cases elevated levels of toxic metals.

A number of water quality indices have been used to characterize and predict the potential of desalinated water to corrode materials used in the distribution system or home pluming units. The commonly used corrosion indices include: Langelier saturation index (LSI), Calcium carbonate precipitation potential (CCPP), aggressive index (AI), and Larson ratio (LR).

The comparison of some common calcium carbonate based indices indicated that CCPP is the best index suited to describe the corrosivity of water as opposed to other indices (Rossum and Merrill 1983). However, Singley (1981) conducted a survey of existing corrosion indices and concluded that all indices developed were based on certain simplifying assumptions that were applicable to the specific cases for which they were developed. Therefore, no single corrosion index is applicable universally. Singley (1981) recommended that a number of water quality parameters should be considered in addition to calcium carbonate solubility, including calcium, magnesium, alkalinity, carbonate, carbon dioxide, pH, chlorides, sulfates, ionic strength, conductivity, total dissolved solids, color, hydrogen sulfide, buffer capacity, phosphate, silica, dissolved oxygen, chlorine, and temperature.

Aesthetics

Blending desalinated water with other sources of water prior to introduction into distribution systems may result in compatibility problems, which may impact the aesthetic quality of the water. Because low concentrations of calcium in the desalinated water causes a "flat" taste, addition of calcium to the product water can ease the aesthetic problems and make it compatible with other waters in the distribution systems. In addition, significant removal of many constituents by RO may make the water too pure for healthy human consumption (Dickie 2007, WHO 2005). There are questions whether post treatment should also include supplementing cations commonly associated with natural waters (e.g., magnesium, potassium and other minerals important to human health) in addition to $CaCO_3$ stabilization. The new Israeli recommendations for desalinated water have included magnesium addition (Yermiyahu et al. 2007).

POST-TREATMENT, BLENDING, AND DISTRIBUTION

The goal of post-treatment is to protect public health (by disinfection and mineral addition), and to safeguard the integrity of the water distribution system (WHO 2007). The common post-treatment of both BWRO and SWRO desalination plants includes one or more of the following:

- Stabilization or recarbonation by addition of bicarbonate and carbonate alkalinity
- Remineralization by increasing mineral content by addition of those which increase the bicarbonate or carbonate alkalinity of the desalinated water
- Corrosion control

- Disinfection
- Water quality polishing by removal of specific compounds such as boron, silica, and DBPs

In some cases, one post-treatment process may achieve multiple goals. For example, the addition of calcium and magnesium salts to desalinated water may re-mineralize the water with essential elements, stabilize the product water, and protect the water distribution system against corrosion. There are various methods for achieving post-treatment goals. Usually the goal of any multi-purpose chemical addition is to minimize the dosage needed while achieving all intended purposes (WHO 2007). The choice between the different post-treatment processes is project specific and depends on issues including economics; volume of desalinated water to be treated; availability, quality and cost of locally available chemicals, and ease of operation.

Corrosion Control Methods

RO product water is highly corrosive due to low concentrations of calcium and carbonate. The acidic water has to be properly treated to prevent adverse effects to the distribution system. One possible adverse effect may be the dissolution of chemicals such as lead and copper into the water and may result in health risks to consumers.

Corrosion control is a complex science, requiring considerable knowledge of corrosion chemistry and of the system being evaluated. Corrosive water can be managed by:

- Installation of post-treatment systems
- Installation of non-conductive units
- Replacing copper piping with PVC for low-pressure piping and high molybdenum content stainless steel alloy for high-pressure piping
- Establishing a thin film of calcium or magnesium carbonate on the inside of the piping, which acts as a physiochemical barrier

Table 4.1 lists some published water quality criteria for post-treatment of soft and corrosive waters. The criteria may be used as a guide for developing post-treatment strategies.

Table 4.1
List of published water quality criteria for post-treatment of soft and corrosive waters

Location/ source	Alkalinity (mg/L as $CaCO_3$)	Ca^{2+} (mg/L as $CaCO_3$)	CCPP (mg/L as $CaCO_3$)	pH
Cape Town, South Africa[1]	>50	>50	2–5	
Cyprus[2]	>50		LSI > 0	6.5–9.5
France[3]	70<Alk<120	0.8<Ca/Alk<1.2	LSI>0	
Israel[4]	>80	80-120	3-10 LR<5	<8.5
Sweden[5]	>50	50–150	7.5–9.5	
USA[6]	>40	>40	4–10	
USA[7]	40–80	40–80	4–10	
USA[8]	>80		LSI>0	
World Health Organization[9]	≥40	Total hardness > 50	4–10 LR<5 LSI: 0.5-1.0	6.8–7.3

1. Loewenthal et al. 2004. 2. Marangou and Savvides 2001 3. Plottu-Pecheux et al. 2001. 4. Lahav and Birnhack 2007. 5. Berghult et al. 1999 6. Merrill and Sank 1977 7. Ramond 1999. 8. Imran et al. 2005a, 2005b. 9. WHO 2007

Degasification/Decarbonation

Unlike distilled water, reverse osmosis product water often has high concentration of carbonic acid, particularly where acid is fed for scale control. Packed degasification tower and tray aeration have been used to remove carbonic acid from desalinated water and obtain equilibrium with atmospheric carbon dioxide (WHO 2007). More recently hollow fiber membrane contactor has been used for degassing oxygen and carbon dioxide in pharmaceutical industries, power plants and breweries. Membrane contactors might offer a compact and clean alternative to the conventional decarbonation tower for RO product water post-treatment (http://www.liqui-cel.com/).

De-carbonation is typically used in combination with other post-treatment processes because it may be beneficial to convert some carbonic acid back to bicarbonate alkalinity. Combined use of de-carbonation with pH adjustment may be more economical because this will help control the cost of chemicals used to increase pH while still producing the desired pH, alkalinity, and CCPP (WHO 2007).

Addition of Alkalinity

Alkalinity is commonly added to help stabilize water and prevent corrosion. Alkalinity can be added through:

- Addition of caustic soda or lime to permeate containing carbonic acid:

$$2CO_2 + Ca(OH)_2 \rightarrow Ca(HCO_3)_2$$

$$CO_2 + NaOH \rightarrow NaHCO_3$$

- Addition of carbonic acid, if its concentration is not sufficient, followed by addition of caustic soda or lime
- Addition of sodium carbonate or sodium bicarbonate

Addition of Hardness

There are a variety of post-treatment methods used to add hardness back to desalinated water (WHO 2007). These may include addition of slaked lime (calcium hydroxide) to permeate water to provide calcium and alkalinity (i.e., hydroxide alkalinity) as well as to adjust product water pH. When adding lime to desalination permeate, it is important to consider that the solubility of calcium carbonate is dependent upon pH, temperature, and ionic strength.

Lime may not dissolve easily and may cause residual turbidity, which is a disadvantage of this approach. Post-treatment may require the addition of acid (e.g., H_2CO_3, H_2SO_4) to help dissolve the lime and produce the desired hardness concentration and CCPP. Warm permeate water however can slow down the rate of lime dissolution. This method is commonly used to add alkalinity to water to make it more stable and corrosion protection. Alkalinity and hardness can be added through:

- Addition of lime or contact filtration through limestone (calcite or dolomite) filters:

$$2CO_2 + CaCO_3 + H_2O \rightarrow Ca(HCO_3)_2$$

  The method theoretically requires only 50 percent of the required CO_2 quantity in the method of adding alkalinity because of the contribution of the carbonates from the limestone ($CaCO_3$). However, in practice, the CO_2 requirement of the limestone process as compared to the lime process could typically be 65-85 percent of the required CO_2 quantity used within the lime process. Disadvantages of this process compared to the alkalinity addition include a greater degree of plant and process complexity. For example, the plant items required include limestone absorption units, CO_2 desorption tower, and re-pumping chamber. In addition, lime, caustic soda or sodium carbonate dosing will be required to neutralize any excess CO_2 to attain the desired alkalinity and pH. Limestone filters have been used extensively in Europe and the Middle East. This method is also being used or tested in the USA at large desalination plants such as Tampa Bay and the MMWD pilot plant. To add hardness and produce stable product water, additional adjustments in pH, alkalinity, and CCPP are often employed in conjunction with carbonic acid addition. Limestone (calcite or dolomite) pebbles are widely used for this application. While calcite pebbles provide only calcium hardness to the water, use of dolomite contributes both calcium and magnesium, which could be an advantage if the water is used for irrigation of certain crops, or for nutrient embellishment of drinking water. Limestone filters combine two advantages: enhanced contact time and final filtration of the plant product water allowing the controllable production of low turbidity permeate (WHO 2007).
- Addition of slaked lime to provide calcium and alkalinity as well as to adjust product water pH.
- Dissolving calcite with sulfuric acid in the post-treatment stage, as employed in the Ashkelon desalination plant (Birnhack and Lahav 2007). Due to the rapid dissolution rate of calcite at low pH, only a fraction of the desalted water can be passed through

the calcite reactor (between 18% and 30% of the total flow rate of the plant, typically around 25%). This renders the reactor considerably cheaper than using CO_2 gas. In addition, SO_4^{2-} concentrations can achieve 20 to 25 mg/L as sulfur, which is similar to freshwater level, and beneficial to agricultural irrigation. However, H_2SO_4-based calcite dissolution processes result in dissolved calcium to alkalinity concentration ratios equal to, or higher than 2:1 (in equivalent units) while the alternative process, i.e. CO_2-based calcite dissolution, results in a ratio of approximately 1:1. Following the adoption of the new criteria for desalted water quality prior to release to the distribution system in Israel (see Table 4.1), dissolution of calcite via H_2SO_4 processes became impractical for future desalination plants in Israel. As an immediate result, the new Hadera desalination plant in Israel was changed to the more expensive alternative of dissolving calcite with CO_2 gas (Birnhack and Lahav 2007).

Blending with Source Water

Blending RO permeate with appropriate amounts of source water for remineralization and stabilization is a common practice for brackish water desalination. The source water should be of high quality or pretreated appropriately (at least through cartridge filters) for both microbial and chemical concerns. The blend should meet all applicable water quality standards.

Corrosion Inhibitor

Corrosion inhibitors are widely used to reduce the corrosivity of desalination plant permeate; usually after corrosion has already occurred. Phosphate and silicate inhibitors form protective films on pipe walls that limit corrosion or reduce metal solubility.

Use of corrosion inhibitors instead of alkalinity addition is often more suitable when the water distribution system is made of non-metallic piping (i.e. PVC, fiberglass or HDPE pipe). In this case, the use of corrosion inhibitors avoids the potential problems that stem from the increase in product water turbidity associated with addition of lime or other calcium-based minerals and reduce the overall chemical conditioning costs (WHO 2007).

Disinfection of Desalinated Water

Chlorine in various forms (e.g., chlorine liquid or gas; on-site sodium hypochlorite generation, calcium hypochlorite) is by far the most widely used disinfectant for desalinated water. All the desalination plants surveyed in this study exclusively use chlorine to disinfect the product.

Capital and operating costs, safety, availability of chemicals, and other issues of concern to the designer and client are used to decide the optimum solution, and all influence the selection of disinfection chemicals.

Chlorine, if available, will provide the cheapest whole life cost for the disinfection system. The choice of gas or liquid chlorine depends on issues such as the total chlorine requirement and chlorine withdrawal rate. The typical target chlorine dosage that provides adequate disinfection depends on two key factors – permeate temperature and contact time. Usually, chlorine dosage used for disinfection is 1.5 to 2.5 mg/L with 30 minutes retention time

(Withers 2005). Although very popular worldwide, the use of chlorine gas is associated with potential safety considerations concerning accidental gas releases.

The capital cost of installing on-site generation of sodium hypochlorite would be typically 25 percent more expensive than a liquid chlorine installation and up to 40 percent more expensive than a chlorine gas installation (Withers 2005). On site generation using seawater is not really suitable for disinfection of water intended for human consumption due to possible contamination of the seawater with undesirable components (Withers 2005). The use of calcium hypochlorite is not appropriate for large desalination facilities primarily because of cost factors (Withers 2005).

It is important to consider the impact of disinfection processes on finished water pH and the resultant impact to the CCPP. Chlorine gas addition decreases pH and alkalinity due to the formation of hypochlorous acid, while use of sodium hypochlorite and calcium hypochlorite increases pH and alkalinity of the product water.

Remineralization to Meet Agricultural Needs

Yermiyahu et al. (2007) compared different options for adding calcium and magnesium in desalinated water to meet agricultural needs:

- Calcium and magnesium addition to desalinated water in the form of fertilizers: cost approximately \$0.024/kgal (\$0.09/m^3) to supply calcium and magnesium at 24 mg/L and 12 mg/L, respectively.
- Direct chemical dosing: adding approximately \$0.012/kgal (\$0.045/m^3) to the overall post-treatment cost when 10 mg/L Mg^{2+} is supplied as $MgCl_2$. This also results in addition of unwanted counter anions
- Additional \$0.0026/kgal and \$0.0053/kgal (\$0.01/m^3 and \$0.02/m^3) above the cost of existing calcite dissolution by dissolving dolomite rock ($CaMg(CO_3)_2$) to meet calcium, magnesium, and alkalinity criteria. Yet there are several potential problems associated with dissolved dolomite rock, most notably the relatively slow dissolution kinetics.
- Birnhack and Lahav (2007) developed an alternative process to balance SO_4^{2-}, Ca^{2+}, Mg^{2+}, alkalinity and pH composition in desalinated water. The excess Ca^{2+} ions (generated in the common H_2SO_4-based calcite dissolution post-treatment process) are replaced with Mg^{2+} ions originating from seawater (extracted using specific ion-exchange resins). A case study showed the overall cost is \$0.011/kgal (\$0.042/m^3) as compared with \$0.007/kgal (\$0.027/m^3) estimated for the current operation in Ashkelon desalination plant and \$0.01/kgal (\$0.038/m^3) estimated for the case in which the post-treatment in the Ashkelon plant is upgraded to result in a higher buffer capacity (alkalinity value of 65 mg/L).

Considerations on Blending Desalinated Water with Other Water Sources and Distribution

Usually, blending of well stabilized desalinated water with surface water or groundwater of elevated salinity has a very positive effect on the whole quality of the water blend in terms of salinity, TOC and DBPs, and is therefore highly desirable. However, the compatibility of the various water sources has to be taken into consideration prior to their blending. Specific issues that must be investigated before blending drinking waters of various origins were discussed in the Desalination for Safe Water Supply: Guidance for the Health and Environmental Aspects Applicable to Desalination (WHO 2007). Briefly, the following should be considered:

- Propensity and types of DBP formation and concentration in the blend
- Compatibility of water quality of different water sources, such as sodium, chloride, calcium, magnesium and temperature
- Loss of disinfectant residual and calcium alkalinity during conveyance of desalinated water in long pipelines
- Chloramines have slower decay rates than free chlorine and may provide a more reliable residual in long pipelines
- Re-injection of calcium conditioning chemicals or corrosion inhibitors along the pipeline route at locations where the water LSI is reduced to a negative level may be needed to prevent corrosion occurrence

SUMMARY

As highly purified water from unconventional water sources, using desalinated water for domestic and agricultural irrigation is a relatively new practice in many regions. There are increasing concerns on the quality of desalinated water regarding disinfection byproducts, algal toxins, and the key constituents such as boron, calcium, magnesium and sulfate.

The impacts of direct use of desalinated water or changing existing water supplies by blending with desalinated water have to be taken into consideration. The formation of brominated and iodinated disinfection byproducts, loss of chlorine residual due to presence of bromide and iodide in desalinated water are challenging the conventional disinfection process using chlorine. It infers that implementation of desalination may require modification of current water management practices developed for conventional water supplies.

The common post-treatment processes for desalinated water include degassing to removal carbon dioxide, stabilization and remineralization to increase the missing mineral content and bicarbonate or carbonate alkalinity, and disinfection with chlorine. Currently the most broadly employed post-treatment is dissolving $CaCO_{3(s)}$ (typically calcite) for alkalinity and Ca^{2+} supply, followed by pH (and CCPP) adjustment using NaOH. A drawback associated with calcite dissolution processes is it does not result in the addition of magnesium ions to the water. Magnesium ions, although not included in the current desalination quality criteria, are essential micro-nutrient for both plants and human health, and might be included in future water regulations. To enhance desalinated water quality, the cost-effective addition of magnesium is required for post-treatment, in particular if the desalinated water is used for irrigation.

Desalination facilities are long-term water supply system. Selecting appropriate post-treatment technology, and ensuring the compatibility with other water sources and for various water usages are essential for integrated planning of water sources.

CHAPTER 5
MANAGEMENT OF CONCENTRATE AND OTHER TREATMENT RESIDUALS

Typical waste streams generated by membrane processes include cleaning and storage chemical solutions, and concentrated source water. Membrane processes separate feed water into a stream of product water and a stream of concentrate (brine or reject). Concentrate management and disposal is currently one of the most challenging issues associated with water desalination, especially for inland applications. The disposal method of concentrate is determined by its quantity and quality, permitting requirement, geographical and geological availability (e.g., accessibility to ocean or sewer, appropriate geology for deep well injection, availability of land uses), costs, and potential impacts on the receiving water, soil, or use. This chapter focuses on membrane concentrate management, treatment technologies, beneficial uses, and environmental considerations.

CONCENTRATE QUANTITY AND QUALITY

The quantity and quality of desalination concentrate depends on source water quality, pretreatment, membrane type, and recovery. Concentration factor (*CF*) is usually used to determine the expected strength of a concentrate stream, assuming 100 percent rejection of salts (Equation 5.1):

$$CF = \frac{1}{1-R} \qquad \text{(Equation 5.1)}$$

Where *R* is water recovery (i.e., ratio of permeate flow and feed flow).

A membrane system operating at 75 percent recovery and processing feed water with 3,000 mg/L TDS will generate concentrate that is four times more concentrated. As water recovery increases, the concentration of dissolved solids in the concentrate stream may exceed solubility, and sparingly soluble salts such as calcium carbonate, calcium sulfate, silicate, and barium sulfate will precipitate. In addition, colloids, organic matter, and bacteria can foul membrane and system surfaces, thereby reducing the process efficiency and limiting the process recovery. Typically, acid, scale inhibitors, and biocides are added to the feed in order to reduce scaling and fouling, and to enhance water recovery. In SWRO processes, another parameter that limits water recovery is the trans-membrane pressure. Because the osmotic pressure of the concentrate stream increases with increasing concentration, the required trans-membrane pressure increases in order to maintain productivity, but the pressure is limited by the design tolerances of the membrane and associated process components. The ranges of concentration factors of common desalination technologies are summarized in Table 5.1.

Commonly, the recovery of brackish water desalination is between 60 to 85 percent (Younos 2005); therefore, 15 to 40 percent of the feedwater is wasted as concentrate. Some BWRO plants operate at even lower recovery such as 50 percent due to scaling or energy saving considerations (Cress 1999). While using electrodialysis (ED) and electrodialysis reversal (EDR), recovery can increase to 90 percent depending on feed water quality.

The water recovery of SWRO varies between 30 and 60 percent. The Fukuoka SWRO desalination plant (raw water TDS 35 g/L) operates at 60 percent recovery (Matsumoto et al. 2001). Feed water to Tampa Bay Desalination Plant has an average TDS concentration of 30 g/L and the plant is operated at nearly 60 percent recovery. Feed water to the Perth Desalination Plant has TDS levels between 35 and 37 g/L, and the plant is operated at 49 percent recovery. The Ashkelon Desalination Plant has the highest feed water salinity (approximately 41 g/L TDS) and it is operated at approximately 45 percent recovery.

Table 5.1
Typical ranges of recovery and concentration factor of desalination technologies

Technology	Recovery	Concentration Factor	Relative Cost
1 SWRO	30% – 60%	1.4 – 2.5	-
2 BWRO	50% – 85%	2.5 – 6.7	Moderate
3 Emerging Technology/ Hybrid configurations*	85% – 97%	6.7 – 33.3	Low-Moderate
4 Near-ZLD	97% – 99%	33.3 – 100	High
5 ZLD	99% – 100%	>100	Very High

*Emerging technologies and hybrid configurations are discussed in section: Technologies for Water Recovery Improvement and Concentrate Volume Minimization

The low product water recovery is a big concern in the implementation of desalination. Traditional sources that have less TDS can be treated by NF/MF/UF or lime softening resulting in only about 10% water loss. For brackish water and seawater desalination substantial amount of feed water is wasted as concentrate. This is an important fact that even affects permitting of desalination facilities because raw water withdrawal volumes are a key factor for permitting.

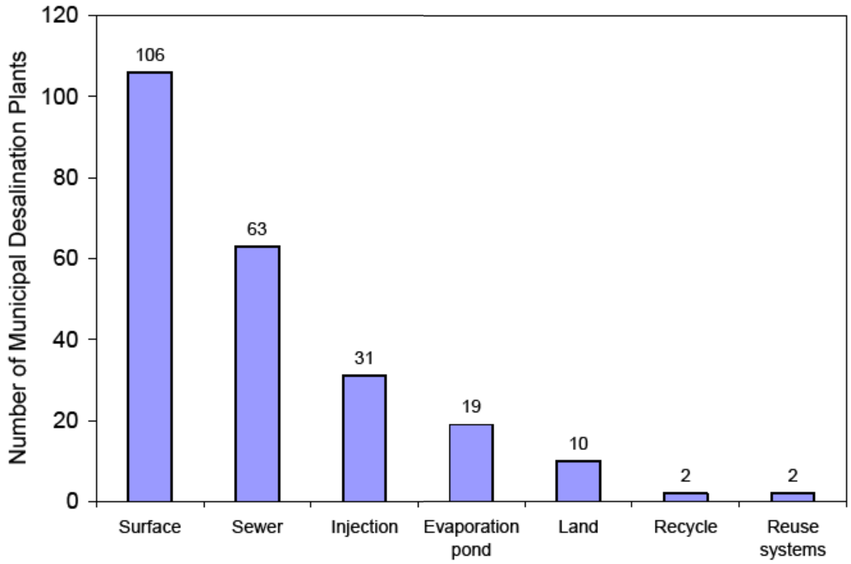
The disposal of large quantities of concentrate is not only a loss of valuable resource and energy, but also an environmental challenge, especially for inland facilities. Although several disposal methods are available, there are inherently high costs, accessibility constraints, permit challenges, and other limitations associated with all methods. The burden of concentrate management precludes the widespread use of desalination technologies for inland applications.

In addition to the natural salt concentrate from feed water, the concentrate contains the process-added chemicals such as coagulants, acids, antiscalants, scale inhibitors, and disinfectants. Heavy metals may also be introduced into concentrate due to corrosion of desalination equipment (USBOR 1998).

Depending on the quality of the concentrate and the discharge permit, discharged concentrate may need post-treatment to remove toxic constituents, adjust pH, and increase dissolved oxygen concentration by aeration. For example, the concentrates from 16 plants in Florida, Iowa, Illinois, and Missouri contain radium at high concentrations and thus would require concentrate post-treatment (Mickley 2006).

CONCENTRATE MANAGEMENT TECHNOLOGIES

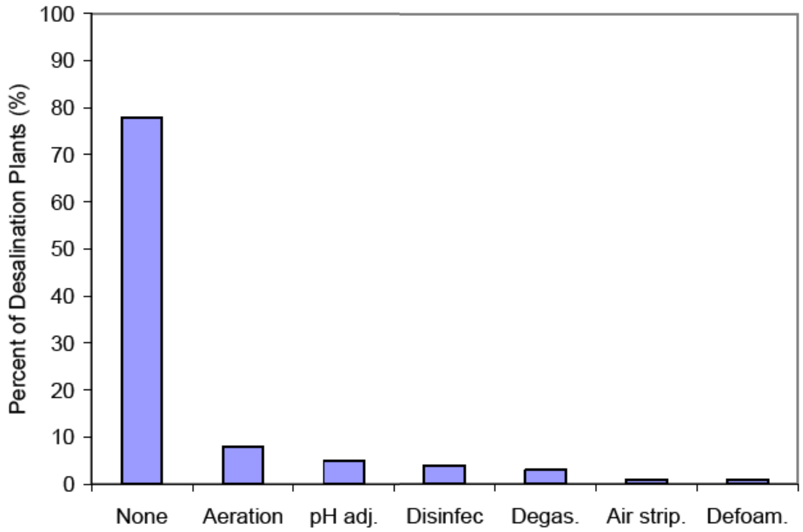
Concentrate management technologies include surface water discharge, sewer discharge, deep well injection, evaporation ponds, land application, and thermal evaporation towards zero liquid discharge or near-zero liquid discharge applications. The disposal methods of membrane concentrate for the municipal desalination plants built through 2002 in the USA is summarized in Figure 5.1 (Mickley 2006).



Source: Data from Mickley 2006.

Figure 5.1 Number of municipal desalination plants (through 2002) in the USA by concentrate disposal methods
Note: Definitions used for the disposal options are:
Surface: Discharge to any surface water requiring National Pollutant Discharge Elimination Standard-type permit.
Sewer: Discharge to the sewer or directly to the front end of a WWTP.
Injection: Injection into a deep or shallow well including for aquifer recharge.
Evaporation pond: Concentrate is impounded in a pond and gradually evaporates over time.
Land: Disposal that may influence underlying ground water such as disposal via a percolation pond, disposal via spray irrigation, or disposal via a leach field.
Recycle: Recycle of concentrate to the front of the process.
Reuse system: Further treatment of concentrate by a reuse facility.

It should be noted that close to 78 percent of total desalination treatment facilities in the U.S. dispose concentrate with no treatment (Figure 5.2). A few facilities use aeration, pH adjustment, disinfection, degassing, air stripping, and de-foaming to treat concentrate before disposal (Mickley 2006).



Source: Data from Mickley 2006.

Figure 5.2 Concentrate treatment before disposal

Surface Water Discharge

Surface water discharge is the most common concentrate disposal practice in the world and is very popular for desalination projects of all sizes. In the U.S., approximately 41 percent of desalination facilities employ this method to discharge desalination concentrate to a surface water body, including ocean, river, and estuary discharge (Mickley 2006). The discharge permits may limit the discharge loads of total suspended solids (TSS), TDS, and specific nutrients and metals (e.g., nitrogen, arsenic). Disposal costs are low if the length of the pipeline to the receiving body is relatively short and the concentrate meets the permit requirements.

Ocean Discharge

Concentrate discharged into the ocean often occurs through:

- Direct ocean discharge via a dedicated ocean outfall
- Blending with cooling water from a co-located power plant via an existing outfall
- Blending and diluting with wastewater effluent
- Discharge via beach wells
- Discharge to coastal rivers and canals

Discharge via a dedicated ocean outfall. Over 90 percent of large seawater desalination plants in operation dispose concentrates through a new ocean outfall designed specifically for that purpose (WHO 2007). The design of an ocean outfall should minimize the impact of desalination concentrate on the marine environment. Because desalination concentrate plumes have higher salinity than seawater, they are denser and have negative buoyancy, and therefore they tend to sink to the seabed. A key challenge for these ocean outfalls is to minimize the zone of elevated salinity before adequate mixing with ambient waters (Roberts et al. 1997). The outfall can be located in a tidal zone utilizing the high mixing capacity. A second option may be to discharge the concentrate beyond the tidal zone with the addition of diffusers to improve mixing (WHO 2007).

The salinity threshold mixing/transport capacity of the tidal zone and/or necessary diffuser configuration can be estimated with hydrodynamic modeling (Rhodes 2006). Two models used for salinity plume analysis are CORMIX and Visual Plumes (Voutchkov 2005b). Both models depict concentrate plume dissipation under a number of outfall and diffuser designs and operational conditions. Other modeling techniques and criteria enhancing concentrate diffusion have also been described (Roberts et al. 1997, Purnama and Al-Barwani 2004 and 2006). However, it should be noted that the science of predicting near field dilution achieved by dense fields has not been greatly studied (Khan et al. 2006).

Although the tidal zone usually provides much better mixing than that of diffuser outfall systems, tidal zones have limited capacity in transporting saline discharge load to the open ocean (WHO 2007). The mixing and transport capacity of tidal zones should be determined using hydrodynamic modeling to ensure that no excess salinity will accumulate. Such accumulation may result in salinity increments beyond the level of tolerance for the aquatic life. If the total dissolved solids discharge load is lower than the tidal zone's threshold mixing/transport capacity, then concentrate disposal to this zone is preferable and more cost effective than the use of a long open outfall equipped with a diffuser system (WHO 2007).

Small plants usually use shore discharge to take advantages of the turbulent mixing created by waves. The high mixing turbulence in these zones can dissipate the concentrate and quickly bring the discharge salinity of the small volume to ambient conditions. The desalination plants on the islands of Malta, and Santa Catalina, CA, are examples for such methods. Similarly, beach well injections are used to allow mixing with ocean water within the sand and takes advantage of wave turbulence for additional mixing (Jordahl 2006). The Marina Coastal District seawater RO plant near Monterey, CA, uses this method for concentrate disposal.

Large seawater desalination plants typically construct outfalls with diffusers beyond the tidal zone, such as in the Perth Desalination Plant in Australia. A well-designed outfall can prevent the heavy saline plumes from accumulating at the ocean bottom in the immediate vicinity of the discharge. The length, size, and configuration of the outfall and diffuser structure for a large desalination plant are typically determined based on hydrodynamic modeling for the site-specific conditions of the discharge location (WHO 2007).

The Perth desalination plant outlet is 3.94 ft (1.2 m) in diameter and has a 175 yard (160 m) long, 40-port diffuser. These ports are spaced at 16.4 ft (5 m) intervals with a 0.72 ft (0.22 m) nominal port diameter, located 0.3 mile (470 m) offshore, at a depth of 32.8 ft (10 m), adjacent to the plant in Cockburn Sound (Crisp and Rhodes 2007). The diffuser is a bifurcated double-T-arrangement and incorporates a discharge angle of 60°. This design was adopted with the expectation that the plume would rise to a height of 27.9 ft (8.5 m) before beginning to sink due to its elevated density. Extensive real-time monitoring is currently being undertaken in Cockburn Sound to ensure the model predictions are correct and that the marine habitat and fauna are protected (Rhodes 2006). This includes monitoring of dissolved oxygen levels via sensors on the bed of the sound. Visual confirmation of the plume dispersion was achieved by the use of Rhodamine dye added to the plant discharge. The experiment showed that the discharge rapidly mixed with the surrounding waters (Crisp and Rhodes 2007).

Discharge via power plant outfall (co-location). The key feature of co-location is the direct connection of the desalination plant intake and discharge facilities to the discharge outfall of an adjacently located coastal power generation plant (Voutchkov 2004). This approach allows using the power plant cooling water both as source water for the desalination plant and as a blending water to reduce the salinity of the desalination plant concentrate prior to the discharge to the ocean. In the United States, the first desalination facility built with a power station on a large scale is the Tampa Bay Seawater Desalination Plant. The Ashkelon desalination plant in Israel has used this approach to discharge RO concentrate with the cooling water from the Ruthenberg Power Plant. A dilution ratio of 1:10 is achieved (Survey Result).

There are numerous advantages in the co-location of desalination and power plants. These include (1) the capital cost savings by avoiding construction of separate intake and outfall structures; (2) reduced salinity discharge as a result of pre-dilution and mixing of the concentrates with the power plant discharge, which has ambient seawater salinity; (3) decreased power plant thermal loading on the aquatic environment because a portion of the discharge water is converted into drinking water; and (4) faster salinity and thermal dissipation from the blending of the desalination plant and the power plant discharges (Voutchkov 2005b).

For co-location to be feasible and cost-effective, the power plant cooling water discharge flow must be larger than the desalination plant capacity and the power plant outfall configuration must be adequate to avoid entrainment and recirculation of concentrate into the desalination plant intake. It is preferable that the length of the power plant outfall downstream of the desalination plant discharge is adequate to achieve complete mixing prior to discharging into the sea.

Plans for the Perth Seawater Desalination Plant were revised in 2004 to include a capacity expansion and securing location to potentially allow for co-location with the Newgen Power Station (located on the Synergy Kwinana Power Station site). However, despite the desalination plant's siting adjacent to the power station, the two plants are discretely operated with no sharing of facilities. The key reasons for this included the timing of the development of the two plants, guarantee of supply, and complexity of both operations. It was also considered that blending of discharges was not necessarily ideal because it was important to prevent the warmer cooling water (combined with the desalination concentrate) from becoming too dense and sink to the seabed (Khan et al. 2006).

Discharge via blending with wastewater. The advantage of blending brine with wastewater is the accelerated mixing that stems from blending the heavier high-salinity concentrate with the lighter low-salinity wastewater discharge. Depending on the volumes of the concentrate and wastewater streams and on how well the two streams mix prior to the point of discharge, the blending may reduce the size of the wastewater discharge plume and dilute some of its constituents. Co-discharge with the lighter-than-seawater wastewater effluent would also accelerate the dissipation of the saline plume by floating this plume upwards and expanding the ocean-water mixing-zone (WHO 2007).

Blending with treated effluent is a common practice in Florida (Mickley 2006) and is also planned by the Marin Municipal Water District (MMWD) (MMWD 2007b) for concentrate disposal. Key considerations of this method are: the availability and cost of wastewater outfalls, and the potential for whole effluent toxicity (WET) that may result from ion imbalance of the blended discharge. Bioassay tests completed on desalination plant concentrate and wastewater effluent blend from the El Estero wastewater treatment in Santa Barbara, California (Bay and Greenstein 1992/93, cited from WHO 2007) indicated that its blend can exhibit toxicity on fertilized sea urchin (Strongylocentrotus purpuratus) eggs. Parallel tests on desalination plant concentrate diluted to similar TDS concentration with seawater rather than wastewater effluent did not show such toxicity effects on sea urchins. Long-term exposure of red sea urchins on the blend of concentrate and ambient seawater confirm the fact that sea urchins can survive elevated salinity conditions when the discharge is not mixed with wastewater. Thus, the wastewater component is the critical issue.

The most likely factor causing the toxicity effect on the sensitive marine species is the difference in ratios between the major ions (calcium, magnesium, sodium, chloride, and sulfate) and TDS that occurs in the wastewater effluent-concentrate blend (WHO 2007). Wastewater effluent has fresh water origin, and often has very different ratios of key ions (Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-} and SO_4^{2-}) to TDS. Blending this effluent with seawater concentrate may yield a discharge which has ratios of the key ions to TDS significantly different from these of the ambient seawater. Changes in the concentration or composition of ions, particularly over long periods of time, can cause chronic stress affecting important functions of an organism such as growth and reproduction. Sudden changes in ion concentration or composition can result in death (SETAC 2004).

These findings clearly indicate that introducing extra wastewater effluent to receiving waters by blending with desalination plant concentrate may have negative effects on some aquatic species. However, blending desalination concentrate with wastewater effluent that is being discharged into the ocean may correct the ion imbalance problem, increasing mixing/dilution, and mitigate the adverse ecological impact. For instance, the MMWD proposes to blend the concentrate discharge from its desalination plant with freshwater effluent that is being discharged into San Francisco Bay through the Central Marin Sanitation Agency (CMSA) deepwater outfall. CMSA operates a wastewater treatment plant and discharges its effluent through a 1,050 ft (320 m) long diffuser to the Bay. The CMSA effluent consists mainly of fresh water and its flow rate ranges roughly from 2 to 40 mgd (7,570 to 151,400 m^3/d), following both seasonal and diurnal patterns. Since the diffuser's hydraulic capacity is 125 mgd (473,000 m^3/d), its capacity allows a co-discharge of additional 15 mgd (56,800 m^3/d) desalination concentrate. This blending solution could have a net environmental benefit by raising the salinity of the CMSA outfall to match the receiving waters of San Francisco Bay (MMWD 2007b). Hydrological modeling indicated a sufficient mixing in the local discharge area. Both acute and chronic bioassay tests using blended desalination concentrate/CMSA effluent showed no significant affects on the tested marine organisms.

Another concern that may restrict the discharge via blending through treated sewage outfalls is a likely reduction in the volume of sewage discharges as wastewater recycling becomes more prevalent. In general, most communities have implemented all feasible conservation and water recycling before embarking on desalination. This reduces the risk of running out of wastewater for blending in the future. For example, the MMWD has a comprehensive conservation and recycling program. The treated wastewater from the CMSA that is proposed for blending with desalination concentrate is not suited for landscape irrigation because of widespread saltwater intrusion into the sewer system. The most economical and practical use of this effluent in MMWD's setting is to use the effluent to dilute the desalination concentrate (Castle 2008).

Discharge via subsurface discharge facilities. Beach well injection is a new discharge technology. Beach wells are used to allow mixing with ocean water within the sand and takes advantage of turbulence from wave action for additional mixing (Jordahl 2006). The Marina

Coastal District seawater RO plant near Monterey, California, used this method for concentrate disposal (Campbell and Jones 2005). This involved injecting the brine (TDS 43 g/L) into a shallow dune sand aquifer via a conventional well. The brine was blended with native groundwater and ultimately diffused into the turbulent surf zone. A year of physical monitoring of the sea near the discharge point observed no identified impacts on benthic life (Campbell and Jones 2005). However, discharge through the beach well was eventually discontinued due to severe scaling problems (Voutchkov 2006).

A recent study conducted in Spain suggests that actual dilution of the brine from a beach-discharge outfall may be lower than normally expected (Fernandez-Torquemada et al. 2005). Elevated salinity was reported in deep localities several kilometers from the discharge point.

Currently Long Beach Water District (LBWD website) is testing seabed filtration system for seawater intake and concentrate discharge.

Discharge to coastal rivers and canals. In addition to direct ocean discharge, some coastal RO facilities discharge concentrate to nearby rivers or canals that lead to the sea. Facilities in Virginia near Chesapeake Bay discharge concentrate to Elizabeth River. Likewise, facilities in Florida discharge concentrate to Indian River estuaries or to brackish canals that feed it (Jordahl 2006). The Javea desalination plant on the Mediterranean coast of Spain discharges concentrate to a canal (Malfeito et al. 2005). The reported benefits include the input of saline water to the canal to bring the density and temperature more inline with that of seawater before it reaches the sea. This effect has been enhanced by the incorporation of a novel concentrate dilution system (Malfeito et al. 2005).

Surface Discharge in Inland Areas

For inland areas, the concentrate can be discharged to surface water bodies (e.g., rivers and lakes) if they are available. The desalination plants in Colorado discharge the RO concentrate into the South Platte River and Arkansas River, which are located close to their respective plants. However the discharge of high salinity and more contaminated concentrate to surface water may cause the degradation of receiving water bodies. New regulation may impact existing discharge limits and it is a matter of time before new and current discharges will be severely restricted if not prohibited (CWQCC 2006). These inland desalination plants are actively seeking solutions to meet the new discharge standards.

Sewer Discharge of Brackish Water Concentrate

Discharge of concentrate to an existing sewer system is one of the most widely used concentrate disposal practice for brackish water desalination plants. This method is employed by approximately 31 percent of all desalting facilities in the U.S. (Mickley 2006). For example, the desalination plants in Cities of Scottsdale and Goodyear in Arizona both discharge RO concentrate to the sewer. The sewer discharge requires a permit from the local sanitation agency because of the potential negative effects of the concentrate's high TDS content on the wastewater treatment plant operations. The permit may impose some discharge limits in order to protect sewer lines and treatment plant infrastructure, wastewater treatment processes (mainly biological), and final effluent and biosolid quality. Discharge of small volumes of concentrate to sewer systems is more economical and may have only limited permitting requirements. Some regions have installed regional interceptors or "brine lines." A regional interceptor is used specifically to collect streams (which can include concentrate) from multiple dischargers. An example is the Santa Ana Regional Interceptor (SARI) in Southern California, which consists of over 90 miles (145 km) of pipeline (Jordahl 2006).

The feasibility of this disposal method is limited by the hydraulic capacity of the wastewater collection system and by the treatment capacity of the wastewater treatment plant receiving the discharge. Typically, a wastewater treatment plant's biological treatment process is inhibited by high salinity when the plant influent TDS concentration exceeds 3,000 mg/L (WHO 2007). If the effluent from the wastewater treatment plant is designated for water reuse, the amount of concentrate that can be accepted by the wastewater treatment plant is limited not only by the concentrate salinity, but also by the content of sodium, chlorides, boron, and bromides in the blend. All of these constituents could have a profound adverse effect on the reclaimed water quality, especially if the effluent is used for irrigation.

Deep Well Injection of Brackish Water Concentrate

Deep well injection (DWI) or subsurface injection involves the disposal of concentrate into a deep geological formation, which permanently isolate the concentrate from shallower aquifers that may be used as a source of drinking water. Regulatory considerations include the transmissivity of the receiving aquifer, the TDS, and the presence of structurally isolating and confining layers between the receiving aquifer and any overlying potable aquifers. Approximately 17 percent of all treatment plants in the U.S. inject concentrate into deep or shallow wells and some for the purpose of aquifer recharge (Mickley 2006). DWI is typically expensive and employed only for larger concentrate flows (> 1 mgd) and thus commonly used for larger RO plants.

Deep well injection has been widely used for disposal of desalination concentrate in Florida, and more recently in El Paso, Texas, which have some of the best geologic formations to support deep well injection (Mickley 2006, Hutchison 2007).

Deep well injection is limited to site-specific conditions of confined aquifers with large storage capacity and good soil transmissivity (Mickley 2006). DWI is not feasible for areas of elevated seismic activity or near geologic faults that can provide direct hydraulic connections between the discharge aquifer and a water supply aquifer. The permit for DWI is becoming more stringent because of the potential of leakage from the wells. If the injection aquifer is not adequately separated from the water supply aquifer in the area, the groundwater supply may be contaminated by the injected concentrated pollutants. The injection wells may also experience potential scaling and decrease of well discharge capacity over time (WHO 2007).

Evaporation Ponds of Brackish Water Concentrate

Approximately 2 percent of all desalination plants in the U.S. use evaporation ponds for concentrate disposal (Mickley 2006). In this method, the concentrate is pumped into a lined, shallow pond and evaporated naturally using solar energy. After the water evaporates, the salt sludge is either left in place or removed and hauled offsite for disposal. Evaporation ponds can be a viable solution in relatively warm and dry areas and where land is inexpensive. They are typically economical and employed only for smaller concentrate flows. Regulatory requirements, ecological impacts, and possible concentration of trace elements to toxic levels may determine the design, construction, and operation of evaporation ponds. Discharge to evaporation ponds requires a large footprint and may not be possible for many developed and urban areas.

Due to the high evaporation rate and readily available land, the primary concentrate disposal method in Nevada is evaporation (Jordahl 2006). A zero discharge permit is required for desalination plants from the Nevada Division of Environmental Protection (Jordahl 2006). Limitations to the applicability of evaporation ponds include the need for large areas of land in regions where the evaporation rate is low compared to the concentrate production rate. Furthermore, poorly designed or constructed ponds may risk contamination of underlying aquifers by seepage. In most cases, impervious layers of clay or synthetic membranes are required to prevent loss by seepage. While maintenance needs can be relatively minor, the need for active erosion control, seepage control and wildlife management should be considered in all cases.

Land Application of Brackish Water Concentrate

Land application, such as spray irrigation, is a beneficial reuse of concentrate. It can be used for lawns, parks, golf courses, or crops. Approximately 2 percent of total desalination plants in the U.S. use land applications in the form of percolation ponds, spray irrigation, or a leach field (Mickley 2006). Land application depends on the availability and cost of land, irrigation needs, water quality, tolerance of target vegetation to salinity, percolation rates, and the ability to meet ground water quality standards.

Land application may have a negative impact on any groundwater aquifers beneath the irrigated area, especially if the concentrate contains arsenic, nitrates, metals, or other regulated contaminants. An early case study from India indicated that the concentrate discharged to an earthen canal resulted in contamination of the desalination source well leading to increased salinity and hardness (Rao et al. 1990). Concentrate discharge to soils can also have detrimental effects on soil productivity (Mohamed et al. 2005).

A large number of inland brackish water desalination plants were recently surveyed in the United Arab Emerites (Mohamed et al. 2005). Some of these are mobile and some are stationary; all of them discharge concentrate to land via unlined pits. Sampling at these sites has revealed that discharged concentrate is commonly contaminating local groundwater.

Zero Liquid Discharge

Zero liquid discharge (ZLD) technologies have only been used in extreme conditions where no other concentrate disposal method is available. The technology involves brine concentrators, crystallizers, or spray dryers that convert concentrate to highly purified water and solid dry product suitable for landfill disposal or perhaps recovery of useful salts (WHO 2007). ZLD requires significant capital costs, high energy consumption, and potential high cost related to final brine or salt disposal. However, ZLD can avoid a lengthy and tedious permitting process for concentrate disposal and gain quick community acceptance (Mickley 2006).

Brine Concentrators (Vapor Compression Evaporator Systems)

Concentrators are single-effect thermal evaporator systems in which the vapor produced from boiling concentrate is pressurized by a vapor compressor. The compressed vapor is then recirculated for more vapor production from the concentrate. Product water quality is normally less than 10 mg/L TDS. Brine reject from the concentrator typically ranges between two to ten percent of the feedwater flow, with TDS concentrations as high as 250,000 mg/L (Mickley 2006). Ultimately, the concentrated salt product could be designated for commercial applications.

Vapor compression processes are well established and have been used for seawater desalination as well as treating RO concentrate in a near-ZLD application (Bryant et al. 1987, Turek 2004, WHO 2007, Mickley 2006). Brine concentrator technology was developed in the early 1970s to help thermal power stations achieve zero discharge of wastewater. For example, brine concentrators (vapor compression evaporators operating with seed recycle) are used in Australia to treat RO concentrate from cooling tower blowdown to achieve ZLD in power plants (Bryant et al. 1987). At present, approximately 75 brine concentrators are in operation in the United States and overseas. Of these, approximately a dozen are being used to concentrate reject streams from industrial RO plants. The operating experiences of these plants have shown that using brine concentrator evaporators on RO concentrate is a viable application and that the systems are highly reliable. Many operating systems have achieved on-stream operating availabilities greater than 90 percent over an extended period of years (Mickley 2006).

Individual brine concentrator units range in capacity from approximately 0.014 to 1 mgd (54.5 to 3,785 m^3/d) of feed water flow. Units below 0.22 mgd (830 m^3/d) of capacity are usually skid mounted, and larger units are field fabricated. A majority of operating brine concentrators is single-effect, vertical tube, falling film evaporators that use a calcium sulfate-seeded slurry process.

Crystallizers

For RO concentrate disposal, crystallizers would normally be operated with a brine concentrator evaporator to reduce brine concentrator blowdown to a transportable solid. Crystallizers can be used to concentrate RO reject directly, but their capital cost and energy usage is much higher than for a brine concentrator of equivalent capacity. Crystallizer technology is especially applicable in areas where solar evaporation pond construction cost is high, solar evaporation rates are negative, or deep well disposal is costly, geologically not feasible, or not permitted (Mickely 2006).

Crystallizer technology has been used for many years to concentrate feed streams in industrial processes. Crystallizers used for wastewater disposal range in capacity from approximately 0.003 to 0.072 mgd (11 to 273 m^3/d). The crystallization vessels are vertical units operated using steam supplied by a package boiler or heat provided by vacuum compressors for evaporation. The mineral cake removed from the concentrate contains 85 percent solids that readily can be transported for land disposal. The energy requirement for concentrate evaporation and crystallization is high (100 to 250 kWh/kgal, or 26.4 to 66.1 kWh/m^3) (Mickely 2006).

Spray Dryers

Spray dryers provide an alternative to crystallizers for concentration of wastewater brines to dryness. Spray dryers are generally more cost effective for smaller feed flows of less than 0.014 mgd (53 m^3/d) (Mickely 2006).

Spray dryer technology for wastewater concentration was developed in the early 1980s. Like crystallizers, spray dryers offer an alternative to evaporation ponds, percolation ponds, and deep well disposal for RO concentrate disposal. For such applications, spray dryers are usually operated in conjunction with brine concentrator evaporators for feedwater flows up to 0.014 mgd (53 m^3/d). If the RO concentrate stream ranges from 0.001 to 0.014 mgd (5.3 to 53 m^3/d), spray dryers can be cost effective when applied directly to the stream, thus eliminating the brine concentrator evaporator (Mickley 2006).

MANAGEMENT OF CLEANING AND WASTESTREAM HANDLING AND TREATMENT

Chemical Cleaning Solutions

Most desalination plants perform chemical cleaning with median cleaning frequency of twice a year to ensure product water quantity. Chemical cleaning solutions usually contain acids, alkaline, and complexing agent (such as ethylenediamine tetraacetic acid (EDTA), dispersants, or surfactants) (Jordahl 2006). Cleaning solutions for ED/EDR may include chlorine for treating biofilms or other organic contaminants. Cleaning solutions represent less than 0.1 percent of the feed flow; small volumes of spent cleaning solutions are generated every three to 12 months (AWWA 2004, Malmrose 2005).

Typically, cleaning solutions are either blended with concentrate (using the same discharge method) or discharged separately to the sewer (Mickley 2006). Table 5.2 summarizes the disposal methods and treatment of spent cleaning solutions generated in 110 desalination plants in the US (Mickley 2006).

Table 5.2
Disposal of waste cleaning solutions of the desalination plants in the USA

No. of plants	Percent	Disposal Method	Treatment prior disposal
67	61	Sewer disposal	14 with pH adjustment
24	22	Surface water disposal	9 with pH adjustment; 1 of these with settling; 2 to dry tributaries
8	7	Land disposal	7 lagoons (1 with pH adjustment) 1 spray irrigation
7	6	Well injection	1 with pH adjustment
2	2	Evaporation pond disposal	1 with pH adjustment
1	1	Recycling	After pH adjustment
1	1	Hauling	

Source: Data from Mickley 2006.

Waste Stream Handling and Treatment

Wastes such as backwash solutions from media filters or MF/UF need to be treated before blending with membrane concentrate and discharging. Significant suspended solids are present in the filter backwash water. Coagulants such as ferric chloride, ferric sulfate or aluminum sulfate are sometimes used in the pre-treatment process to reduce silt derived from organics, small colloids and other suspended material. These flocculants form flocs of ferric oxyhydroxide (or aluminum hydroxide), which are washed from media filters, cartridge filters, MF, or UF membrane units in the filter backwash.

In most cases, the filter backwash water is settled prior to removal and the sludge that contains the vast majority of the coagulant is either disposed of to the sewer or dewatered and disposed of to a landfill as solid waste. If the filter backwash water is discharged without treatment, ferric oxyhydroxide floc may settle on the seabed or, more likely, be dispersed (Khan et al. 2006).

Typical pretreatment usually consists of total suspended solid removal such as through a settling tank. The Carlsbad desalination plant for example, will either recycle the settled filter backwash water to the inlet of the desalination plant, upstream of the pretreatment filters, or will discharge it to the ocean via the concentrate disposal pipeline (Poseidon Resources 2005).

For deep well injection, cartridge filters may be required to remove particles as down to five microns to avoid clogging the receiving formation. Depending upon the specific characteristics of the wastewater and receiving formation water, pH adjustment may also be necessary. When pH is adjusted, scale formation can be minimized with two incompatible waters.

COSTS FACTORS OF CONCENTRATE DISPOSAL

In addition to being site specific, concentrate disposal is a major factor in desalination costs. The costs of concentrate disposal depend on site characteristics (geologic features, soil conditions, proximity to potential disposal site), concentrate flow, regulatory requirements, public approval, and the type of concentrate disposal methods. Based on those limitations, concentrate disposal cost can range from 5 to 33 percent of the product water cost (Tsiourtis 2001). Cost estimates of some disposal options are shown in Table 5.3.

Cost of Surface Disposal

In general, surface water disposal is the most common and least expensive option. The costs for surface water discharge are site specific, and mainly determined by (Mickley 2006):

- Concentrate conveyance costs from the desalination membrane plant to the surface water discharge outfall. The costs are typically closely related to the concentrate volume and the distance between the desalination membrane plant and the discharge outfall.
- Costs for outfall construction and operation. The costs depend on the outfall size, diffuser system configuration, outfall length and material, and concentrate treatment prior to discharge.
- Costs associated with monitoring environmental effects of concentrate discharge to surface waters. The costs associated with environmental monitoring of surface water discharge may be substantial, especially if the discharge is in the vicinity of an impaired water body, in an environmentally sensitive area, or in areas with limited natural flushing.

Cost of Sewer Disposal

The second most common and economical concentrate disposal method is discharge of concentrate to an existing wastewater treatment plant (sewer disposal). Sanitary sewer discharge conditions are usually very site specific and the key cost elements for this disposal method are the cost of conveyance (pump station and pipeline), fees for connecting to the sanitary sewer, and for treatment/disposal of the concentrate at the wastewater treatment plant. While the volume of the concentrate mainly drives the conveyance costs, the sewer connection and treatment fees can vary substantial. The town of Julesburg in Colorado built a $2.5 million brackish water RO treatment plant to treat groundwater with high nitrate concentration. In addition, the town also had to construct a $1.7 million sewer plant to treat its RO concentrate water (Energy Services Bulletin 2004).

The disposal cost to a brine interceptor or wastewater treatment plant may increase considerably if the available treatment capacity is reached. Currently, the RO concentrates from the Menifee and Perris I Desalter plants of Eastern Municipal Water District (EMWD) are disposed via a 22-mile-long (35 km) Temescal Valley Regional Interceptor line, a non-reclaimable waste pipeline connecting EMWD to the Santa Ana Regional Interceptor (SARI) line. The disposal cost of $36,600,000 ($28,800,000 for SARI, treatment & disposal cost; and $7,800,000 to reach four brine lines) accounts for 25.5 percent of the total desalination program costs ($143,400,000) (Survey results). The desalination concentrate disposed into the SARI line is transported and blended with wastewater at the Orange County Sanitation District Plant No.2 for secondary treatment and then ultimately discharged to the ocean. A third desalination plant (Perris II Desalter), with three more extraction wells, is under design. These three desalination plants will ultimately produce concentrates in excess of EMWD's permitted capacity in the SARI line. The Santa Ana Watershed Project Authority has indicated that there is no available capacity for purchase in the SARI system, and the cost of treatment and disposal is expected to increase exponentially in the future.

As a result, EMWD has decided to further investigate recovering drinking water from the primary RO brine stream and converting the entire system to zero-liquid discharge (ZLD). The project evaluated five promising technologies that, individually or in combination, could act as an intermediate brine treatment step to further concentrate the existing brine and recover more potable water at a lower cost. This study involved desktop modeling and bench-scale testing to evaluate individual technologies, and combinations of technologies, from which the most appropriate treatment combination could be selected by EMWD for potential testing (EMWD and Carollo Engineers 2008). The least expensive alternative evaluated was Primary RO + Softening + Electrodialysis reversal (EDR) + Brine concentrator + Evaporation pond-disposal. The treatment costs for secondary RO and EDR were nearly equivalent. For inland communities where access to the sewer line is not a viable option, brine minimization by brine concentrators and further crystallization prior to landfill are comparable to thermal evaporation ponds. Although the capital costs of Brine concentrator + Crystallizer are more expensive than evaporation ponds, operation and maintenance (O&M) costs for the Brine concentrator + Crystallizer alternatives are slightly cheaper. Evaporation pond, however, occupies substantial land, as much as 12 acres for the proposed treatment alternatives.

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Cost of Deep Well Injection

The costs of deep well injection strongly depend on the depth of the well, the diameter of well tubing, and casing rings. Because injection wells are costly and less suitable to be expanded after they are built, they are frequently designed for a much larger capacity than immediately required. In practice, the well costs do not necessarily correlate with the concentrate flow level. Other factors that influence deep well injection costs are (1) the need for concentrate pretreatment prior to disposal; (2) pump size and pressure which vary depending on the geological conditions and depth of the injection zone; (3) environmental monitoring well system size and configuration; and (4) site preparation, mobilization and demobilization (Mickley 2006). Cost estimates for deep well injection are shown in Table 5.3.

Cost of Evaporation

Evaporation is a land intensive disposal technology. The capital costs depend on the land area required, which is determined by the concentrate flow and the net evaporation rate. Costs for the evaporation pond disposal option associated with land purchase and clearing can be substantial (Mickley 2006). The cost estimate for evaporation ponds is shown in Table 5.3.

Cost of Spray Irrigation

Spray irrigation is possible only if the concentrate meets groundwater compatibility limits and a level acceptable for crops/vegetation irrigation. The key cost factors of this disposal method include the cost of land, the storage and distribution system, dilution water, and irrigation system installation, which in turn are driven by the concentrate volume and salinity (Mickley 2006). The cost estimates for spray irrigation are shown in Table 5.3.

Cost of Zero Liquid Discharge

The zero liquid discharge (ZLD) approach is often the most expensive option for concentrate disposal because it requires the use of costly mechanical equipment for evaporation, crystallization, and concentration (dewatering) of the salts in the concentrate. Energy costs associated with the evaporation processing are significant. Mickley (2006) estimated the annual costs as a function of electricity and brine concentrator rejection level. The rejection level has only a small effect on the cost, while both flow and cost of electricity have major effects (Table 5.3).

Table 5.3
Cost estimate of concentrate disposal methods (in 1000 US$)

	Depth of deep well (ft)			Evaporation*[1]		Loading of spray Irrigation*		ZLD		
Concentrate Flow (mgd)	500	5,000	10,000	4-ft dike height 20 mil[3] thickness	12-ft dike height 120 mil[3] thickness	5-ft/yr	20-ft/yr	Energy cost[2] ($/KW/h)	2% rejection	10% rejection
0.5	819	4,212	7,982	1,419	6,578	569	163	5	800	1,102
1.0	964	4,359	8,127	Area larger than 100 acres		1,151	744	5	2,818	3,120
2.0	1,256	4,650	8,419			2,313	1,907	5	6,854	7,155
0.5								20	5,089	5,390
1.0								20	7,107	7,408
2.0								20	11,142	11,444

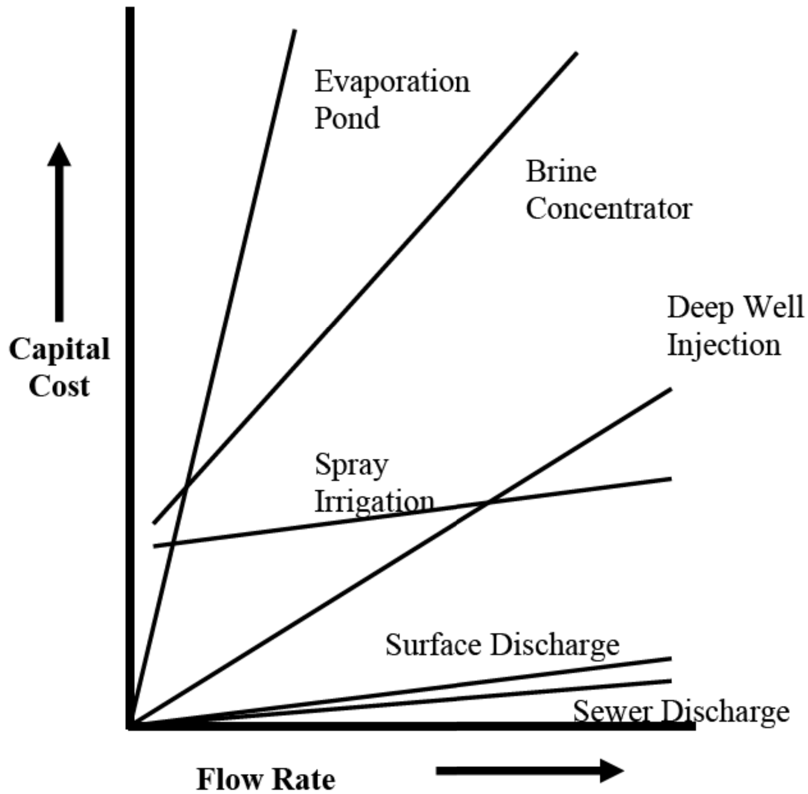
Source: Data from Mickley 2006.
Note: *The costs of land and clearing of the land are eliminated from cost estimate for evaporation pond and spray irrigation

1. The net evaporation rate is 8ft/yr
2. The assumed cost of electricity is $0.10/kWh
3. mil is equivalent thousandth of an inch

Summary of Cost Comparison

Figure 5.3 illustrates the relative capital costs of the different concentrate management options and reflects economy of scale factors as well as general (relative) level of cost (Mickley 2005). Although surface discharge is typically the most cost effective option whereas zero liquid discharge options are the most costly ones, the cost analysis of the concentrate disposal alternatives is site specific, and is dependent upon the concentrate flow rate.

Mickley (2005) reported a cost comparison on a range of concentrate disposal options for a hypothetical situation in Phoenix, Arizona. The estimates obtained are presented in Table 5.4. These figures (while theoretical) indicate that ZLD has the potential to be cost-competitive in some situations, especially when the recovery of otherwise wasted water is considered. Significantly, the inclusion of high recovery RO was found to dramatically reduce the size of the required subsequent thermal brine concentrator, thus significantly reducing energy costs. However, these decreased energy costs were not fully realized because they were largely substituted by increased costs of chemicals and sludge disposal.



Source: Adapted from Mickley 2005

Figure 5.3 Relative capital cost of different disposal options

Table 5.4
Comparison of concentrate disposal alternatives for a hypothetical case in Phoenix, Arizona (in million US$)

	Traditional disposal		Advanced ZLD options		
	Pipeline to sea of Cortez	Evaporation ponds	Thermal evaporation +evaporation ponds	High recovery RO + thermal evaporation + evaporation ponds	High recovery RO + evaporation ponds
Capital cost	310	410	136	76	92
Annual operating cost	0.8	1.6	33	29	21
Annual cost	24	33	43	35	27
Water lost (mgd)	20	20	0.8	0.8	2.5

Source: Data from Mickley 2005. The costs were estimated based on $0.05/kWh, sludge disposal at $30/ton; annualized cost at 40 years and 7.125% interest.

ENVIRONMENTAL CONSIDERATIONS OF CONCENTRATE DISPOSAL

Concentrate disposal and management may present a number of environmental concerns that require careful consideration. The concentrate from a desalination process typically contains a waste stream that is typically two to five times higher in salinity than the surrounding water (assuming 50-80 percent recovery). This waste stream may contain antiscalants, cleaning chemicals, coagulants, and pretreatment filter backwash. It may also have higher temperatures if cooling water is used as source water. This waste stream can cause significant impact to the receiving environment if it is not handled correctly.

Impact on Surface Water

Key environmental issues associated with concentrate disposal to surface waters include (WHO 2007):

- Salinity increase beyond the tolerance thresholds of the surrounding discharge environment
- Concentration of metals and radioactive ions to harmful levels
- Concentration and discharge of nutrients that trigger change in aquatic flora and fauna in the area of the discharge
- Compatibility between the desalination plant concentrate and receiving waters (ion-imbalance driven toxicity)
- Elevated temperature from thermal desalination processes
- Disturbance of bottom aquatic flora and fauna during outfall installation

Each receiving environment is unique and aquatic species in the discharge area vary in their susceptibility to deleterious effects (Khan et al. 2006). Many marine organisms are highly sensitive to variations in salinity (Whitfield et al. 2006). Simple marine organisms such as plants and invertebrates are usually ‘osmotic conformers’, meaning that they have no mechanism to control osmosis so their cells conform to the same salinity as their environment. Large decreases in salinity cause water to enter the cells of these organisms, which eventually leads to cell rupturing (lysis). Salinity increases can lead to cell dehydration, which can result in cell death.

Several studies revealed that Mediterranean Posidonia seagrasses and their associated ecosystems appear to be highly sensitive to salinity increases (von Medeazza 2005, Fernandez-Torquemada et al. 2005, Latorre 2005). Salinities of 45 g/L may lead to 50 percent death of some Posidonia species. Furthermore, salinities of 50 g/L may cause 100 percent death within 15 days (Fernandez-Torquemada et al. 2005).

A marine ecological assessment for the Sydney seawater desalination plant indicated that dense, hypersaline plumes tend to sink and disperse slowly. Thus the affected biota will likely be bottom-dwelling or non-mobile species that live on or are physically attached to the reef (The Ecology Lab 2005). These include fan corals, sponges, stalked and sessile ascidians, anemones and attached algae. At present there is little information available on the salinity tolerances of these species or their responses to chemicals contained in the discharge plume. Similar to marine organisms, many microorganisms and plants in freshwater environments are sensitive to salinity (Hart et al. 1991). In addition, the introduction of excess nutrients such as nitrogen and phosphorous to receiving water bodies can contribute to algal blooms, and subsequent exhaustion of dissolved oxygen. Many fish and aquatic insects cannot survive in such an environment.

One method widely used in the U.S. to determine the environmental impact of a given discharge to a water body is the whole effluent toxicity (WET) test. The WET test estimates the percentage survival of test organisms at various levels of effluent concentrations diluted with ambient receiving water quality. Saltwater organisms widely used for WET test in the U.S. are: sheephead minnow, silverside and topsmelt fish; mysid shrimp and sea urchin; as well as ocean algae such as kelp and red alga. The test, however, was not specifically designed to determine salinity tolerance thresholds of marine species living in desalination plant discharge areas (Voutchkov 2006).

Recently, a novel method was reported for the assessment of the salinity tolerance of marine organisms on seawater desalination plant discharges (Voutchkov 2006). This method was used for the evaluation of the environmental impact of the discharge of the 50 mgd (189,000 m^3/d) Carlsbad and Huntington Beach seawater desalination plants located in Southern California. The testing concluded that TDS discharge concentration of 40 g/L or less has no measurable effect on the marine environment in the vicinity of the discharge. Chronic toxicity testing of the concentrate using topsmelt (a fish inhabiting the area of the discharge and used as a standard chronic toxicity-test organism) indicated that this species can withstand salinities of up to 50 g/L.

USEPA guidance indicated that a discharge's salinity levels should not exceed the natural variability of the receiving water. For example, in the open waters of the California coast, seawater salinity varies about ± 10%, so the discharge salinity should also be within that range (Luster 2008).

Strategies to Mitigate Environmental Impacts

To minimize negative environmental impacts, concentrate disposal options must be carefully designed. Some key considerations include:

- Evaluation of discharge dispersion and recirculation of the discharge plume to the plant intake
- Establishment of aquatic organism salinity tolerance for the site-specific conditions of the discharge location and outfall configuration
- Evaluation of the potential for whole effluent toxicity of the discharge
- Assess whether the discharge water quality meets effluent water quality standards applicable to the concentrate discharge

Concentrate disposal to environmentally sensitive areas may require special measures to protect aquatic life and endangered species. For example, the Taunton River 5 mgd (18,900 m^3/d) brackish water desalination plant uses concentrate storage and blending tanks to hold RO concentrate, and discharges to the estuary based on the tide cycles. This ensures the salinity of blended concentrate is similar to the receiving river, and minimizes the impact on aquatic organisms by preventing the exposure to a wide range of salinity variation (Clunie et al. 2007).

TECHNOLOGIES FOR WATER RECOVERY IMPROVEMENT AND CONCENTRATE VOLUME MINIMIZATION

The disposal of large quantities of concentrate is not only a loss of valuable resource and energy, but is also a challenge, especially for inland facilities with regard to environmentally sustainable disposal options. There are also economic consequences of water loss associated with water pumping and disposal.

Though several disposal methods are available, there are inherently high costs, accessibility constraints, permit challenges, and other limitations associated with all methods. Therefore, the burden of concentrate management is precluding the widespread use of desalination technologies for inland applications.

One of the driving forces for the development of alternative technologies is to improve water recovery and reduce the volume of concentrate. Alternative and emerging technologies under different stages of development aim to improve certain aspects of the performance limits of current desalination processes. These include increasing recoveries, reducing fouling, decreasing energy consumption, and reducing capital and operating costs. These new technologies can be classified under four categories:

- Thermal - e.g., dewvaporation (Hamieh et al. 2001, Hamieh and Beckman 2006), and membrane distillation (Cath et al. 2004, Sirkar and Li 2003)
- Physical - e.g., forward osmosis (Cath et al. 2005a, 2005b, 2006, McCutcheon et al. 2005)
- Chemical - e.g., capacitive deionization (Xu et al. 2008, Farmer et al. 1996, Tran et al. 2002, Pekala et al. 1998, Gabelich et al. 2002b))
- Hybrid membrane configurations
    - physical-chemical or biological treatment of primary RO concentrates followed by a second RO (Williams et al. 2002, Williams and Pirbazari 2003, Gabelich et al. 2007a)
    - membrane system with seeded slurry processes to remove scaling compounds in a controlled fashion (Juby and Schutte 2000)

- electromagnetic field for scaling control in membrane system (Pelekani et al. 2005, Palmer et al. 2005)
- membrane filtration enhanced by vibratory shear process (Madole and Peterson 2005, New Logic Research Inc.)
- RO/ED or RO/EDR (Davis 2006, Tanaka et al. 2003, Xu et al. 2007, Gabelich et al. 2007b).

Recently, there are several projects funded by the Foundation focusing on concentrate volume minimization for inland desalination, including "Zero Liquid Discharge and Volume Minimization for Inland Desalination" conducted by Black & Veatch, and "Desalination Product Water Recovery and Concentrate Volume Minimization" conducted by Carollo Engineers and Colorado School of Mines. The first study evaluated chemical softening fluidized bed crystallization, and activated alumina followed by secondary RO to treat the concentrate from the primary RO (Bond 2006). The second project included a two-phase study to assess the state-of-science and advance desalination technologies for enhancement of system recovery and minimization of concentrate volume (Sethi et al. 2008). Phase I focused on reviewing the state-of-science and performing a technical assessment of promising and emerging desalination configurations or technologies for recovery enhancement, as well as conceptualizing an innovative desalination configuration for increasing recovery and minimizing concentrate. Phase II focused on the advancement of desalination technologies via further development and testing of the innovative approach through bench-scale experiments, modeling, and economic assessment. Based on the assessment of a broad range of desalination technologies, it was revealed that the combination of well established and commercialized technologies is more promising for full-scale implementation in the short term (e.g. in the next five years).

Although novel desalination technologies and hybrid configurations have merit in minimizing the concentrate volume, they likely exhibit similar concentrate disposal challenges as present technologies, unless ultimate ZLD discharge will be employed. Volume reduction eliminates the use of most conventional disposal options and complicates the concentrate disposal challenge (Mickley 2005). For example, Ionics Inc. used a large EDR system for RO concentrate reclamation in a major aerospace facility (Reahl 1992). An overall RO/EDR water recovery of approximately 97 percent was achieved. However, because of this high recovery, the concentrate disposal pond dried out and a subsequent dust problem forced the shut-down of the EDR system (Reahl 2006). Therefore, appropriate concentrate management strategies remain one of the critical issues for desalination and need to be developed site- specifically.

BENEFICIAL USE OF CONCENTRATE

Another solution to concentrate disposal is beneficial use of concentrate or concentrate byproducts. A recent study conducted by Jordahl (2006) investigated the viability of beneficial and nontraditional uses of concentrate, including oil well field injection, solar ponds, land application and irrigation (including halophyte irrigation), ZLD, and near-ZLD, aquaculture, salt marsh discharge, wetlands treatment, and separation and recovery of individual salts. A survey of water utilities confirmed that various utilities are considering some of these options for concentrate management. These uses, however, were found to be either not well-proven or not cost-effective. A combination of more conventional options with beneficial or nontraditional uses may be more cost-effective and can provide redundancy, reliability, and potentially some ancillary benefits (Jordahl 2006). For beneficial and nontraditional uses, there are numerous and critically important site-specific considerations including climate, markets, and regulatory issues as well as ecological risks.

Wetland Restoration

This method is site-specific and suitable for conditions where the concentrate quality is compatible with the native flora and fauna of the saltwater marsh or wetland. Usually, the type of wetlands or marshes that would be used for concentrate discharge are hydraulically interconnected with the ocean or a brackish water body and therefore, this essentially is an indirect method for concentrate disposal to surface waters. Wetland vegetation may assimilate some of the nitrate and selenium in the concentrate thereby providing effective reduction of these contaminants (Bays et al. 2007).

The City of Oxnard in California has proposed a combination of a discharge/beneficial reuse project to investigate the feasibility of conveying desalination concentrate to a local tidal wetland and using it to supplement tidal flows and mitigate neglected areas of the wetland (Bays et al. 2007). California's coastal wetlands occur in estuaries where freshwater streams meet the sea. There is a pronounced salinity gradient in these estuaries that overlaps membrane concentrate ionic strength and composition. Therefore, membrane concentrate could be used for beneficial creation of coastal marshes or for enhancing flow to existing marshes.

Salt Recovery

Desalination concentrate is often viewed as an undesirable residual that requires disposal. If the chemical components in the concentrate can be solidified and recovered for additional applications, the overall recovery of the system will be greatly enhanced and the concentrate stream minimized.

In Israel, Mekorot Water Company owns and operates a dual purpose SWRO plant in Eilat for the production of 2.64 mgd (10,000 m^3/d) of desalinated water and high-quality table salt (Ravizky and Nadav 2007). The feed to the desalination plant is a blend of 80 percent seawater and 20 percent BWRO concentrate from adjacent BWRO plants. The concentrate from the SWRO plant is blended with seawater, and this stream is fed to a series of evaporation ponds, and thereafter to the salt processing factory of the salt company. The concentrate discharge system and potential environmental impacts were avoided. Tanaka et al. (2003) reported that using the concentrate from the SWRO plant as raw material for salt production might be more advantageous than using seawater for salt production, and might save 20 percent of the energy.

Jibril and Ibrahim (2001) proposed a process involving absorption of ammonia in concentrate. The ammoniated concentrate was then contacted with CO_2. In a series of reactions, concentrated sodium chloride (NaCl) was converted into valuable products such as sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), ammonium chloride (NH_4Cl) and magnesium chloride ($MgCl_2$).

The patented SAL-PROC™ process uses sequential or selective extraction to recover beneficial salts from inorganic saline waters (e.g., irrigation drainage, produced water and RO concentrate) (Geo-Processors USA, Inc.). Depending upon the chemical composition of the saline feedwater, the process route may involve one or more steps of reaction and evapo-cooling supplemented by conventional mineral and chemical processing steps.

Kumar et al. (2006) employed a series of innovative tests utilizing ion exchange, bipolar electrodialysis and electrochlorination technologies to recover useful products from RO concentrate that can be utilized at the treatment facility. Experiments were conducted on RO concentrate obtained from a pilot-scale integrated membrane system treating wastewater. The ion exchange experiments focused on recovering phosphate from RO concentrate using a chelating ion exchange resin and converting the phosphate rich regenerant into struvite, a commercially viable fertilizer. Bipolar electrodialysis was used for generating mixed acids and bases from the RO concentrate solution after suitable softening pretreatment.

Davis (2006) investigated a ZLD process for SWRO with enhanced freshwater yield and production of salable sodium chloride, magnesium hydroxide ($Mg(OH)_2$), and bromine (Br_2) from the SWRO discharge. The process used electrodialysis to reduce the salinity of the reject stream from SWRO so that the salt-depleted concentrate stream could be recycled to the SWRO to improve the yield of freshwater. The approach of this ZLD study was to remove in sequence the most accessible amounts of abundant constituents in seawater, water, and NaCl and leave remaining valuable constituents in a concentrated solution. After recovery of the most accessible portions of water (NaCl, Br_2, and $Mg(OH)_2$), the residual solutions can be evaporated to dryness to produce road salt, but ultimately minor constituents might be recovered from that residue.

The positive attribute of salt solidification is the recovery of salts, potential for revenue generation through resale, and near ZLD. The sale of products from the facilities might provide revenues that could offset costs involved in installing and running the full-scale facilities. The economics and market of products, however, require further investigation.

SUMMARY

Challenges to Concentrate Management

Concentrate management is facing increasingly difficult challenges including:

- Larger concentrate flows of increasing plant size limiting disposal options
- Cumulative environmental impacts on receiving waters from an increasing number of desalination plants in a region
- More stringent discharge regulations making disposal more difficult and complicating the permitting process
- Increased public concerns over environmental issues, affecting desalination decision making
- Increasing number of desalination plants being built in semi-arid regions where conventional disposal options are limited or unavailable
- Increasing need to limit loss of water resource and recovery water from concentrate, particularly in water short, semi-arid regions

The concentrate management challenge is particularly acute in the arid southwest U.S. where disposal to surface water and sewer are typically not viable options for large-scale plants. For areas where deep well injection and surface discharge are potential options, concentrate management is challenged by more stringent discharge regulations.

The Colorado Water Quality Control Commission has expressed a concern that if membrane technology is to be viable, it must be implemented responsibly, with residual disposal options that do not adversely impact the environment or beneficial uses of water. Some of the existing desalination plants are requesting permit effluent limits based on assimilative capacity of the receiving stream during times where flows are greater than low flow conditions as defined in Section 31.9(1) of Colorado's Basic Standards and Methodologies for Surface Water (CWQCC 2006).

In Florida, leakage has been monitored in some Class I concentrate injection wells. Regulatory agencies may not renew their disposal permit, and new disposal permit will be more difficult to obtain in the future (Akpoji 2007a).

Concentrate Management Considerations

To face the increasing challenges of concentrate management, several considerations may help to develop technical, economical, and environmentally suitable concentrate disposal options including:

- Beneficial use of desalination concentrate
- Developing technologies to improve water recovery, and in the extreme leading to ZLD
- Regional concentrate management
- Watershed concentrate management

Direct beneficial use of concentrate is an attractive option for the sites where concentrate can find an environmental friendly application. Another alternative option is to further treat concentrate to facilitate disposal or reuse. Increasing recovery may help other disposal options such as evaporation ponds (now a smaller volume to evaporate), deep well injection (disposal of a smaller volume), and zero liquid discharge (smaller volume going to high cost thermal evaporative systems). However, increasing recovery and minimizing concentrate volume do not help disposal to receiving water bodies, such as surface water disposal, sewer disposal, or land applications. It typically makes the concentrate less compatible (in terms of salinity) with the receiving water.

Regional concentrate management includes regional collection, treatment, centralized disposal (e.g., co-discharge desalination concentrate with wastewater effluent), or beneficial uses of concentrate from a number of desalination plants. A regional approach may take advantage of site-specific beneficial conditions for disposal and of the economies of scale of constructing larger concentrate disposal facilities. Another advantage of regional management is the use of concentrate from brackish water desalination plants as source water to seawater desalination plants, such as the case in Eilat, Israel (Ravizky and Nadav 2007). The use of concentrate in this manner will reduce the feedwater plant salinity, even when blended with ocean water for the feed source. This will decrease the seawater desalination plant's energy and treatment costs and potentially increase recovery, while also avoiding the brackish desalination concentrate disposal issues.

Watershed management may provide an option that may manage concentrate disposal at a desired watershed scale. It would ensure concentrate discharges be protective of beneficial uses of receiving waters for agriculture, environmental uses, and drinking water. Watershed management could be structured in a manner that would support a system for pollutant trading. Receiving water quality requirements could be imposed at the point of use rather than for the entire watershed. The effective protection level could be based upon preserving existing ambient water quality to protect aquatic life and agricultural uses, or drinking water supplies. It might also be possible to specify effluent limitations, waste load allocations, and/or treatment requirements in a watershed-based control regulation focused on a specific water body (CWQCC 2006).

CHAPTER 6
ENERGY

Desalination is an energy intensive process. This chapter discusses the energy demand and efficiency of brackish water and seawater desalination, the approaches to decrease energy demand, and the use of renewable energy to reduce the carbon footprint of desalination plants.

ENERGY DEMAND AND EFFICIENCY

Energy Intensities of Different Water Supply Alternatives

Providing water supplies require large amounts of energy to pump, transport, treat, and deliver quality water to end users. Each element of the water use cycle has unique energy intensities. Table 6.1 illustrates the ranges of energy intensities of desalination as well as other water use segments in California.

Table 6.1
Energy intensities for water use cycle segments as compared to desalination

Water supply alternative	Energy use	
	kWh/kgal	kWh/m^3
***Water-use cycle segments in California*[1]**		
Supply and conveyance	0 to 14	0 to 3.70
Water treatment*	0.1 to 16	0.026 to 4.227
Water distribution	0.7 to 1.2	0.185 to 0.317
Wastewater collection and treatment	1.1 to 4.6	0.291 to 1.215
Wastewater discharge	0 to 0.4	0 to 1.06
Recycled water treatment and distribution	0.4 to 1.2	0.106 to 0.317
Desalination		
Brackish Water Desalination[2]	2.61 to 4.60	0.70 to 1.22
Desalination of Pacific Ocean Water[3]	8.59 to 11.04	2.269 to 2.917
Affordable Desalination Collaboration Project[4]	5.6 to 7.5	1.5 to 2.0

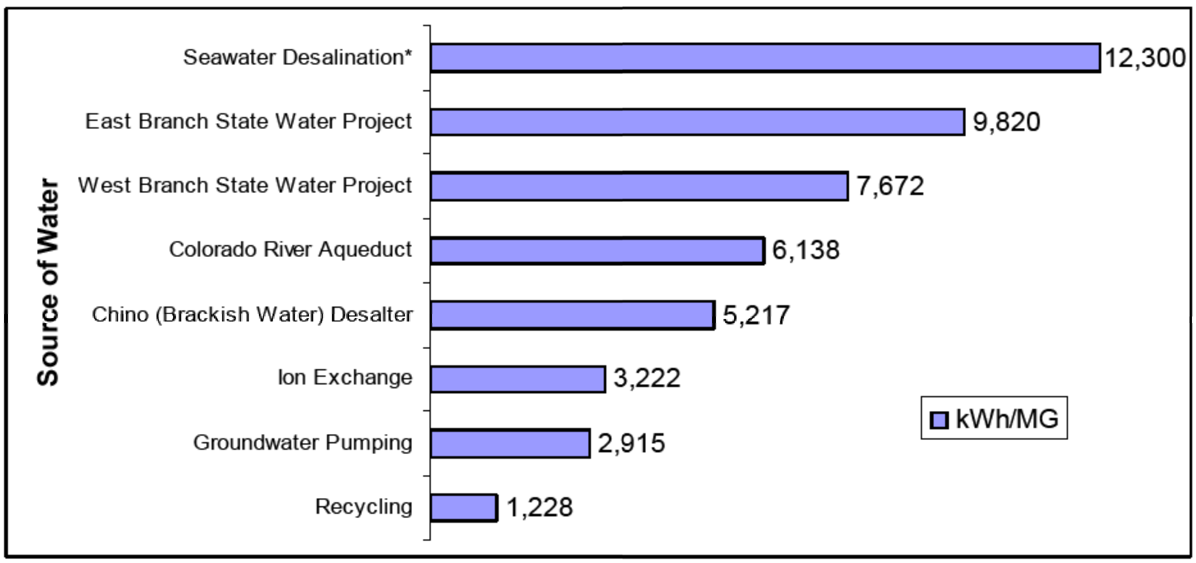
Source: 1. CEC 2005. 2. Voutchkov 2007. 3. Survey results. 4. ADC 2007
* Water treatment includes brackish water and seawater desalination. Average energy use by conventional surface water treatment plants is 1.42 kWh/kgal.

Supplying water by way of desalination, especially seawater desalination is an energy intensive process. In California, the energy consumption of brackish water desalination varies from 2.61 to 4.60 kWh/kgal (0.70-1.22 kWh/m^3) depending on feed water salinity (Voutchkov 2007). Most of the brackish water desalination plants do not use energy recovery devices. The recent seawater desalination projects in California estimated the energy consumption in the range of 8.59 to 11.04 kWh/kgal (2.27-2.92 kWh/m^3) (Survey results). The Affordable Desalination Collaboration Project claimed the SWRO energy demand could be further decreased to 5.6-7.5

kWh/kgal (1.5-2.0 kWh/m^3) (ADC 2007). The total energy consumption of SWRO plant in Southern California was projected to be 12.3 kWh/kgal (3.25 kWh/m^3) for a 10 mgd (38,750 m^3/d) plant, and 11.3 kWh/kgal (3.0 kWh/m^3) for a 50 mgd (189,000 m^3/d) plant (ADC 2008).

As compared to desalination, water transportation could also be energy intensive in some regions. Water transports to Southern California in particular require intensive amounts of energy due to the need to convey water over 3,000 vertical feet through the Tehachapi Mountains. On average, the water conveyance energy requirement for Southern California (8.9 kWh/kgal or 2.35 kWh/m^3) is over 50 times the water conveyance energy requirement for Northern California (0.15 kWh/kgal or 0.04 kWh/m^3), and is also five times the national average (CEC 2005).

Figure 6.1 illustrates the relative energy intensity of water supply options for one Southern California regional water and wastewater utility, the Inland Empire Utilities Agency (IEUA). For the IEUA, the energy consumption for the East Branch State Water Project is the second most energy intensive as compared to seawater desalination. Recycled water is the least energy intensive supply option.



Source: *ADC 2008, CEC 2005.

Figure 6.1 Energy intensities of various water supplies in IEUA
* Seawater Desalination values based on a 10 mgd (37,850 m^3/d) plant according to ADC pilot testing results

Regardless of seawater desalination energy consumption being comparable to water transportation, the overall goal is still to reduce the energy demand as much as possible. The following discussion is focused on the issues related to energy use with an emphasis on seawater desalination.

Factors Affecting Energy Requirement

The minimum theoretical energy requirement for membrane desalination is to overcome the membrane's osmotic pressure. For seawater containing 35 g/L TDS, the osmotic pressure is calculated as 2.85 kWh/kgal (0.75 kWh/m^3) at 25°C. However, the actual energy consumption of a RO process is much higher than the osmotic pressure due to membrane resistance, equipment efficiencies, and operating parameters. In general, the energy consumption of SWRO alone varies between 8 to 12 kWh/kgal (2.1 to 3.2 kWh/m^3). The energy consumption of the entire desalination plant is even higher, typically greater than 16 kWh/kgal (4.2 kWh/m^3), which includes intake, pretreatment, and distribution (Veerapaneni et al. 2007).

The energy consumption of recently built large-scale desalination plants has significantly decreased. For example, the energy demand of the 7.2 mgd (27,500 m^3/d) Santa Barbara SWRO plant built in 1991 used approximately 20.25 kWh/kgal (5.35 kWh/m^3). The 38 mgd (144,000 m^3/d) Perth SWRO desalination plant operating since 2006 has an overall 24 MW requirement and a production demand between 15.1-22.7 kWh/kgal (4.0 to 6.0kWh/m^3) (Crisp and Rhodes 2007). Power consumption of the entire 87 mgd (330,000 m^3/d) Ashkelon desalination plant operating since 2005 is between 13.2-13.70 kWh/kgal (3.50-3.62 kWh/m^3) including water desalination, conditioning, transfer from intake to client reservoir, and all other electricity uses in the plant (Survey results). The entire 36 mgd (136,380 m^3/d) SWRO plant in Tuas, Singapore, consumes 16.4 kWh/kgal (4.345 kWh/m^3) of power (Veerapaneni et al. 2007).

The energy required to desalinate water is a function of water quality (salinity and temperature), permeate flux, recovery, membrane resistance, energy efficiency of the equipment (high-pressure pumps and energy recovery devices), and system design.

Feed Water Quality

Higher salinity and colder water requires more energy to desalinate than lower salinity and warmer water. MMWD (2007a) estimated the energy intensity of their seawater desalination plant will be 10 kWh/kgal (2.64 kWh/m^3) to desalinate water from the Bay and deliver it to customers in normal years. During droughts (higher salinity), the plant would operate at full capacity (up to 10 mgd or 38,750 m^3/d) and require 14 kWh/kgal (3.70 kWh/m^3). Higher feed water temperature, such as cooling water from power plants, can significantly facilitate the water permeability through membranes and result in lower energy consumption.

Recovery

Water recovery has a significant impact on energy consumption. The concentration of dissolved solids increases exponentially with recovery, with a corresponding increase in osmotic pressure, as well as the effect of concentration polarization. Although higher operating pressure is required at higher recovery, the amount of water that needs to be pressurized decreases with recovery. An optimal recovery value may vary depending on the feedwater quality and conditions.

Permeate Flux

Flux is a critical parameter to determine the membrane area of the RO treatment. Higher permeate flux can lower capital cost by reducing required membrane surface area and pressure vessels. However, high flux requires higher energy consumption due to high concentration polarization on membrane surface. This results in an increase in osmotic pressure and excessive fouling, which will result in increase in operating pressure and chemical cleaning frequency. Energy savings may be achieved by optimizing the permeate flux.

Energy recovery devices (ERD)

Energy recovery is now a key component of membrane desalination processes. The pressurized concentrate stream has inherent energy that is "lost" if the concentrate is simply treated or disposed without any attempt to recover that energy. Due to the high-pressure operation of SWRO (often up to 1,200 psi), the concentrate is more pressurized in this application as compared to brackish water desalination applications, and thus energy recovery is very desirable. However, energy recovery is also desired for brackish water applications, especially if the water is moderately or highly brackish, using relatively high operating pressures. It is expected that energy recovery may not result in net cost savings if the operating pressures are less than 100 to 150 psi.

Existing energy recovery devices (ERDs) can be divided into two categories:

- Devices that transfer concentrate pressure to mechanical power and then back to feed pressure (e.g., Pelton turbine, Francis turbine and hydraulic turbocharger). The first ERDs deployed in municipal SWRO plants were Francis turbines. In the 1990s, Francis turbines were eventually taken over by Pelton turbines which operate at higher efficiency, simplicity, and proven reliability. Another type of centrifugal EDR employed for desalination processes is the hydraulic turbochargers, which provide similar performance to Pelton turbine ERD systems. The net efficiency with which the Pelton turbines transfer energy (the product of the efficiencies of the turbine, the coupling and the high-pressure-pump impeller) can reach as high as 80 percent (Stover and Cameron 2007).
  The 13.2 mgd (50,000 m^3/d) SWRO plant in Fukuoka, Japan that initially had no ERD was retrofitted with a Pelton turbine. The Pelton turbine reduced the SWRO energy consumption from 19.76 to 15.3 kWh/kgal (5.10 to 3.96 kWh/m^3). The turbine operates at about 81 percent efficiency resulting a net transfer efficiency of 65.4 percent (Stover and Cameron 2007).
- Devices that transfer the concentrate pressure directly to the feed stream (e.g., pressure exchanger). To avoid the efficiency losses associated with the energy transformation inherent in centrifugal devices like Pelton turbines, the positive displacement technologies were developed such as the Energy Recovery Inc. Pressure Exchanger and Desalco Work Exchange. These devices place the concentrate and feedwater in direct contact in pressure-equalizing or "isobaric" chambers resulting in net transfer efficiencies approaching 98 percent (Stover and Cameron 2007).
  Most SWRO plants built after 2002 utilize pressure exchange ERDs. For example, the Ashkelon desalination plant uses double work exchanger energy recovery (DWEER) to recover energy from concentrate (Stover and Cameron 2007). The Perth I desalination plant uses Isobaric pressure exchange (PX) ERDs from Energy Recovery Inc. Some SWRO plants in Spain and the Caribbean that formerly use Pelton turbines have been retrofitted with isobaric devices (Stover and Cameron 2007)

While the pressure exchanger offers higher efficiency, the equipment costs are also comparatively higher than in the indirect device group. The advantage of one approach over another depends upon several factors, such as unit energy costs, project capacity, projected lifetime, performance, and ease of operation and maintenance. Table 6.2 summarizes the comparison and considerations in selecting energy recovery devices.

High Pressure Pumps

Significant energy efficiency can be achieved through selecting the optimal specific speed of the high pressure pumps (Veerapaneni et al. 2007). For large desalination plants, the feed water flow can be increased by centralized RO feed pumps that feed either larger skids or several smaller skids. The total dynamic head of the pump can be decreased by dividing the pressure between a booster pump and a high pressure pump, as it is in Ashkelon desalination plant (Liberman et al. 2005).

Centralized System Design

Each RO train could have a dedicated high pressure pump and energy recovery system or the pumps and energy recovery could be designed as a manifolded “pressure center” for potentially greater system efficiency and flexibility. While the “pressure center” design approach has typically been used on large facilities such as the Ashkelon SWRO facility and the Yuma Desalter Facility, it can offer increased flexibility for smaller facilities as well (MMWD 2007a). At the Ashkelon SWRO Desalination Plant, four high-pressure pumps supply seawater to the RO trains in each half of the plant through a common line. One of the four pumps is installed as stand-by. Forty DWEER units in the energy recovery center receive pressurized concentrate from all of the RO trains and transfer the energy to the RO feed water. The pressurized feed water is then pumped to the RO trains through a common feed line. This approach allows optimization of each system independently. Pump efficiency is a function of capacity and in the Ashkelon plant the maximum pump efficiency can reach 88.5 percent (Liberman et al. 2005).

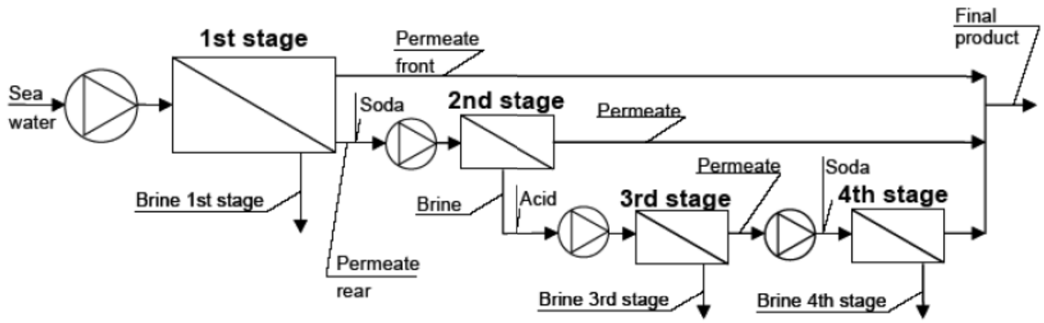
Membrane System Design

Membrane system design can also affect energy consumption. For example, the Ashkelon SWRO plant uses a four-pass system to meet final permeate water quality (chloride <20 mg/L and boron<0.4 mg/L) while minimizing energy consumption. Figure 6.2 illustrates the seawater stage and the Cascade in the Ashkelon SWRO plant.

Table 6.2
Comparison of ERDs between Pelton turbine and pressure exchanger

	Pelton turbine	Pressure exchanger (PX)
Description	Transfer the hydraulic pressure of RO concentrate to drive high-pressure pump. No booster pump is required	Place the concentrate and feedwater in direct contact in pressure-equalizing or "isobaric" chambers. Pressurized feedwater from the ERDs combines with the discharge of the high-pressure pump to feed the membranes. A booster pump is required to circulate high-pressure water through the membranes and the ERDs.
Net energy transfer efficiency	80%	98%
Concentrate disposal	A Pelton pump must discharge at atmospheric pressure, a concentrate disposal pump may be required.	Isobaric ERDs discharge at pressures greater than atmospheric pressure, so a brine disposal pump is not typically required
Performance	The design of Pelton turbines is often optimized for a particular operating window. Flow changes, in particular, can significantly reduce device efficiency.	Isobaric ERDs decouple the ERD and the high-pressure pump. The performance of Isobaric ERDs varies little with water recovery, flow rate or pressure.
Ease of operation	Both are easy to operate. Both are flow-driven and self-adjusting to changes in flow rates. However operators are generally more familiar with Pelton turbines	
Reliability	Both have a strong track record for reliability. Close to 100% uptime can be expected.	
Impact on feed water	Pelton turbines keep the brine and feedwater separate so that no mixing occurs and no impacts on feed water quality and flow rate.	Because feedwater and brine streams are mixed in the PX rotor, the feedwater concentration and flow rate increase prior to RO.
Fail-safe operation and redundancy	Failure of a turbine requires immediate shutdown of the RO train or a significant operating cost increase.	For medium and large SWRO trains, several PX devices are arrayed in parallel. One rotor out of service has minimal impact on SWRO membrane performance. A plant can typically continue running until service is performed during a scheduled maintenance shutdown.
Maintenance	Require periodic changes of seals and bearings.	Require no periodic maintenance and no service of seals or bearings
Device life	Pelton turbines are typically made with stainless steel alloys which offer resilience against damage by debris. Like other stainless steel equipment in SWRO plant, the metal may corrode, wear and fatigue.	Pressure transfer in the PX device occurs in a ceramic rotor enclosed in ceramic components. Ceramic is more brittle than most of metals, but three times harder than stainless steel and never corrode in seawater.

Source: Information extracted from Stover and Cameron 2007



Source: Gorenflo et al. 2007

Figure 6.2 Seawater stage and the Cascade at Ashkelon SWRO Desalination Plant

- The first pass is a conventional seawater RO (Filmtec) system operating with a recovery of approximately 45 percent. Part of the permeate is collected from the feed side (front permeate) of the pressure vessels. This part has a lower concentration of salts (boron) than the whole permeate, and can be mixed directly with the permeate water of the other stages.
- The rear permeate from the first stage feeds the second pass which operates at a higher pH to increase boron rejection by the membranes. This pass is operated at 85 percent recovery. The permeate of this stage is part of the final product.
- The concentrate of the second pass is the feed to the third pass. This pass is operated at 85 percent recovery and operated at lower pH. Due to an acidic environment, there is no concern about scaling on the membrane surface, even at high recovery and high concentrate concentration. However, at low pH, boron rejection is very low and some boron remains in the third pass permeate. Therefore, this permeate cannot be considered product water and must be treated through the fourth pass.
- The fourth pass operates at 90 percent recovery and high pH, and completes the boron removal of the second pass concentrate. Thus treated, the fourth pass permeate is suitable to be mixed with the final product.

This Cascade membrane system design achieves high product water quality while minimizes membrane fouling potential, which in turn, is significant to energy saving by maintaining operating pressure and reducing cleaning frequency.

The Long Beach Water Department in California (LBWD) has developed a two-pass NF/NF process for seawater desalination (LBWD 2006). The NF/NF process is arranged in two pass configuration with Pass 1 NF vessel permeate used as feed for Pass 2 NF vessel. The LBWD estimated that the NF/NF process could save 20-30 percent energy as compared to SWRO. A 0.3 mgd (1,136 m^3/d) demonstration-scale testing is being conducted to compare the two pass NF/NF process with conventional SWRO.

Co-generation and Co-location

Co-generation offers a solution to cost reduction by improving energy efficiency through simultaneously supplying and consuming electricity and heat in the same system. From an energy saving standpoint, co-generation plants are much more efficient than those desalination plants that do not produce their own energy (Mesa et al. 1997). The energy consumption and cost of desalinated water from co-generation plants are lower than the most efficient technology using an electricity supply from the public network (Mesa et al. 1997). However, the capital investment for co-generation plants is high. The total cost of co-generation should be evaluated for each specific case.

In addition to energy co-generation, the co-location concept can bring other economic and environmental benefits (Voutchkov 2004 and 2005b). The cooling water discharged from the condensers is usually 5 to 15°C warmer than the ambient source ocean water. This may be beneficial because RO separation of 10°C warmer seawater requires approximately 5-8 percent less feed pressure, and therefore proportionally lower energy use (i.e., power costs) for seawater desalination. As a result of co-location, the grid transmission portion of the power fees could be substantially reduced or avoided, allowing the desalination cost to be further reduced. However, because of a warmer water source, there may also be potential adverse impacts on membrane biofouling and higher solute transportation which leads to lower rejection. Such impacts have previously been observed at the West Basin Seawater RO pilot system (Lauri et al. 2007). A balance between lower energy consumption of the RO and potential fouling and lower rejection from higher temperatures need to be considered.

DESALINATION AND GREEN HOUSE GAS EMISSIONS

Greenhouse gas emission associated with desalination has received increasing concerns in Europe and Australia, as well as in the United States. SWRO energy demand in California is estimated to be 13.2 kWh/kgal (3.4 kWh/m^3) water produced, translating to 3.64 kg CO_2/kgal (0.94 kg CO_2/m^3) water (Cooley et al. 2006). Carbon dioxide emission would be even higher in Australia with coal as the major energy source. The proposed Sydney plant has an estimated energy consumption of 19.1 kWh/kgal (4.93kWh/m^3) water, produced translating to 19.7 kg CO_2/kgal (5.2 kg CO_2/m^3) water from the state's coal fired power plant (Australia Institute 2005). The 38 mgd (144,000m^3/d) Kwinana desalination plant in Perth Australia is estimated to emit 180,000 tones of CO_2 per year if renewable energy credits are not applied towards the plant (EPAWA 2002). On a similar level, the 39.6 mgd (150,000 m^3/d) Thames Gateway Water Treatment Plant in London would emit more than 150 tons of carbon dioxide into the atmosphere every day in full use (www.timesonline.co.uk, May 24, 2006). The Mayor of London, Ken Livingstone, stated "We are already facing the effects of climate change which is putting a strain on our water resources. We cannot fight climate change by building a desalination plant, which will worsen the problem by pumping 25,000 tons of carbon dioxide into the atmosphere every year." The concern of greenhouse gas emissions caused public opposition to the proposed plant in London.

In the United States, increasing the number of desalination facilities will also increase the amount of carbon emitted. This is a concern particularly to California which recently called for an aggressive reduction in its carbon dioxide emissions (Executive Order S-3-05, signed by Governor Arnold Schwarzenegger June 1, 2005) with goals to:

- Reduce emissions to 2000 levels by 2010
- Reduce emissions to 1990 levels by 2020 (a 25 percent reduction to its current carbon dioxide emissions)
- Reduce emissions to 80 percent below 1990 levels by 2050

In the draft "Statewide Assessment of Energy Used to Manage Water," the California Energy Commission estimated that an average of approximately 44 million tons of carbon dioxide is emitted into the atmosphere each year to provide water in California. Any reductions in energy consumption related to water will help the State meet its greenhouse gas reduction goals (DWR 2006). In additions, California's AB32 Global Warming Solutions Act introduced in 2006 have set goals to reduce the state's greenhouse gas (GHG) emission to 1990 levels by 2020 (Poseidon Resources 2008). Since water management and use are a significant part of California's energy matrix, both in terms of energy generation and consumption, concerns on carbon dioxide emission might become a major hurdle for seawater desalination and its growth in this area.

RENEWABLE ENERGY FOR DESALINATION

In addition to developing high energy efficient membranes and devices, using alternative energy sources (i.e., wind, solar, biofuel, hydroelectric, etc.) has been an important step to promote seawater desalination as a viable and sustainable water resource option. Renewable energy and desalination represent different technologies which may be combined in various ways. Typically renewable energy is expensive and may add to the already expensive desalination technology. This dilemma may need to be solved with a policy providing incentives to use renewable energy sources at desalination plants.

Renewable Energy Driven Desalination Plants

Although renewable energy conversion and desalination are both considered mature technologies, renewable energy driven desalination plants are rather scarce with very limited capacity. Such systems are typically small experimental plants for remote locations where both water and electricity are in shortage. Exploitation of renewable energy and development of desalination plants require intensive capital investments. The direct use of renewable energy toward desalination may often require operations significantly beyond the experience of a desalination treatment plant. Furthermore, the geographical distribution, availability, and sustainability of renewable energy sources are very site specific, requiring a system-oriented approach to optimize the design of combined plants. The design must take into account local parameters, such as geographical conditions, topography of the site, capacity, type of energy available at low cost, availability of infrastructures (including electricity grid), plant size, and feed water quality.

Solar photovoltaic (PV) and wind are the most commonly used renewable energy for desalination plants. PV is considered a proper solution for small applications in sunny areas. For larger units, wind energy may be more attractive, in particular on islands where there is a good wind regime and often very limited flat ground.

Technically, PV powered RO or ED systems have been proven valid options for desalination at remote sites (MEDRC R&D Report 2000). There are commercially available stand-alone, PV powered desalination systems (Espino et al. 2003). Several RO or ED desalination plants powered by PV have been installed throughout the world in recent decades, most of them being built as experimental or demonstration plants (Mathioulakis et al. 2007, Kalogirou 2001, Tzen et al. 1998, Mohamed and Papadakis 2004, Al Suleimani and Nair 2000 Al Madani 2003, Adiga et al. 1987). For example, the Canary Islands Technological Institute (ITC, Spain) developed a stand-alone system (DESSOL) with capacity of 264 to 1321 gal/d (1 to 5 m^3/d) of nominal output. The precommercial brochure offers a plant capacity of 264 gal/d (1 m^3/d) for 42,000 €, and a plant capacity of 1321 gal/d (5 m^3/d) for 170,000 € (Cited from García-Rodríguez 2003). In Sadous, Saudi Arabia, a PV-RO brackish water desalination plant was installed. It is connected to a solar still with production of 1321 gal/d (5 m^3/d). The feed water of the solar still is the blowdown of the RO unit 2,640 gal/d (10 m^3/d) (Hasnain and Alajlan, 1998). Several pilot plants of ED systems connected to photovoltaic cells using batteries have been implemented. A 740 gal/d (2.8 m^3/d) PV-driven ED plant was installed at the Spencer Valley in New Mexico treating brackish water. It was developed by the US Bureau of Reclamation (European Commission 1998).

The main problem with the PV-driven desalination plants is the high cost of PV cells. The challenge relies on the development of small, autonomous, modular, flexible and reliable units, to serve users at remote areas at reasonable cost. Using batteries increases the overall productivity of the PV system in an intermittent electrical power context induced by fluctuating solar radiation. However, they require careful maintenance and operation skills, which may be difficult in remote sites. The battery-free PV-RO or PV-ED systems can be a more promising option. Recently, Werner and Schäfer (2007) presented results from field experiments using a 264 gal/d (1,000 m^3/d) desalination unit powered by solar energy. It combines ultrafiltration with nanofiltration to achieve the goals of pathogen and turbidity removal with desalination and removal of trace contaminant from brackish ground water. Two 150 W solar panels provided the necessary power for a 300 watt pump. No battery was used due to potential difficulties caused by batteries in remote situations. Advantages of battery-free systems with electronic power converters are simplified configuration, compact design, improved robustness, and long life of all components of the power supply sub-system. Disadvantages are higher cost and possible availability problems of power electronics, longer periods in ‘stand-by’ mode with related risks of membrane fouling, and the critical importance of optimized sizing of sub-systems (Mathioulakis et al. 2007).

The electrical or mechanical power generated by a wind turbine can be used to power desalination plants. Wind power is an attractive option for seawater desalination, especially for coastal areas with a high availability of wind energy resources. Wind turbines may, for example, be coupled with RO and ED desalination units, demonstrating one of the most promising alternatives of renewable energy desalination (Ackermann and Soder 2002, Garcia-Rodriguez et al. 2001). There are several installations powered by wind turbines, either connected to a utility network or operating in a stand-alone mode. Most of them have been installed at Canary Islands, Spain (Garcia-Rodriguez 2003). A wind-powered RO plant for brackish water desalination with capacity of 0.053 mgd (200 m^3/d) installed at Los Moriscos (Gran Canaria, Spain) that is connected to the grid as auxiliary energy (Garcia-Rodriguez 2003). Stand-alone wind turbines installation may not particularly be viable for large desalination plants that need to operate 24 hours a day and 7 days a week (24/7) at relative fixed output unless battery storage is used.

Reducing Carbon Footprint of Large Desalination Plants

The relatively extensive carbon footprint of desalination compared with conventional water treatment may make desalination unfavorable. Independence of fossil fuel energy sources, through the use of renewable energy sources unassociated with greenhouse gas emissions could be highly favorable for desalination in the public's view. The use of biodiesel in Beckton, London, Thames Gateway Water Treatment Plant, to meet desalination energy demand eased opposition against the proposed plant and facilitated the granting of the planning permit (BBC News, June 15, 2007). The development of renewable energy has become a more important component of the desalination investment.

The intense ongoing energy use poses a barrier to the acceptance of desalination in Australia. As a result, renewable energy has been declared to power the majority of the proposed large-scale desalination plants in Australia. The Kwinana SWRO plant in Perth is the largest facility of its kind in the world to be powered by renewable energy credits (Water Corporation 2007). Electricity for the desalination plant, which has an overall 24 MW requirement and a production demand of 15.5 to 23.3 kWh/kgal (4.0 to 6.0 kWh/m^3), from the 80 MW Emu Downs Wind Farm (operated since 2006). Similarly, the Kurnell SWRO desalination plant in Sydney entered a renewable energy supply agreement in which the plant would be powered by wind energy from the new 132 MW Capitol Wind Farm (Mallesons Stephan Jacques 2008).

In California, water agencies also showed general support for the idea of marrying an investment in desalination with renewable energy but some have no clear plans or mechanisms for making this happen as of 2007 (Results of interviews and workshop). Most water agencies acknowledge that using renewable energy will greatly increase desalination support, but contend that the issue of energy in desalination ultimately is not only about the energy source. The power needed for desalination will ultimately still be taken from a pooled power grid. The long-term focus of desalination should be to reduce energy usage. However, several regions are already aiming for increasing and developing new green sources of energy. San Diego Gas and Electric has goals to achieve 20 percent renewable energy in their system by 2010 (SDGE 2007). This is in conjunction with California's state energy action plan where the state goal is to reach 20 percent.

Poseidon Resources Corporation committed the Carlsbad desalination facility to be the first major California infrastructure project to go carbon neutral (Poseidon Resources 2007b). The proposed greenhouse gas emission from the 50 mgd (189,000 m^3/d) Carlsbad desalination plant is estimated to be 97,165 metric tons of CO_2 per year based on the plant's annual electricity consumption and the power agency's emission factor. The project precludes 190,641 MWh/yr of electricity consumption by water imports, corresponding to 67,506 metric tons CO_2/yr. The net emission resulted from the displacement of imported water from the State Water Project is 29,659 metric tons CO_2/yr. The carbon neutral plan is proposed to reduce the net GHG emission of 29,659 metric tons CO_2/yr (Poseidon Resources 2008). The net GHG emission will be offset through a series of offset projects as well as renewable energy credit (REC) purchases. Contracts for offset projects provide more price stability and are typically established for longer terms (10-20 years) than RECs (1-3 years). At approximately 1.5-2 years before operations begin, Poseidon will develop and issue a request for proposals for carbon offset projects and renewable energy credits (Poseidon Resources 2007b).

Onsite carbon footprint reduction measures for the Carlsbad desalination plant will be achieved by applying high efficiency energy recovery devices, green construction of the desalination plant, use of on-site solar power generation, CO_2 sequestration for post-treatment applications, energy reductions in supplemental water reclamation treatment, and sequestration of coastal wetlands. Overall, the associated annual emissions savings from onsite mitigation efforts is approximately 13,190 to 13,431 metric tons of CO_2 per year (Poseidon Resources 2008). Based on Poseidon's desalination demonstration plant's pilot tests, the power savings associated with the use of pressure exchangers will allow recovery and reuse of 33.9% of the energy associated with the reverse osmosis process. The energy recovery device will reduce the baseline form 31.3 aMW to 28.1 aMW (average megawatt), reducing the energy consumption to 3.2 aMW, corresponding to 28,244 MWh/yr and 10,001 metric tons CO_2 per year (Poseidon Resources 2008).

The MMWD also assessed the use of alternative renewable energy sources to power the proposed desalination facility (MMWD 2007a). MMWD considered alternative energy from various suppliers including Pacific Gas and Electric. Alternative renewable energy sources could include solar energy, wind energy, wave/tidal energy, and landfill gas energy. To help minimize the energy requirements for the MMWD desalination facility, the plant design would incorporate high efficiency pumps and the most advanced energy recovery systems available. The desalination facility would also be designed with the flexibility to permit adjusting system operations to minimize energy use depending on the salinity and temperature of the Bay water (MMWD 2007a).

Concerns of Renewable Energy and Carbon Offsets for Desalination

Carbon neutrality for desalination plants may be achieved when renewable energy in the electric network is directly received by the desalination plant, thus offsetting any carbon emissions. Since renewable energy sources cannot be differentiated, energy consumers may ensure its energy supply is received through renewable energy sources by way of purchasing renewable energy credits. Use of renewable energy credits for carbon offset schemes however can be misleading. The primary issue involves a lack of a standardized definition of the term "carbon neutral" (ACCC 2008). The REC market is in its infancy and carbon credit transactions primarily lack a central trading platform which limit's the market's transparency.

Concerns over the reliability and clarity of the renewable energy credits need to be considered. Renewable energy credit reliability refers to the credibility and trustworthiness of the purchased renewable energy credits. REC purchases and trading may be difficult to follow because it involves products that represent the absence of tangible goods or services (GAO 2008). In addition, inherent uncertainty in measuring emissions reduction may create inadequacy or varying degrees of quality amongst offset credits (GAO 2008). Use of renewable energy credits which may lack credibility would undermine the achievement of the carbon neutral goal.

Further concerns in carbon neutral claims include additionality, double counting, and forward credited offsets. Additionality refers to evaluating whether GHG reduction and offset projects are additional to what would have occurred anyways (ACCC 2008). For example, renewable energy increases due to government imposed mandatory renewable energy targets may not be considered an additionality. Despite committing to RECs, the Perth desalination plant received criticism for not attaining credits from beyond business as usual sources and thus do not apply as an additionality (Harries 2008, WA Today June 27, 2008). Double counting occurs when an offset is counted or claimed by more than one business rather than it being retired

(ACCC 2008). Double counting offsets mislead purchasers of the offset, and causes specific claims in reduction in emission to not actually occur. Forward credited offset pertains to accepting or crediting offsets before the offsets have been produced and uncertainty exists in terms of when actual offsets may be generated. One primary example involves carbon offsets generated from tree planting where the offsets may take decades to realize (ACCC 2008).

The Government Accountability Office identified four conditions for offsets to maintain credibility, which entail offset projects to be additional, quantifiable, real, and permanent (GAO 2008). As previously stated, additionality considers GHG emission decreases in addition to business-as usual conditions. Quantifiable conditions demonstrate that reductions can be measured. Real criterion shows that offsets and reductions can be verified. Permanent criterion means emissions reduced, sequestered, avoided by a project will not be released into the atmosphere in the future. In addition, it is important to ensure double counting of a particular offset does not occur (GAO 2008).

SUMMARY

One of the major hurdles to implementation of desalination technology is high energy intensity and its associated greenhouse gas emission. Since 1990s, SWRO's energy consumption has significantly decreased, largely due to several advances in technology. These advances include: (1) new low-energy RO membranes with improved salt rejection; (2) high efficiency pumps and motors; and (3) more efficient energy-recovery devices. Among various factors, energy recovery devices play a key role in reducing energy consumption of SWRO. Most SWRO plants built after 2002 utilize pressure exchange ERDs. In general, the energy recovery devices can typically recover 20 to 48 percent of the input energy for seawater RO given that the energy remaining in the concentrate stream is approximately 40 to 50 percent of the feed energy. The power consumption of recently built SWRO plants has reduced to the range of 13.3-23 kWh/kgal (3.5-6.0 kWh/m^3).

Co-location and co-generation with power plants can further improve energy efficiency of desalination plants. Co-generation offers opportunities of simultaneously supplying and consuming electricity and heat in the same system. The capital investment for cogeneration plants however is high. Using the cooling water discharged from the co-located power plant can reduce RO pressure because the cooling water is usually 5 to 15^{o}C warmer than the ambient source ocean water. However warmer water source may cause membrane biofouling and higher solute permeation.

The issue of high energy consumption in desalination is further compounded with concerns of climate change and greenhouse gas emissions. Renewable energy such as wind and solar energy allows potential for desalination plants to be carbon neutral, and more environmentally friendly. Currently wind energy holds the most potential as a renewable energy source, and has been credited toward large desalination plants in Australia.

CHAPTER 7
ECONOMICS OF DESALINATION

Accurate economic analysis and financing considerations are critical in determining the feasibility and planning of desalination projects. Chapter 7 discusses:

- The costs, values, and external benefits of desalination
- The factors affecting desalination costs, including the potential impact of using different sources of renewable energy
- The advantages and risks of some common financing approaches

COST OF DESALINATION

Determining the actual cost of implementing desalination technologies is highly variable and site specific. Desalination costs comprise of a variety of parameters such as location, ownership of the facility, feed and product water quality, production capacity, local construction costs, energy costs, as well as hidden costs in subsidies and amortization periods (Spang 2006). All these factors make desalination cost comparisons difficult. Typical values for water cost (including treatment and delivery) are shown in Table 7.1. Table 7.2 illustrates the cost of producing potable water of several SWRO plants. The costs of seawater desalination plants decreased significantly from \$7.9/kgal (\$2.09/m^3) for the Santa Barbara SWRO plant built in 1991, to \$3.86/kgal (\$1.02/m^3) and \$2.5/kgal (\$0.66/m^3) for the Perth and Ashkelon desalination plants, built in 2006 and 2005 respectively. The cost reductions of the recently built desalination plants are due to:

- Improvement in the efficiency of technology;
- Technology maturity as such designs become more commonplace
- Increasing plant size with economy of scale
- Lower financial rate
- Intense competition between equipment suppliers worldwide, which lowers profit margins and increases production efficiency

Table 7.3 shows the cost structure for typical brackish water desalination and seawater desalination. The energy consumption and fixed charges (essentially the capital cost of the RO equipment) are the major costs of desalination.

Despite higher costs, significant strides have been accomplished to make desalination less costly. When SDCWA originally performed a feasibility study for desalination from 1991 to 1993, the option was rejected because it was deemed too expensive compared to other resources (Yamada 2007). The cost of desalination has decreased since then (Table 7.2) and SDCWA is currently reconsidering desalination as part of their water supply scheme. Water utilities have been aware that desalination has been in existence for several decades, but have not seriously pursued such options until recent years because the technology has become reasonably affordable while the cost of new, more conventional water supplies has increased.

The energy consumption of seawater desalination can account for 44 percent of the total SWRO cost (Table 7.3), and 50 percent of annual operating cost (Veerapaneni et al. 2007). Although there is a limit in which desalination energy consumption cannot go below, reducing energy consumption still holds the greatest economic potential to lower the total desalination cost.

It should be noted that unit water cost is a strong function of plant utilization. Some facilities will be used intermittently, which will result in higher life cycle costs as less water is produced. For example, the Thames Gateway Water Treatment Plant (TGWTP) is planned to provide supplementary water under dry conditions. It will be used as a backup supply for meeting future peak demands. The cost of desalination at TGWTP at 40% capacity is estimated to be approximately 1.18 US$/kgal (0.81 £/m^3) as opposed to 0.51 US$/kgal (0.35 £/m^3) at 100 percent capacity (Lyon 2006).

Table 7.1
Water costs to consumers, including treatment and delivery, for existing traditional supplies and desalinated water

Supply type	Water cost to consumers ($/kgal)	($/m^3)
Existing traditional supply	0.90-2.50	0.238-0.661
New desalinated water		
Brackish water	1.50-3.00	0.396-0.793
Seawater	3.00-8.00	0.793-2.114
Combined supply		
50% traditional supply+50% brackish water	1.20-2.75	0.317-0.727
90% traditional supply+10% seawater	1.10-3.05	0.291-0.806

Source: AMTA 2007, NRC 2004.
Note: Cost is typical for urban coastal community in the US, but inland desalination costs may be higher.

Table 7.2
Total cost (capital and O&M) of seawater RO desalination plants

SWRO Plants	Cost ($/kgal)	Cost ($/m^3)
Santa Barbara 1991	7.9	2.09
Bahamas 1996	5.5	1.45
Dhekelia 1997	5.2	1.37
Lamaca 1999	3.4	0.90
Trinidad 2000	2.8	0.74
Tampa 2007[1]	2.85	0.75
Ashkelon 2007	2.5	0.66
Perth 2007	3.86	1.02

Source: NRC 2004, and survey results. The cost does not account for additional costs to the customers, such as distribution.
Note:[1] $3.19/kgal for the first year after remediation. The cost will reduce to net $2.85/kgal upon receipt of $85 million in co-funding from Southwest Florida Water Management District.

Table 7.3
Percent distribution of cost factors

	Brackish water (%)	Seawater (%)
Fixed costs	54	37
Electric power	11	44
Labor	9	4
Membrane replacement	7	5
Maintenance and parts	9	7
Consumables(chemicals)	10	3

Source: Miller 2003

The use of subsidies hide the real cost of desalination. Several state and federal grants, as well as funding opportunities exist for cost absorption (Karajeh and BenJemaa 2005). In addition, public agencies can float tax-exempt municipal bonds, which provide low cost financing. Due to the subsidies from the Metropolitan Water District of Southern California (MWD), West Basin is able to offset 25 percent of its cost in its planned desalination production, thus minimizing impacts on its ratepayers. MWD subsidizes \$250 for every acre-foot (\$0.767/kgal or \$0.20/m^3) of water produced by desalination as compared to \$195/acre foot (\$0.60/kgal or \$0.16/m^3) for conservation efforts (CCC 2004). MWD maintains that their subsidies for conservation are significant and although the subsidies for desalination and conservation may not be exactly equal, they are fair and balanced. The difference explained by MWD is that desalination subsidies are based on water being produced more immediately as opposed to projected water savings over a 20-year term for conservation programs.

Groups concerned about desalination desire a more comprehensive economic impacts analysis of a multitude of alternative options and often ask for a *full account* of the benefits and negatives of each approach. For example, desalination opponents would like to see the use of subsurface intakes for reducing impingement and entrainment of marine life rather than using open ocean intake structures. Despite higher capital costs, subsurface intake structures might be more economical than open intakes by providing cost savings in pretreatment operations. Environmental and coastal protection groups also argue that economic comparisons between desalination, conservation, and reuse are not being fully evaluated. Opponents of desalination emphasizes that seawater desalination will only consist of approximately 5 percent of the overall water supply 20 years from now. They argue that this level of supply can be achieved through more aggressive investment in conservation and reuse at a potentially lower cost. Water agencies hold the view that conservation and recycled water efforts are also not cheap to achieve. Until proper cost analyses are readily available, such an issue will remain in contention.

VALUE OF DESALINATION

Despite the higher cost, desalination is considered a viable option for specific communities and regions because of its inherent "value." Desalination is valued differently to different communities because they face different water supply problems and conditions. A community that is highly dependent on imported water and has no emergency water supply will value implementing desalination differently and is likely willing to pay a higher price than a community that has less water stress. The reliability of traditional water supplies is impacted by weather patterns. A significant reduction in availability of traditional water supplies will increase the value of desalination considerably. Although addressing these variations is part of the regional planning process, it highlights the need for supplies that are independent of climate (Ruetten 2004; Howe et al. 1994). Implementation of desalination also increases the diversity of water supply, reduces the risks of reliance on a single or traditional water sources, and increases long-term reliability.

Desalination of brackish water and seawater will bring some unrecognized regional benefits like maintaining or restoring stream flows, or freeing up other existing regional resources for other users. Desalination provides less dependence upon imported water, which mostly is transferred from other rivers and reservoirs. Water overdrafts from such sources have negative environmental impacts on their local watersheds. Desalination is a step to protecting those sources. It also protects groundwater sources near the coast where some communities are already experiencing salt water intrusion.

Desalination projects usually aim at reducing reliance on water imports that would be unsustainable in the long-term; or curtailing over-pumping of already severely deteriorated groundwater aquifers; or curtailing existing water supply practices that have significant environmental impact on fragile river ecosystems (Voutchkov 2007). The 50 mgd (189,000 m^3/d) Carlsbad seawater desalination project is planned to replace the reliance of the City of Carlsbad and a number of other neighboring utilities on water transported from the Sacramento-San Joaquin River Delta and the Colorado River because these sources are drought sensitive and have uncertain futures (Poseidon Resources 2006).

The Marin Municipal Water District proposes to implement one of the largest seawater desalination projects in the San Francisco Bay area. The project is planned to produce between 10 and 15 mgd (37,850 and 56,770 m^3/d) of desalinated water and provide a reliable, drought-proof alternative to the construction of a new pipeline for supplemental water supply from the already over-allocated Russian River. Similarly, the main purpose of the seawater desalination project proposed for the City of Moss Landing in Monterrey County is to alleviate further overdraft of the Monterey Bay coastal aquifers and to comply with the state-mandated curtailment on withdrawal of fresh water from the Carmel River because of the detrimental impact of withdrawal on the salmon population in the river.

In the 1990s, Tampa Bay faced a range of regional water problems. Local groundwater overdraft was adversely affecting natural wetlands and lakes in the area and led to salinity intrusion (Wright 1999). The Tampa Bay desalination plant was proposed to provide 25 mgd (94,625 m^3/d) of the mandated withdrawal reduction, or approximately 10 percent of the region's need, to alleviate the over-extraction on local groundwater source (Rand 2003).

By increasing the water supply through desalination, communities with limited water supplies can reduce the competition between agricultural, municipal, and environmental needs. Desalination also produces water with quality beyond the EPA standards for safe drinking water, ensuring public health and safety.

In addition, desalination benefits domestic consumers from softened water supply through (i) reduced scaling and extended lifetimes of electric and solar water heaters and all house piping, particularly hot water piping; (ii) savings in household soap, detergents, ion-exchange softening resins and regeneration salts. Industrial consumers will save on their water softening and demineralization costs. The lower salinity municipal water supply will in turn result in lower TDS levels in the municipal wastewater which may enhance the operation of wastewater treatment plant, and water quality for surface water discharge or beneficial use.

As a whole, it is recognized that desalination costs more when compared to current imported water supplies, traditional water sources, and water reclamation and reuse for irrigation and industrial use (Voutchkov 2007, NRC 2004). Desalination is accepted because water agencies believe that desalination enhances system reliability and water quality. A feasibility study of the Dana Point Ocean Desalination facility by MWDOC revealed that the cost of desalination in the area will be $1,287 per acre foot ($3.95/kgal or $1.04/m^3), which is dramatically higher than the $600 per acre foot ($1.84/kgal or $0.48/m^3) cost for imported water (MWDOC 2007). However, additional studies by MWDOC also showed that continued dependence on the imported water supply would cause significant economic problems if an emergency outage occurred. This makes desalination an attractive investment because of its water reliability benefits.

ESTIMATING VALUE OF DESALINATION

Economic evaluation of desalination projects is important because it aids in determining whether the public support proposed projects and estimating the degree to which they are willing to pay for the benefits.

One way to evaluate the value of desalination is to assess the cost associated with the next best alternative option. In some areas, the import cost of water may be higher than implementing a desalination plant. In this sense, the values of desalination may be accepted.

Dreizin (2006) reviewed the total desalinated water costs and benefits for the Ashkelon desalination plant. The costs comprised the risks and the Israeli Government's anticipated direct and indirect, fixed and variable costs. The escalated desalinated water costs were compared to the similarly anticipated but differently escalating costs of other water sources in Israel. The benefits were presented against: (i) the background of Israel's current water supply system's water sources' sustainable capacity, reliability, quality and costs, (ii) the anticipated growth in demand by various consumer sectors, and (iii) the continuous deterioration of groundwater quality.

It is challenging to assign value to an enhanced reliability in water, as well as recognized and unrecognized social, environmental, and ecological benefits. Surveys are usually conducted to quantify the economic value of water supply as a public good, and the level in which the water supply may also contribute to environmental benefits. A common survey method is the stated preference approach, also called the contingent valuation method. In the survey, the respondents are offered conditions simulating a hypothetical market in which they are asked to express willingness to pay for existing or potential environmental conditions (Young 1996). Howe and Smith (1993) used contingent valuation survey methods to measure customers' willingness to pay for improved water supply reliability and willingness to accept lower water costs for reduced reliability. Mean annual willingness to pay per household ranged from $80 for approximately a 0.16 to 9.2 percent increase in reliability of water supply.

Modern portfolio theory - as originally devised and applied to financial assets, has also been applied to water resource portfolios (Beuhler 2006, Raucher 2006, Cooley et al. 2006). The central goal is to maximize expected returns (i.e., water yields) while also reducing the overall variance in portfolio yield (Raucher, 2006). Beuhler (2006) reported the potential benefits of an optimized Portfolio including: (1) identifying more reliable water portfolio options; (2) valuing water options and pricing; (3) quantifying the inter-basin benefits; (4) identifying possible negative correlation with outdoor conservation; (5) evaluating the systematic risks due to the hydrologic cycle such as drought, and non-systematic risks such as water quality, climate, and energy. Portfolio theory is used to help water managers in Coachella Valley Water District to make decisions on how to optimally meet future water needs (Beuhler 2006). By explicitly considering volatility and correlations among water resource alternatives, rational resource combinations can be selected.

The Pacific Institute used the Portfolio theory to estimate the unit costs of water supply options (including conservation and end-use efficiency). The method employed constant-reliability-benefit unit costs to compare different supply options on a same level of reliability basis (Cooley et al. 2006). Recent work sponsored by the U.S. Bureau of Reclamation will help explain how the concept of "portfolio theory" can be constructively applied to water supply portfolio choices (Kasower et al. in preparation). Water supply options that are drought-resistant (such as desalination or water reclamation) may provide a special type of reliability value-added, compared to other, more traditional (and drought-sensitive) water supply options.

ECONOMICS OF RENEWABLE ENERGY WITH DESALINATION

Although valued from the perspective of public opinion, the use of renewable energy and carbon neutral schemes to support desalination will be expensive. Renewable energy and carbon neutral driven desalination plants on the large scale have been limited in experience and capacity (Mathioulakis et al. 2007). There are also limitations in temporal and space dependency of these renewable resources, as well as high investment costs (Mathioulakis et al. 2007). In addition, the concept of eliminating emissions from a grid connected desalination plant is somewhat abstract as it is not possible to direct electricity flows from specific generators to specific loads as the network combines all electricity from all generators. The concept of being carbon neutral is achieved when additional renewable energy is supplied in the network equivalent to the electricity consumption of the desalination plant over time (Knights et al. 2007).

Introduction of a renewable energy source may not necessarily be based on economic values. Water costs using renewable energy are found to be higher than water costs using traditional fossil fuel energy sources. Primarily, it will hold significant social value. There is a perception that fossil fuel energy prices may increase due to climate change and oil market dependency concerns. Accordingly, this can force desalination costs to increase. Under such conditions, the use of renewable energy may become more attractive for desalination as compared to conventional fossil fuels.

Cost of Solar Power

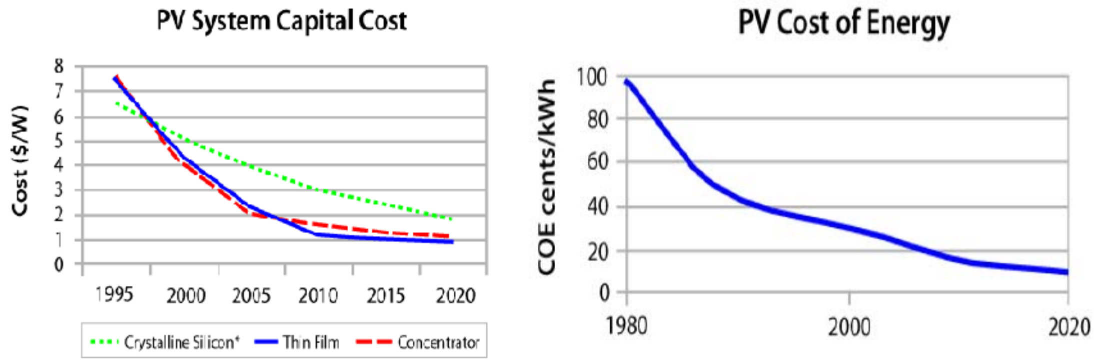
The costs for solar power may be up to ten times the cost of traditional fossil fuels (Table 7.4). Photovoltaic solar energy can cost from 20 cents per kWh up to 80 cents per kWh (REN21 2005). In contrast, fossil fuel costs are approximately 2 to 4 cents per kWh for coal and 3 to 5 cents per kWh for natural gas (REN21 2005). A comparison of photovoltaic solar energy with local electrical energy for seawater RO performed by Afgan et al. (1999) determined desalination costs can increase a factor of 4 just for using solar renewable energy.

Table 7.4
Cost of renewable energy compared to fossil fuel and nuclear power

Technology	Current cost (U.S. cents/kWh)	Projected future cost beyond 2020 as the technology matures (U.S. cents/kWh)
Biomass Energy:		
Electricity	5-15	4-10
Heat	1-5	1-5
Wind Electricity:		
Onshore	3-5	2-3
Offshore	6-10	2-5
Solar Thermal Electricity (insolation of 2500kWh/m per year)	12-18	4-10
Hydro-electricity:		
Large scale	2-8	2-8
Small scale	4-10	3-10
Geothermal Energy:		
Electricity	2-10	1-8
Heat	0.5-5.0	0.5-5.0
Marine Energy:		
Tidal Barrage (e.g. the proposed Severn Barrage)	12	12
Tidal Stream	8-15	8-15
Wave	8-20	5-7
Grid connected photovoltaics, according to incident solar energy (insolation):		
1000 kWh/m per year (e.g. UK)	50-80	~8
1500kWh/m per year (e.g. southern Europe)	30-50	~5
2500 kWh/m per year (most developing countries)	20-40	~4
US (peak watt, including support structure, power conditioning, and land)*	20-50	
Stand alone systems (incl. batteries), 2,500 kWh/m^2 per year	40-60	~10
Nuclear Power	4-6	3-5
Electricity grid supplies from fossil fuels (incl. T&D)		Capital costs will come down with technological progress, but many technologies are largely mature and may be offset by rising fuel costs
Off-peak	2-3	
Peak	15-25	
Average	8-10	
Rural electrification	25-80	
Costs of central grid supplies, excl. transmission and distribution:		Capital costs will come down with technological progress, but many technologies are largely mature and may be offset by rising fuel costs
Natural Gas	2-4	
Coal	3-5	

Source: REN21 2005; * USDOE 2007

Despite the higher cost, the cost trend of electricity from photovoltaic systems has dropped 15- to 20-fold since 1980; and grid-connected PV systems currently cost approximately $5-$10 per peak watt (20 to 50¢/kWh), including support structures, power conditioning, and land (USDOE 2007). They are highly reliable and can last 20 years or longer. The U.S. Department of Energy (2007) estimated that the cost of PV will continue to decline with the improvement of technologies (Figure 7.1). Hundreds of applications are cost-effective for off-grid needs. In addition, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California and other states are currently subsidizing PV systems because it is considered cost-effective to reduce their peak daytime loads for air-conditioning, which matches PV output.



Source: USDOE 2007

Figure 7.1 Costs of solar power from photovoltaic cells

Cost of Wind Power

Of the renewable energy options, the use of wind for energy production may have a higher potential since it is much more comparable to fossil fuel costs at 3 to 5 cents per kWh (REN21 2005). U.S. DOE reported the current performance is characterized by levelized costs of 4 to 5.5 cents per kWh (depending on resource intensity and financing structure), capacity factors of 30 to 40 percent, availability of 95 to 98 percent, total installed project costs (not including construction financing) of $800 to $1,100/kW, and efficiencies of 65 to 75 percent of the theoretical (Betz limit) maximum (USDOE 2007). It is estimated that the wind capital cost and wind cost of energy would not change considerably in the future (USDOE 2007).

Zejli et al. (2004) performed an economic analysis of a small-scale RO desalination facility (0.317 mgd or 1200 m^3/d) using onsite wind turbines connected to a grid system versus a non-renewable grid only energy source. The cost of desalinated water was calculated in terms of levelized water costs. Levelized cost is the total cost of building and operating a power plant over its economic life, converted to equal annual payments. The levelized cost for the study was a function of wind potential, investment costs in RO and wind turbines, O&M costs, discount rate, and the plant lifetime (Zejli et al. 2004). Given a lifetime of 20 years the wind and grid powered desalination plant was determined to be cheaper than the grid only desalination in terms of its levelized costs. Desalination with a grid connected wind turbine plant was lower with a levelized water cost of €1.5/m^3 (US$2.21/$m^3$), as opposed to €1.67/$m^3$ (US$2.46/$m^3$) for the grid only plant.

Wind powered desalination has been seen primarily as small scale systems (Garcia-Rodriguez 2003) and more recently few cases have been implemented on the large scale. The use of wind energy for large scale desalination has been observed at the Kwinana desalination plant in Perth, Australia. The Kwinana desalination plant purchased the equivalent of its power requirement from the Emu Downs 80MW Wind Farm (Dickie 2007). Financially, wind energy use for the Kwinana plant is reported to have no material effect on the price of water (Water Corporation n.d.). However, this may not always be the case. The use of wind energy will increase costs to consumers of water supplied by the Sydney and Melbourne plants. It is reported that Victoria's water users will pay an additional AUD 15 million (approximately US$13.7 million) per year for the plant to be powered by renewable energy (Whinnett 2007). The New South Wales state premier has stated that wind power is more expensive than coal or gas and the additional cost will be passed on to consumers. Consumers will pay an additional AUD 100 to 110 (approximately US$91.7-100.8) per year for water which will include any additional expense resulting from renewable energy use (AAPGN 2007). This dilemma may need to be solved with a policy providing incentives to use renewable energy sources at desalination plants.

CONSIDERATIONS OF FINANCING

When investing in a new desalination projects, most water utilities prefer implementing desalination projects in a more utility driven approach, i.e., in a design-bid-build with the operation part being performed by the utility. However, there is firm agreement that, although it may be desired for all phases of the project to be performed "in house", the financial capacity to do so is getting more limited. The ability to support technical staff full time may not be viable. Quite often, a need to export service may be required. In some cases, public utilities are observed to shift towards a partnership with a private firm. The transfer of services to private sectors would include advantages as transferring risks and responsibilities of asset ownership, operation, maintenance, and replacement to the private sector. Another economic and financing consideration is the flexible approach and strategies of privatized firms in implementing desalination projects. For example, private firms have the ability to implement supplementary restoration and conservation programs that may offset environmental concerns from particular desalination plants. Such flexibility may hold advantages over public utilities.

Ashkelon Seawater Desalination Plant is the first large desalination that is governed by a Build, Operate, and Transfer (BOT) Agreement for a period of 24 years and 11 months between the State government of Israel and private sector's VID Desalination Company Ltd. VID is a special purpose company established by Vivendi Water, IDE Technologies Ltd and Dankner Ellern Infrastructures Ltd to design and operate the desalination plant. The BOT Agreement stipulated that the Consortium could be requested to double the plant production capacity at the request of the government. The capacity extension enabled VID to lower the desalinated water price below 1.89 US$/kgal (0.50 US$/m^3), a first in the desalination history; the doubling of the capacity also made the Ashkelon project the largest SWRO desalination plant in the world.

Conversely, the road to seawater desalination in Tampa Bay was a long one (Rand 2003). In 1999, Tampa Bay Water selected Poseidon Resources of Stamford, Connecticut, USA, after an open competition for a private partner in the project. As a design, build, own, operate and transfer (DBOOT) project, the agreement presumed that Poseidon would assume risk for the plant's development. The DBOOT agreement was to reduce costs while keeping tight government control, flushing out flaws in proposals and typically achieving lower prices through competition (Rand 2003). The DBOOT approach also would allow Tampa Bay Water to leverage the efficiencies of the private sector and still take advantage of the tax-free financing available to governments.

The DBOOT process demonstrated value when the plant constructors Stone and Webster and Covanta each had financial problems (Rand 2003). In July 1999, Poseidon Resources originally selected Stone & Webster to design, engineer and build the plant, but the company went bankrupt. Poseidon then brought in Covanta Energy of Fairfield, New Jersey, in December 2000 to take over responsibility for plant construction. In 2002, Tampa Bay Water decided to acquire the desalination plant, which was approximately 50 percent constructed, thereby assuming full responsibility, and risk, of the desalination plant. Due to the technical challenges related to intake and pretreatment as well as financing of contractors problems, the plant costs increased from the originally estimated $110 million to an additional excess of $40 million (construction oversight: $4 million, remediation and improvements: $36 million, attorney fees for lawsuits: $6.8 million) since Tampa Bay Water bought the facility in 2002. The promised water price increased from $1.71/kgal ($0.45/m^3) in 1999 to $3.19/kgal ($0.84/m^3) in 2007 (Barnett 2007). Tampa Bay Water's experience demonstrated that the public water agency may lose control of the project and treatment process because of selected private entities. In their case, it resulted in an inoperable facility and the need to then hire another private entity to fix their problems at considerably greater total cost than originally anticipated.

SUMMARY

The economic focus in implementing desalination overwhelmingly appears to be instantaneous expenses. The costs of seawater desalination plants have decreased significantly due to advances in technologies, increased plant size, and improvement of production efficiency. Desalination cost is site specific, and is a strong function of the level of plant utilization. Intermittent use of a desalination plant results in higher unit cost. The use of renewable energy to reduce the carbon footprint often results in higher water cost. With the cost decrease of renewable energy and the cost increase of conventional energy sources, the use of renewable energy will be more feasible in desalination.

The economic consideration should include the externalities of a desalination project. Identifying externalities can also demonstrate multiple values in desalination. Desalination has value in diversifying water resources, decreasing stress in water overdrafts, and may provide a constant water supply source in seawater applications. By demonstrating such values, desalination projects may be introduced as an investment rather than comparing it to equivalent costs of conventional water supplies.

Among a variety of financing approaches, the design-build-own-operate-transfer (DBOOT) approach has the advantages of reducing costs through competition of private sectors. However, the public agency might risk of losing control of the treatment process by the selected private entities and resume the responsibilities if the private sectors fail to perform.

CHAPTER 8
SOCIAL, POLITICAL, AND INSTITUTIONAL ASPECTS OF DESALINATION

Social, political, and institutional issues are playing a key role in the regulatory and permitting process, and are often the most significant hurdle in implementing desalination technologies. One focus of the research was to investigate and understand these aspects under different social, political, economic, geographic, and climatic settings. A better understanding of the issues would help water utilities identify and develop potential options and strategies to address these challenges.

A common observation from the case studies is the significant impact of environmental considerations of desalination on the social, political, and institutional justifications. The environmental considerations include impingement and entrainment, benthic damage, greenhouse gas emissions, coastal restoration and land use, and concentrate disposal. Additional issues for the local community include truck traffic to/from the facility, transport of chemicals, health and safety issues associated with facility construction and operation. Fully addressing these issues is critical to avoid the opposition to a proposed desalination project.

This chapter discusses the specific social, political, and institutional aspects of desalination through case studies of the United States (seawater desalination in California and south Florida, and inland desalination), Australia, Israel, and the United Kingdom.

UNITED STATES CASE STUDY

Seawater Desalination in California

Public Perception and Politics

A recent public opinion survey conducted by San Diego Institute for Policy Research, LLC, and Competitive Edge Research and Communications, Inc. tested three methods for dealing with water shortages: seawater desalination, mandated water conservation, and wastewater recycling. The polling showed that 53 percent of San Diego registered voters strongly support, with additional 28 percent "support, somewhat", bringing seawater desalination projects to San Diego (Nienstedt 2007). However, both water utility managers and coastal advocates agree that the general public has not yet engaged in the debate. Consequently, the public does not understand all of the important issues related to the implementation of desalination. One agency noted that in general, the public seldom knew what their current water rates were, let alone the specific issues associated with desalination. It is somewhat natural for people to react favorably to desalination. It offers what appears to be a limitless supply and does not have the stigma often attached to potable reuse.

Although the same technology applies to water reuse, the concept of recycling wastewater from "toilet to tap" has met more opposition. For instance, the Mayor of San Diego, Jerry Sanders, restated his opposition to using treated sewage to supplement San Diego's drinking water supply (10News, September 13, 2007). Instead of a "toilet-to-tap" program, the Mayor said residents need to increase conservation efforts and officials need to explore new sources of water, like desalination. Conservation efforts often call for voluntary management practices and can be viewed as work. Without a serious water shortage or clear indication of climate change, the general public may never become engaged in the debate in Southern California. If the water situation forces the public to become interested and engaged, it will likely mean that the process of implementing desalination will accelerate rapidly, irrespective of the debate on its environmental impacts.

Ultimately, implementation of desalination is a policy decision and support for desalination may be highly dependent on values of policy makers and the political strength of stakeholders. Despite approval of a pilot desalination plant in its area, LADWP has decided to focus on conservation and reuse ahead of ocean desalination (Erb 2007). Conversely, in San Diego, its mayor has been publicly supportive of desalination and the SDCWA board members have been very interested in pursuing desalination. Recently, the San Diego County's congressional delegation, San Diego County state delegation, and San Diego's Sacramento delegation announced their unanimous, bipartisan support for the Carlsbad Desalination Plant in a letter sent to the California Coastal Commission (Carlsbad Desalination Project Public Support 2007).

In addition to public perception, special interest groups exist because the public needs people that are focused on addressing a broad range of interest and values (Ruetten 2004). Often, these special interest groups have significant influence on those who make the final decisions. The interest groups are also important in influencing the perception of the general public. An important factor leading to the successful implementation of desalination is developing a comprehensive public outreach program that introduces, showcases, and informs the public and the media that desalination is a safe and reliable solution to addressing the shortage of freshwater.

On a larger scale, the issue of desalination is associated with the larger issue of funding. Despite public support for desalination, utilities admit that they need to improve public outreach programs and convey the need for continual funding in maintaining and expanding infrastructure.

As discussed above, how the public and the special interest groups perceive desalination will have a significant impact on whether projects are supported. The implementation of desalination projects depends on a good education program, which provides information about how the project will be conducted, what the project will mean to the pubic, and how the project will collaborate with the public. The Marin Municipal Water District (MMWD) in California conducted a pilot study to establish technical, engineering, environmental, and budgetary information for implementation of seawater desalination. A comprehensive public outreach program was developed to inform the citizens of the progress and the results of the pilot study project (Castle et al. 2005). This interaction with the public was essential to the development of a full-scale project.

Proposals to consider ocean desalination in Southern California have increased the scrutiny on progress in implementing conservation and reuse (Cooley et al. 2006, Desal Response Group). Opponents of ocean desalination argue that increased conservation and reuse should come first because they may be more cost-effective and have more environmental benefits; including reduction in wastewater discharge. They further reinforce their arguments by highlighting the negative impacts of seawater desalination on marine life.

Water agencies contend that evaluating and planning for ocean desalination do not supersede conservation efforts. In fact, the California Department of Water Resources (DWR) requires that conservation and reuse be an integral element of a balanced water supply portfolio, and water reuse and conservation should be implemented to the maximum extent practicable

(Desalination Task Force 2003a). The California Coastal Commission also requires evaluation of other water supply alternatives that may be less environmentally harmful, including conservation and reuse (CCC 2004). For example, in the Santa Ana River Basin, practically all wastewater is currently recycled through direct and indirect groundwater recharge, with the exception of a portion of treated wastewater now discharged to the ocean. Orange County Water District has oversized its recently completed $492 million Groundwater Replenishment System project to recycle up to 130 mgd (492,000 m^3/d) (Bell 2008).

As a whole, it is recognized that seawater desalination costs more when compared to current imported water supplies, traditional water sources, and water reclamation and reuse. Despite higher cost, desalination is accepted because water agencies and the public believe that desalination enhances system reliability, in particular that seawater desalination provides drought-proof water supply to the public.

Privatization

It is hard to argue that the efforts of Poseidon Resources in Southern California are not significant. They have certainly made the dialogue more interesting and arguably more controversial. The idea of privatization certainly raises issues that can be contentious. For example, who owns the water delivered by a private company once it is delivered to the customer, recovered, and treated by the wastewater system? Water rights disputes over recycled water are already occurring, even without the private-ownership factor. Many public agencies argue that the private model has few advantages because the public sector has access to all of the expertise and technology of the private sector; they can obtain lower cost financing, and may have greater access to development subsidies, all of which help keep water rates low (Interviews and workshop). They also claim that the risks of not having water are the same for a private or public model; so there is no real mitigation of risk when going with the private sector.

Despite these issues, Poseidon Resources has successfully convinced nine San Diego County public water agencies to approve a 30-year water purchase agreement with Poseidon Resources (Poseidon Resources 2008a). 100 percent of the output from the Carlsbad Desalination Project is subscribed. The private model may offer compelling value to certain communities, and it is known that people are willing to pay for value. They may be attracted to an investment proposal that offers a guaranteed allocation of water to their local community and therefore extremely high water reliability. They may be attracted by water independence, including complete independence from the uncertainties of imported water. They may like the idea of not being reliant on a large water wholesaler that may be required to spread the pain evenly between all communities when there is a water shortage. A privately owned desalination plant may be able to offer these benefits and therefore may be compelling to communities that are willing to pay for local control and high reliability. With drought and the specter of climate change, the need to reserve more water for the environment, and increasing uncertainty about the availability of imported water in California, this value proposition may become increasingly attractive.

As public entities face growing budgetary constraints, many locally-elected officials are attracted to the perceived benefits of “privatizing” all or some of their water service responsibilities (CCC 2004). Concurrently, a number of domestic and multinational business entities have identified providing water or “water services” as an attractive profitable investment opportunity. In California, among the approximately two dozen desalination projects currently proposed along the coast, at least six are proposed as private-held facilities or public/private partnerships, including two (in Huntington Beach and Carlsbad) that would be the largest coastal desalination facilities in the United States. Allowing ocean water to become a commodity and marketed for profit would result in a substantial change in how seawater is used and valued by society. As a private commodity, desalination may be developed, managed, and marketed as a for-profit product subject to market forces and practices. The full range of public interest values might not be fully considered during planning, design and operation. The consequences of such "privatization" need to be carefully evaluated (CCC 2004).

Growth Inducement

Another critical issue associated with social and public perception is growth-inducement. In coastal areas throughout California, potable water is sometimes considered a limiting factor constraining development and population growth. Because a new water supply will remove this limitation, some desalination opponents worry that water provided by desalination may facilitate growth (Cooley et al. 2006). The California Coastal Commission pointed out that, "A desalination facility's most significant effect could be its potential for inducing growth" (CCC 2004). The CCC considers that desalination plants that provide a new source of water will have a greater growth-inducing effect than those that provide water to replace an existing supply source. Similarly, water that provides a baseline supply will likely have more of a growth-inducing effect than water produced only during emergencies or droughts (CCC 2004). California's Department of Water Resources (DWR 2003) also discussed the potential of growth-inducing impacts of desalination. It should be noted that some of the desalination projects in planning, specifically the Marin Municipal Water District desalination project, are designed to operate under drought-only conditions. Local communities and the appropriate regulatory agencies should evaluate desalination projects on a case-by-case basis through existing environmental review and regulatory processes. Desalination does not necessarily have to equal growth inducement.

Facing the concerns on growth-inducing effect of desalination projects, Voutchkov (2007) argued that, "Even if all of the proposed desalination projects are built at their maximum planned capacity, they would only be adequate to supply 1.1 percent of the total current state water demand of 40,000 mgd and approximately 5.6 percent of its urban water demand of 8,000 mgd." According to the 2005 California Water Plan, by the year 2030 the State's population is projected to increase by 31.5 percent, which averages approximately 1.26 percent per year. The 5.6 percent increase of water supply resulted from the proposed desalination plants would not meet even half of the population growth. Also the desalination projects are urged to alleviate the environmental concerns of current water management, such as reducing water transfers and curtailing over-pumped groundwater aquifers and rivers. Therefore, the concern that the proposed desalination plants in California will cause growth-inducing effect is unjustified (Voutchkov 2007).

Some utilities also argue that the growth issue in Southern California is less important because the area has already been built to near full capacity. This may still be a bigger issue in Central and Northern California. The MWDOC proposed their desalination project as a way to provide higher reliability for the current population as opposed to supporting new growth. It is indeed prudent to address growth concerns, however, the belief that all coastal advocates do not support desalination based on growth is not completely accurate. Coastal advocates, such as the

California Coastal Commission (CCC), have acknowledged that ocean desalination is and will be part of the state's future and have approved multiple proposals over the last 5 to 6 years. The CCC has stated that the case for needing a new water supply should be very clear (CCC 2004, Luster 2007). This does not mean that the case cannot have provision for growth. It does mean, however, that the water supply investment should be tied to a specific and approved growth plan. Producing a growth plan allows water accountability and allows for proper assessment of the impact of growth on the coastal environment.

Permitting

One of the past concerns in desalination is the lack of direction in the permitting process. It is estimated that approximately 20-25 permits are required to establish and construct an ocean desalination plant (Desalination Task Force 2003b, interviews and survey). Although permitting processes are currently slow, clarification of permitting requirements are progressing. The California State University, Sacramento, was working with the California Department of Water Resources on a desalination permitting roadmap titled "California Desalination Planning Handbook" (2008). The report provides a planning framework for developing economically and environmental acceptable seawater and brackish groundwater desalination facilities in California.

Agencies working transparently and flexibly with the permitting agencies can expedite permits rather than having closed or pre-set plans. Permitting for Sand City's desalination plant took only four months because of their early coordination efforts and their willingness to collaborate and compromise with CCC requests (Luster 2007). On the contrary, Poseidon's construction permitting process for the Carlsbad Desalination plant stretched six years because they were locked into a particular site and design. The project's permitting process began in 2003 and closed in August 2008 with the final permit approved by the California State Lands Commission. The CCC stresses that the regulatory requirements of the Coastal Act should be viewed as an engineering specification or challenge, and not a policy to be debated (Luster 2007).

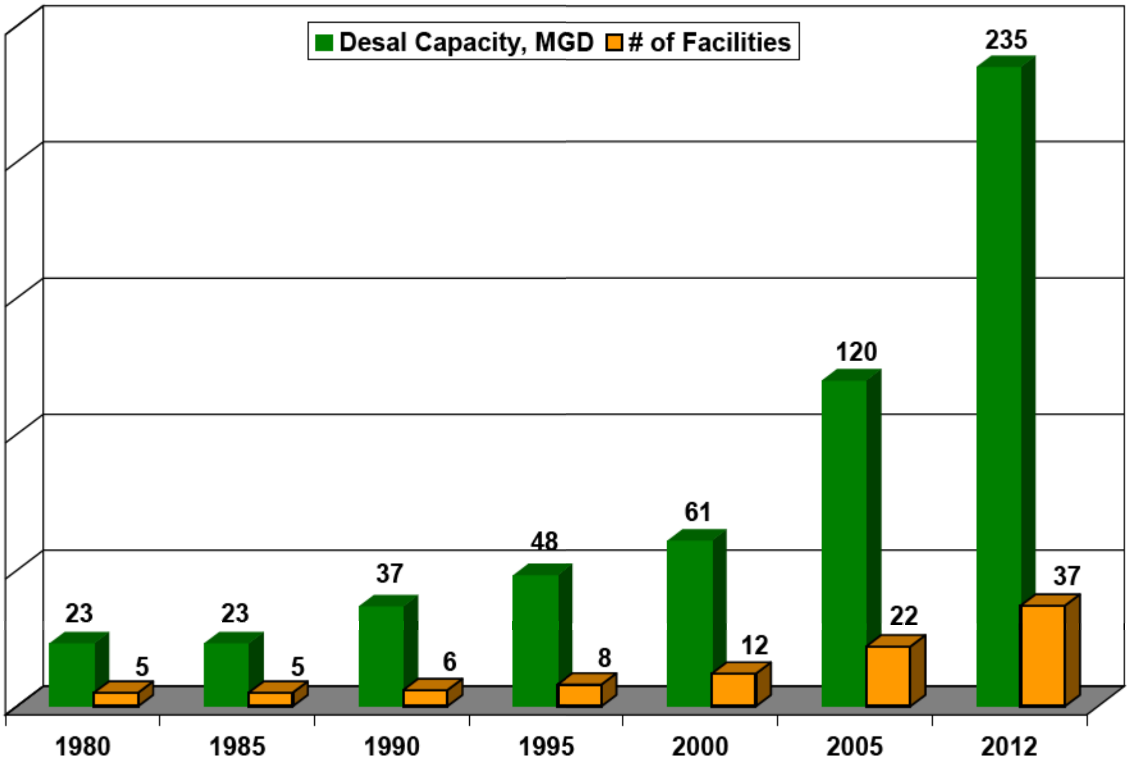
A detailed discussion on regulations and permitting for desalination plants is presented in Appendix B.

Desalination in South Florida

Public Perception and Politics

Replacing all sources with desalination is not the intent of South Florida Water Management District (SFWMD), but desalination is expected to augment water supply reliability through a mixture of sources. Current desalination plants provide more than 20 percent of the region's public supply needs. For the most part, desalination is appropriate for communities in south Florida because of the abundance of brackish water in the region. The 31 brackish water desalination plants in south Florida (Figure 8.1) have a capacity of 185 mgd (700,000 m^3/d). Six additional facilities are under construction, expected to be completed by 2012, will increase the total capacity to 235 mgd (890,000 m^3/d). Projections from the SFWMD regional water supply plans indicate that desalination capacities will account for about 540 mgd (2 million m^3/d), or a 35 percent share of public water supply by 2025 due to new plant additions or existing plant expansions (Akpoji 2007a). The primary means of concentrate disposal is deep well injection.

Although desalination is already extensively practiced in south Florida (Figure 8.1), there has been public concern on the cost and environmental effects, including energy needs. The bottom-line of desalination implementation is cost; increase in water rates due to high cost of desalination is perceived by some to be politically unacceptable. In south Florida, the current water treatment cost is less than \$1/kgal (\$0.264/m^3) for traditional water supplies, and approximately \$1.5-\$2.5/kgal (\$0.4-0.74/m^3) for brackish water.



Source: Akpoji et al., 2008.

Figure 8.1 Growth of desalination in the South Florida Water Management District

During the recent 2007/2008 drought, significant attention and media was provided on desalination through the District's alternative water supply programs, public meetings, newspaper inserts, educational programs, school-based education programs, and science fairs, etc. The public should be familiar with the fact that desalination provides a reliable and drought-proof water supply to south Florida, and the water quality of desalinated water is very high. But, because of the cost, desalination is also often seen as a last resort, if all other source options cannot be used or permitted. The precedent-setting Florida Law SB444 - the Water Protection and Sustainability Act of 2005 encourages cooperation between municipalities, counties, and the state's five water management districts in the protection and development of water supplies. The SFWMD has also established the regional water availability rule to limit increased dependence on the Everglades regional system for water supply in Florida's southeastern coastal counties, furthering the need for development of alternative water supplies.

Reuse is an integral part of water supply in south Florida. The District requires all users to use reclaimed water, unless they can demonstrate its use is not feasible. In 2006, the average water reuse rate was 27 percent in the SFWMD. In the Kissimmee Basin and the Lower West Coast planning areas, 100 percent and 90 percent of wastewater flows, respectively, have been reused. In comparison, the Lower East Coast planning area uses on average only 10 percent of its wastewater. In Miami-Dade and Broward counties, average reuse ranged from five to six percent of the combined 519 mgd (2 million m^3/d) in wastewater flows (FDEP 2007). This minimal reuse encourages regulatory agencies to put water reuse projects first, before supporting desalination projects.

Obtaining the necessary permits for a desalination project is an involved process. Excluding crisis-driven desalination projects, the normal permitting process may take 1-2 years, depending on the specific situations and water demands in the permit applicant's service area. Next, desalination pilot tests must be conducted to alleviate regulatory concerns for environmental impacts associated with concentrate disposal. Finally, a clear and meaningful dialogue with the public, politicians, and environmental groups is necessary to assist desalination proposals in gaining the approval of regulatory agencies.

Typically, multiple stakeholders are involved in the implementation of desalination, including utilities, local and federal regulatory agencies, environmental groups, anti-growth groups, local political units, and businesses. The progress of implementation can be slowed down by balancing the interests of the stakeholders. However, the public's interest and perception, and regulatory and political justifications towards the decision to implement desalination, can be significantly changed by a water crisis. In south Florida, approximately 50 percent of desalination plants were installed primarily due to the following reasons:

- Water was needed to support new growth as mandated by state law (SB444)
- Alternative sources of water were needed as stipulated by water permit regulatory agencies
- The occurrence of droughts necessitated the development of new water sources
- Desalination was needed to mitigate saline water intrusion on shallow coastal aquifers
- Competition for existing cheaper sources resulted in the need for additional sources

Impacts of New Ocean Outfall Legislation on Desalination

During the 2008 session, the Florida Legislature passed laws that will result in the elimination of the six ocean outfalls that are used for effluent disposal. This legislation requires the utilities that currently utilize ocean outfalls as a wastewater disposal method to:

- Go to advanced wastewater treatment by 2018;
- Eliminate the discharges by 2025, except for wet weather; and
- Achieve, at a minimum, 60 percent reuse of the facility's actual annual flow by December 31, 2025.

The elimination of ocean outfalls – all of which are located along Florida's southeast coast within the SFWMD's boundaries – will generate an estimated 300 mgd (1.1 million m^3/d) of reclaimed water for use within some of the most heavily populated areas of south Florida. This may make more water available and may reduce the need for desalination plants.

Funding Assistance

To encourage desalination, the SFWMD administers funds for desalination projects through the Alternative Water Supply Funding Program. Cities, utilities, homeowners associations, community development districts, and other water users and suppliers can apply for up to 40 percent of project construction costs under the new program. The funding program provides annual recurring state funding, underscoring the state's commitment to protect and enhance water supply. Funds available are administered and matched by Florida's five water management districts, for alternative water supply projects. The SFWMD, in cooperation with the State, has provided over $110 million to users developing alternative water supplies in the last three years, including use of brackish and seawater sources.

Desalination in Inland Areas

Regarding public perception, there are no direct or social stigmas specifically relating to inland brackish water desalination. In general, the public is seen to be supportive of desalination. Indirect factors associated with desalination, however, may need to be addressed. Utilities believe the major limiting factor in desalination by the public may be the cost of desalination.

Although, the public and regulators seem open to the issue of desalination, desalination is typically considered a last resort. From the utility standpoint, public opinion is an important factor. However, utilities may sometimes go against the current of public opinion to provide a sustainable water supply. Because inland brackish water desalination is of lower profile, there is generally less opposition from the public. In addition, many of the public concerns characteristic of seawater desalination may not be applicable to inland processes. For example, inland desalination may not be viewed as an unlimited supply of source water as is assumed with seawater desalination. Thus, inland desalination may be considered as more of an investment to the community, rather than as a threat of potential population growth.

One limiting factor in inland applications may be concentrate disposal, and revised regulations on disposal. For example, the concentrate disposal to surface water from three municipal desalination plants in Colorado is challenged by the revised federal and state regulations. Some inland desalination plants dispose RO concentrate to sewer. The major concern associated with this concentrate disposal is the impact of concentrate salinity on wastewater where concentrates are disposed to the sewer, such as City of Goodyear in Arizona. Additional concentrate post-treatment process will increase significantly water costs. Currently these desalination plants are evaluating various options to address the concentrate disposal challenge.

Another limiting factor for implementing desalination in inland areas is water efficiency. Lower water recovery of desalination technology affects permitting of a desalination facility because raw water withdrawal volumes and concentrate disposal are the key factors to permitting a water project.

Water transfer and exchange might make desalination a potentially viable future water resource for inland areas where implementing desalination is not feasible. The Southern Nevada Water Authority (SNWA) is exploring the feasibility of ocean desalination with other municipal Colorado River users within the United States and Mexico (SNWA website). For example, Southern Nevada could pay California or Mexico to construct and operate desalination facilities in exchange for an equivalent portion of their Colorado River water allocation. The SNWA is also interested in participating in a partnership that would allow it to access water from the Yuma Desalting Facility, which would treat brackish groundwater in the Yuma, Arizona. However, several challenges including the permitting process, environmental concerns, costs, access to coastal property and existing treaties make water transfer and exchange a long-term resource option. Also, because desalinated water would be exchanged for Colorado River water, supply shortages associated with drought conditions are left unresolved. The Nevada's reliance upon the Colorado River is further challenged given the projected water resource needs of California and Mexico in the coming decades.

AUSTRALIA CASE STUDY

Public Perception and Politics

Australia, like other countries, has established guidelines in order to ensure that water quality is at an appropriate level for maintaining public health. The National Action Plan for Salinity and Water Quality is responsible for facilitating coordination and setting targets for water quality management (Australian Government NRM Team 2007). Management of this plan is undertaken jointly between federal departments, with bilateral agreements being sought between the national body and individual states and territories. The standards enforced by these departments are largely similar to those of other developed countries.

Despite this system for water quality management, the Australian public still appears suspicious towards water provided by alternative means (such as desalination, water recycling, etc). Alternative water sources have caused significant public debate in recent years, with prominent media coverage influencing public attitudes. In some instances, opinion has been positive, with desalination and water recycling being welcomed as a necessary investment in Australia's future prosperity (Koehne 2007). However, the alternative water plans have also been criticized from a number of perspectives. Some critiques come from an economic perspective, arguing that the plans are expensive and do not make economic sense (Moran 2007). In addition, significant public opposition comes from an environmental perspective, particularly for desalination. Environmental issues of concern include damage to endangered species (Whinnett 2007b), crop damage (Ker 2007), the destruction of beaches (Dortch 2006), and salinity (Harmer 2007). As in many other countries, salinity is a significant concern because excess salt produced by the desalination process is fed back into water systems. This is a particular problem for Australia, since its waterways have been experiencing salinity problems for some time, even prior to the introduction of desalination practices (Jessop 1999). Combined with this, many of Australia's natural features (such as coral) are significantly threatened by a possible increase in salinity levels (ABC News 2006a).

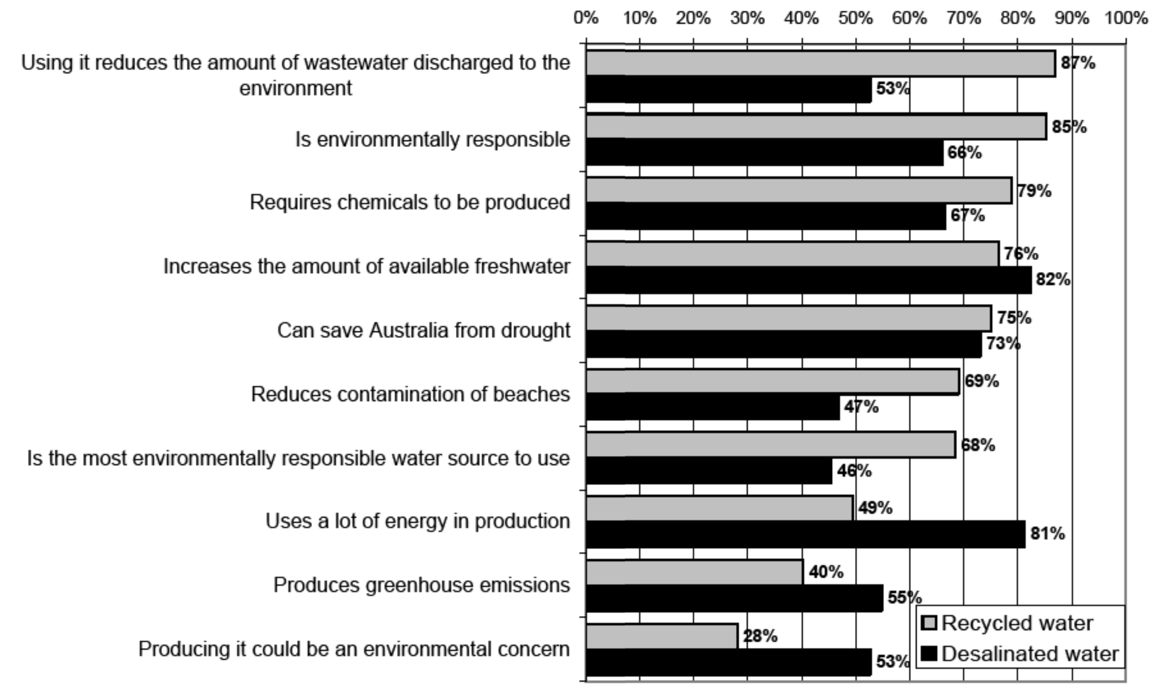
In addition, desalination is also opposed because of the high ongoing energy requirements. As with many other countries, energy efficiency and climate change are central political issues (SBS 2007). Due to a shortage of clean energy solutions, public concerns have arisen over how desalination plants will be powered. Therefore, the prospect of energy-intensive desalination plants represents another key barrier for Australian citizens' acceptance of desalinated water solutions.

In response to various environmental issues, community-based action groups have been established. Some groups, such as the South-West Environment Centre and Birds Australia exist to protect endangered species (such as the Western Ringtail Possum and the Hooded Plover, respectively) from the impacts of desalination (ABCNews 2007b, Whinnett 2007b). Other groups, such as the Conservation Council, exist to protect entire marine ecosystems (Banks 2006). The Secret Harbour Residents Association has also recently protested about the impact of a desalination plant upon a local beach (Dortch 2006). Media coverage has also reported farmers associations who have suffered the result of crop damage due to improper water recycling safeguards (Ker 2007). The existence of these groups demonstrates that the environmental issues associated with desalination are significant. The groups also identify that many members of the Australian community strongly oppose desalination on the basis of these environmental factors.

Another factor influencing public opinion is the fear of personal danger stemming from alternative water solutions. In July 2006, an industrial desalination facility was contaminated with uranium, placing one hundred workers at risk (The Gold Coast Bulletin 2006). This led to fear in the community, regarding the safety of desalinated water. On a much wider scale, fear was a major contributing factor to the outcome of a referendum in the town of Toowoomba, where residents rejected a proposal to introduce a controversial recycled water scheme (Langford 2006, Weisser 2007). The action group "Citizens Against Drinking Sewage" were accused of an aggressive "scare campaign" by government members (The Canberra Times 2007). Tactics used involved spreading rumours with little scientific basis, such as that recycled water would be simply "toilet to tap" solutions and even that recycled water is capable of changing the gender of fish (SBS 2006). In addition, residents also protested that Toowoomba's reputation would be significantly damaged, impacting tourism, property values, and jobs (Adams 2006). This strong response to recycled water demonstrates the impact of public opinions on the adoption of alternative water solutions in Australia.

In response to this incident in Toowoomba, recommendations have arisen for the better management of the introduction of alternative water options. Better education is one of the key recommendations that government parties made after reflecting on this incident. It was argued that establishing a recycling plant could serve as a demonstration for other communities considering water recycling as an option (Crawshaw 2006). In addition, the establishment and clear communication of water recycling standards could also assist in overcoming resistance to the option (ABC News 2006b). Despite these recommendations, however, there is concern that the result of the Toowoomba referendum has further ingrained fear of alternative water sources in Australia.

An empirical study conducted in April 2006 with 1000 Australian respondents representative of socio-demographic criteria (Dolnicar and Schäfer 2006) indicated that perceptions Australians hold about alterative water sources differ significantly, as can be seen in Figure 8.2.



Source: Dolnicar and Schäfer 2006

Figure 8.2 Comparative perceptions / knowledge about environmental issues

From the open-ended questions included in the survey, it becomes clear that the "three main concerns raised by the respondents were health concerns, environmental concerns, and cost. Recycled water is perceived as more risky from a health perspective (55 percent of respondents listed health-related concerns in the open-ended question), desalinated water is primarily perceived as bad for the environment (12 percent, only 23 percent mention health-related concerns), but is also viewed as the more expensive alternative with 11 percent mentioning a cost-related concern. This confirms the earlier findings by Bruvold (1988), Dishman et al. (1989), Higgins et al. (2002) and Marks et al. (2002) (cited from Dolnicar and Schäfer 2006).

The results from the empirical survey and public rejection of proposed alterative water sources by the Australian population in the past illustrate clear findings. While the population in Australia is aware of the water crisis, they have serious concerns which need to be managed in order to ensure the political feasibility of alterative water projects. It even appears that the public opposition experienced in Toowoomba may well be one of the reasons that all states which have announced major plans for alternative water solutions have chosen the avenue of desalination rather than water recycling for potable water.

Use of Renewable Energy

The high energy consumption of seawater desalination poses a barrier to the acceptance of desalination. As a result, renewable energy has been declared to power the majority of the proposed large-scale desalination plants in Australia. The Kwinana plant is the largest facility of its kind in the world to be powered by renewable energy (Water Corporation 2007). It should be noted, however, that the plants which are declared to be powered by renewable sources in Australia source the energy from the electricity grid. The energy used is supposed to be offset by an equivalent amount of new electricity being generated by a renewable energy provider. Thus – it is argued - there is no extra demand for traditional greenhouse gas emitting sources of energy from the plant operation and no reduction in the supply of renewable energy for other users.

One of Australia's greenhouse gas abatement measures is the Mandatory Renewable Energy Target (MRET), which requires electricity retailers and large buyers to source additional renewable energy. Compliance with the MRET is monitored through Renewable Energy Certificates (RECs), which are created by renewable energy generators (1 REC = 1 MWh) (MRET Review 2003). In order for desalination plants to be using renewable energy that is created in addition to that which is required, a retrospective audit is needed to ensure that the operator has purchased an REC for every MWh of electricity used. The REC must then be surrendered to the Office of Renewable Energy Regulator for extinguishment, so it will not be used by retailers to meet MRET targets (Knights et al. 2007). Knights et al. (2007) undertook a case study of the energy use structure for the Kwinana desalination plant. The Water Corporation has communicated to the public that they will buy the equivalent amount of energy they draw from Western Power's grid annually from Emu Downs wind farm. However, the RECs will actually be purchased by Western Power and surrendered as part of their renewable energy requirement under MRET. Therefore it appears that no additional renewable energy is produced that would not have been produced regardless.

The Kurnell desalination plant operators state that committing to using such a large amount of renewable energy may help to encourage investment in renewable energy sources (Sydney Water 2007b). However this will only be the case if renewable energy is produced in addition to that, which would be produced anyway.

A representative from the Nature Conservation Council of New South Wales believes that the move to use renewable energy to power the Kurnell desalination plant is in response to community concerns about the high-energy demands (ABC News 2007a). The use of renewable energy at Kurnell has been criticised in the media as a means of politicians gaining the public's acceptance, making "the desalination plant look better in the eyes of the public" (ABC News 2007a). The desalination plant has been accused of limiting "opportunities for new wind turbines that could reduce the need for coal power" (AAPGN 2007). It is argued that the use of renewable energy will do nothing to reduce New South Wales high greenhouse gas emissions (AAPGN 2007). The public discussion reveals that there are not only concerns about the high energy demands of desalination, but awareness that renewable energy use does not automatically equate to carbon neutrality or environmental friendliness.

Legal Responsibilities for the Water Portfolio in Australia

One key challenge for water management in Australia is the allocation of legal responsibility. Australia's water resources flow beyond the borders that divide states and territories, leading to confusion regarding who has final responsibility for its management (ABC Online 2006, Wilkins 2007). Various responsibilities for the management of water are divided amongst all three levels of Australian government (local, state, and federal). However, the state governments have held traditional responsibility for water. Despite this, Prime Minister John Howard's announcement to set up a new Office of Water Resources has fuelled confusion over lines of responsibility (ABC Online 2006). This office has possibly been established in response to criticisms that traditional structures have been ineffective in managing water (Tingle 2007). Indeed, a parliamentary commission has recently declared that Australian states have failed their water responsibilities (Shanahan et al. 2006). The Office of Water Resources has described itself as providing greater leadership to water management (Prime Minister of Australia 2006) but debate continues regarding where responsibility lies for the issue.

The mismanagement of the Murray-Darling drainage division, for example, resulted in significant political "bickering" over responsibility (O'Brien 2006). Adding to this confusion is the fact that local councils also have a say in the management of water (Australian Local Government Association 2007). There is significant variation among individual states as to the responsibility of local governments: some states, such as Queensland, allocate responsibility for water pricing, markets, and supply to local councils. In contrast, other states, such as Victoria, allocate almost complete responsibility for water issues to the state government (National Water Commission 2007c).

In New South Wales alone there are 109 water utilities. The largest utility is Sydney Water followed by Hunter Water. The other 107 water utilities are local councils. They control the water supply and are consequently responsible for the development of alternative water supply options within their local areas. The large number of units in charge of water supply makes it extremely difficult to develop a comprehensive overview of initiatives in place to combat the water crisis.

This fragmented structure may well have negative effects on future large scale plant development. The major desalination plants proposed or operating in Australia to date have all been implemented by major water utilities. The division of water responsibility between local councils may prevent economies of scale being reached for large alternative water schemes and thus discourage their development.

ISRAEL CASE STUDY

Legal Responsibilities and Water Management in Israel

In June 2002, a special parliamentary inquiry committee published the results of its investigation of the water crisis in Israel (Parliamentary Inquiry Committee 2002). One of the harshest remarks made by the committee was the lack of organization and control of water in Israel and minimal coordination among responsible authorities. The committee listed more than a dozen entities dealing with water including the Ministry of National Infrastructure (Israel's water system, Israel's Water Commission, Sea of Galilee Administration); Ministry of Agriculture (water rates and quotas); Ministry of Finance (budgeting of ministries dealing with water and the National Water Company, control and issuing of biddings and tenders); Ministry of the Environment (source protection, water quality, monitoring, all sewer issues); Ministry of Health (water quality control, separation of sources (potable and sewer), reuse for irrigation); Ministry of Interior (water and wastewater issues in local municipalities, wastewater treatment plants); Ministry of Science (promotion of water related research); Foreign Ministry (bilateral water issues, especially during peace talks); and Ministry of Defense (water related issues in the occupied territories). In addition there are four parliamentary committees dealing with water issues, the Israeli Water Commission, and Israeli Water Council, and 'Mekorot' (the Israeli central water agency).

Some of the important conclusions of the committee regarding water resources included recommendations to enhance development of non-conventional water resources, including seawater desalination, and improvement and enhancement of water reclamation and reuse. The committee called for establishing seawater desalination capacity of 362 mgd (1.37 million m^3/d) until 2010.

Public Perception

There is growing public demand in Israel for a reduction in water pollution. Israel has always had strong and widely supported nongovernmental organizations (NGOs) in the environmental field - most notably, the Society for the Preservation of Nature in Israel (SPNI) (Lonergan and Brooks 1994). Growing support for focusing attention on water quality as well as quantity in Israel is reflected in the increasingly vigorous use of the court system to protect environmental values; an environmental NGO — the Israel Union for Environmental Defense — has been formed specifically to use the legal system, much in the manner of the US Environmental Defense Fund.

Yet another problem is that the cost of water to the user in Israel is highly subsidized, especially water earmarked for agriculture. The true cost of water would reflect all of the pumping, treatment, and delivery costs, most of which are not passed on to the farmers (Wolf 1996). Recently, NGOs, the media, and the public in Israel have been critical of the government for the water inefficiency and poor management of water resources, especially in regard to the new water supplies generated in the newly commissioned seawater desalination plants. Critics of the government contend that although the price of desalinated water is high, the government spends money buying the expensive water but not passing the cost to the customers, and at the same time continues to subsidize water to the farmers; thus, discouraging any desire to increase efficiency and conservation. Currently, farmers in Israel pay \$1.32/kgal (¢35/m^3) while households pay \$5.19/kgal (¢1.37/m^3). Furthermore, because the public does not yet pay for the new and expensive water supplies, there is currently pressure in Israel to expand the desalination program from 166 to 365 mgd (0.63 to 1.38 million m^3/d). In the 2008 budget, the Israeli Finance Ministry is planning to increase water rates to households by 10 percent and to farmers by only 2.5-3.6 percent. Critics still contend that without more of a substantial increase in water rates to agriculture, water use efficiency will not be achieved.

UNITED KINGDOM CASE STUDY

Public and political opponents to the proposed desalination project have serious concerns regarding the environmental impact of the plant, and the comparison of desalination with other alternative such as fixing leakage and water conservation.

Leakage versus Desalination

The root concern for London's water supply is its aged infrastructure. Because of over half of its water lines are over a hundred years old, leakage rates in the water lines are particularly high. In 2004-5 the network leaked 242 mgd (915,000 m^3/d) of drinking water. 2005-6 values showed little improvements with a leakage rate of 236 mgd (894,000 m^3/d) (Lyon 2006). Opponents agree that London's corrosive soils promote leakage more than other regions, as it tends to dry out in the summer and expand in the winter, which creates fracture potentials. In addition, London's dense development makes repair access more difficult. But at a 33 percent leakage rate, they are by far among the worst performers, making up a quarter of all water lost in England and Wales (GLA 2005b). Opponents to the Thames Water desalination project maintain that such a high rate is unacceptable, even with harsh soil conditions and densely developed areas.

Surrounding water utilities which also deal with the harsh soil conditions do not have as significant leakage rates. In addition, Thames Water is the only utility which had consistently missed their annual leakage reduction targets goals. Although the water leakage often returns to the groundwater, the amount of groundwater abstraction allowed is dictated by the Environment Agency (Lyon 2006), and there is the added concern of energy wasted in treatment. It is estimated that treatment cost of the water which leaks back into the ground is runs approximately £100,000 (approx. US$197,000) per day (London Assembly 2006).

In addition, opponents argue that the daily capacity of TGWTP would be dwarfed by the leak which is six and a half times the TGWTP capacity. It is also suspected that an estimated one-third of the TGWTP water would leak from the network delivering only 25 mgd (95,000 m^3/d) (Lyon 2006).

Thames Water acknowledges that leakage reductions are necessary and the most significant strategy in closing the gap between water supply and demand. However, leak reduction does not close the gap fast enough, and the case for building desalination considers the predicted savings from the work in leakage reduction.

Thames Water has set goals to save approximately 63.4 mgd (240,000 m^3/d) by 2009/2010 from leakage repairs (GLA 2005a). Such goals have been aggressively pursued with daily expenditures of approximately US$995,000 (£500,000) for repairs, and achieving approximately 240 repairs per day (Thames Water website). In the past, Thames Water had achieved major leak reductions from 238 to 159 mgd (900,000 to 600,000 m^3/d) between 1999/2000. Unfortunately, particularly wet rainfall in 2001 caused ground conditions to change, damaging the water network, and increasing leakage levels back to 211 mgd (800,000 m^3/d) in 2001/2002 (Cascade Consulting 2004). Such challenges result in uncertainties in water saving from leakage repairs alone and thus require desalination as a more secure option. Replacements provide greater reliability in water saving, but the full extent of the replacement work can not be achieved within the suggested timescale without causing adverse impacts (Cascade Consulting 2004). Central to asset management, an economic level of leakage needs to be considered in mains and pipeline repairs and replacement. There is a limit to the amount of repairs which can be conducted, as pipe repair and replacement disrupts local traffic (Baldwin 2007). At a certain point, costs in repairs will exceed costs of generating new water sources.

Thames Water maintains that leakage repairs and replacement require long term planning, while desalination is expected to mitigate short to medium term water supply issues. However, opponents question the sustainability of short term investment in desalination. The proposed TGWTP is intended to be operational by 2010 to provide water during times of drought.

Water Conservation

Opponents argue that Thames Water has been poor in promoting water conservation to customers and that a demand-side management be fully employed before new water supply-side measures are adopted. Londoners consume an average of 40.7 gal/d (0.154 m^3/d), approximately seven liters more than the national average (Ofwat 2006). Opponents argue that Thames Water do not maintain an aggressive enough conservation program in terms of increasing low water devices and education awareness. Currently, only 20 percent of its customers are metered. Of this, only 17 percent are metered in London, which is among the lowest level of metering in the southeast of England (Lyon 2006). UK's Environment Agency reports that Thames Water's plans to meter 23 percent of its London customers by 2010, 43 percent by 2020, and 51 percent by 2050 are low and should increase its metering goals (Lyon 2006). In addition, opponents claim that Thames Water should increase their water audits, currently auditing only 5000 of 2.75 million household and 4-5 non-households out of several hundred thousand a year (Lyon 2006).

Thames Water disagrees with such claims highlighting conservation efforts to reduce toilet flush volume by distributing 2.5 million toilet tank displacement devices with approximately 670,000 effectively installed by customers, and installing water butts (rainwater collection barrels) (Cascade Consulting 2004). These measures achieved a combined savings of almost 10.6 mgd (40,000 m^3/d). Thames also insists that domestic metering in London is limited because 40 percent of the properties are multi-household apartments, where metering would be expensive and have fewer opportunities for discretionary savings since water supplies are shared (Cascade Consulting 2004). There are also factors such as "bounce back" where some customers do not see significantly higher bills following metering. However, the Environment Agency maintains that while it may be difficult to meter multi-household apartments in London, this is not a valid reason to plan for limited household metering (Lyon 2006). In terms of water auditing, Thames Water asserts that water audits will not save water, and that households must act on the results for water savings, and this may not be guaranteed.

The overlying factor in water conservation is similar to that of leakage control. Thames Water asserts that water conservation is also a long term effort to decrease the water demand. While the Environment Agency and Ofwat both agree that Thames Water's conservation and water efficiency programs can be more assertive, they also both agree with Thames Water that feasible increases in conservation efforts may not be enough to eliminate the supply gap.

Energy

Another contentious matter in the proposed TGWTP is the energy intensive nature of the desalination plant. The energy consumption of TGWTP is estimated to be 7.44 kWh/kgal (1.92 kWh/m^3) and a predicted carbon output of 20,650 tons of CO_2 per year by using electricity from grid (Lyon 2006). This is significantly higher than traditional treatment works in the surrounding area. Hornsey Water Treatment Works, a 13.2 mgd (50,000 m^3/d) slow sand filtration water treatment plant for example, uses 0.23 kWh/kgal (0.06 kWh/m^3) (GLA 2005a). Without the benefit of economy of scale, Radnage Water Treatment Works, a 0.5 mgd (2,000 m^3/d) groundwater treatment operation uses 3.88 kWh/kgal (1.0 kWh/m^3) (GLA 2005a). The East London Water Resource Development scheme, a 6.3 mgd (24,000 m^3/d) operation which redeveloped dewatering boreholes drilled during the Channel Tunnel Rail Link construction uses an average of 3.18 kWh/kgal (0.82 kWh/m^3) (GLA 2005a). Desalination is also twice as much as the estimated energy output of an indirect reuse plant previously considered (Lyon 2006). Thames Water estimates that the desalination plant will increase its overall average energy consumption for water production throughout the Thames Water supply by seven percent from 2.2 to 2.36 kWh/kgal (0.568 to 0.610 kWh/m^3) (Lyon 2006).

Thames maintains that although the desalination plant will require more energy, it has implemented best management practices to reduce energy consumption. These practices include abstraction in a three hour window close to low tide ensuring lower salinity water is treated by the plant, use of variable speed drive pumps, and energy recovery turbines (Baldwin 2007). In addition, the TGWTP is not a base load plant and will be used only in times of supply shortages and for replacing regular supplies in emergencies, which will equate to an estimated average of 40 percent plant operational capacity (Baldwin 2007).

To further mitigate the CO_2 emissions issues, TGWTP plans to use renewable energy to coincide with the London Plan. The London Plan requires large development projects, such as the desalination plant, to generate a minimum of 10 percent renewable energy onsite (GLA 2005a). A number of on and off-site renewable energy options were considered for the desalination plant, including solar photovoltaic cells, tidal and hydro-energy generation, on-site biomass plant, as well as onsite wind energy. All were discounted due to excessive cost and physical or environmental constraints (GLA 2005a). However, Thames Water is still planning to use 100 percent renewable energy source for the desalination plant. Its current plans for renewable energy is to establish an onsite biodiesel combined heat and power (CHP) plant using biogas (methane) from sludge digestion, which may be obtained from the adjacent Beckton Sewage Treatment Plant to power the CHP engines (Thames Water website). In addition, Thames Water is still exploring options in wind energy and also potentially reprocesses locally discarded cooking fat and oil for energy generation (Thames Water website). Because of this commitment, TGWTP is expected to be one of the first major construction projects that will be covered 100 percent by renewable energy in the UK (Baldwin 2007). Although actual carbon offset from biodiesel has not yet been established, its use of renewable energy retains a social license with the public.

Public Opinion and Politics

Since TGWTP is the first proposed desalination plant in the UK, Thames Water concentrated on maintaining an open and transparent dialogue with the public. Communications with the public were well received with broad support from the general public and the local planning authorities for the desalination plant, as well as its delivery pipeline construction through open space (Baldwin 2007). Reviews by Ofwat and the EA, also found the desalination plant to be beneficial in increasing London's water supply (Baldwin 2007). Thames Water applied for planning permission to the London Borough of Newham for the desalination plant and the application was granted, initially in March 2005 (GLA 2005a).

As discussed in Chapter 1, the desalination project received considerable opposition from the Mayor of London at the time despite the support from regulatory agencies. Mayor Ken Livingston overrode Newham Council's decision and directed Newham Council to reject the proposed desalination plant on claims that it was "not in line with strategic planning policy which aims to encourage sustainable management of water supply resources" (GLA 2005a). Thames Water lodged an appeal of the refusal, in which the proposal was re-approved in July 2007, two years after the refusal (Lyon 2006) However, Mayor Livingstone again challenged the decision shortly thereafter and appealed to UK's High Court. The issue was again held up in court for another year until May 2008, in which the appeal was withdrawn under new mayoral leadership of Boris Johnson (BBC news 2008).

As demonstrated, political opinion poses a major challenge for desalination in the case for the UK. In the case in London, desalination saw more opposition from political figures than from the general public. In general, the proposal for the desalination plant received support from local authorities as well as approval from the regulating agencies, Ofwat and EA. Despite the support, Thames Water still saw resistance from the Mayor Livingstone, who has authority to refuse the desalination proposal. Although the public and interest groups have influence on policy issues, political leaders have a much more direct roll on policy such as refusing proposals. Such refusals can lead to costly delays. In London's case a three year delay occurred over such differences. Open dialogue for desalination projects should be emphasized during planning stages. It is important that desalination projects must be accepted, especially among major political figures before further plans may proceed.

SUMMARY

High cost, intensive energy use, and environmental concerns are the key issues that affect the social perception and political and institutional justification on desalination. These issues can significantly impact the regulatory and permitting process of a proposed desalination project. However the level of water crisis (quantity and quality) and long-term climate conditions can significantly change the public perception and political decision on implementing desalination technology.

In the US, public water agencies often take a lead in managing local water supplies. The proposed water projects are under intense scrutiny by US federal and state regulators. Brackish water desalination has been implemented in the US for many years to improve water quality and augment fresh water supplies. In general, there are no direct or social stigmas specifically relating to brackish water desalination. Currently multiple seawater desalination facilities are being proposed along the California coast. These facilities are proposed as a "drought-proof" solution to increase the reliability of local water supplies and reduce the dependence on imported water. However, concerns have been raised regarding the social, environmental, and economic impacts of desalination projects.

Australia is facing a serious water crisis due to increasing demand from population, as well as drought and climate pressures. The state governments are currently looking at desalination as the main solution to this crisis, while continuing to communicate the importance of water conservation to community members and imposing usage restrictions. The level of public information is low with respect to all alternative water sources. Consequently, it is very difficult for the Australian population to develop an informed view about currently proposed projects. Environmental impacts associated with concentrate disposal and greenhouse gas emissions are the major concerns against desalination. Most desalination projects declare that the electricity they use from the main electricity grid will be offset by renewable energy sources. The true environmental friendliness of this mechanism has been questioned fundamentally and argued that no additional energy from renewable sources appears to be produced to power the desalination plant.

Water resources are always a tense subject in the Middle East. The State of Israel has been forced to initiate a massive desalination program to mitigate political conflicts, and augment fresh water supplies, thereby addressing the rapid population and economic growth and frequent drought periods. The government of Israel has taken a lead and provided substantial subsidies in the implementation of extensive seawater and brackish water desalination. Israel is also subsidizing water reuse, conservation, and other water use efficiency measures to address water crisis in the state.

In the UK, the first large desalination plant is in the planning stage. Thames Water believes a desalination plant is the most cost effective method to provide water within the specified timeframe. However the proposed desalination project encountered opposition from political authorities regarding its cost, energy use, impact on climate change, and the leakage issues of aged infrastructures. Thames water remained flexible and collaborative in addressing the barriers to implementing a desalination project. Thames Water is continuing to fix the leakage issues and plans to use 100 percent renewable energy to power the desalination plant, thereby reducing energy emissions. The open dialogue has helped in granting the planning permit from the regulatory agency.

Implementation of desalination projects is a multilateral process and requires a meaningful dialogue among communities, regulators, and water agencies. Water agencies should lead a meaningful dialogue with the community that fully addresses the need for water and the available alternatives. They should also seriously investigate the technologies and strategies to mitigate negative environmental impacts, and collaborate with the community about the appropriate investment in desalination or its alternatives.

CHAPTER 9
MANAGING THE PUBLIC DIALOGUE ABOUT DESALINATION

The previous chapters emphasized the importance of keeping an open and engaging dialogue with stakeholders and the public before desalination is considered as a new water source for a community or a region. Desalination will impact the community or region in several respects, including:

- It will determine the timing and amount of investment in new water supplies and potentially affect the quality of life in the region
- It will determine the features of a proposed desalination project; especially features designed to produce a broad range of value, including environmental benefits
- The dialogue will affect the image or brand of the sponsoring water agency

The overview in this chapter provides insight and guidance to public dialogue by addressing the following topics:

- Fundamentals of public outreach and managing public dialogue
- Important topics in the dialogue about seawater desalination
- The value and compelling features of seawater desalination
- Specific insight or conclusions from the current research on subjects related to implementation of seawater desalination
- Unique features of dialogue about implementation of brackish water desalination

All of the case studies covered in this research have as their background the public dialogue. This dialogue is arguably more critical for seawater desalination because of coastal advocates and the unique coastal environment. The dialogue about brackish water desalination will be addressed later in this document.

FUNDAMENTALS OF MANAGING PUBLIC DIALOGUE

It is important to recognize that the objective of a dialogue with the public is not necessarily to sell the community a specific idea or approach; the fundamental goal is for the community to invest appropriately in adequate water supply and maintain high living standards. Conflict can arise rapidly when the sponsoring agency is locked on a predetermined approach.

There are many resources on best practices for constructive management of public dialogue. One of the current most sensitive issues associated with public dialogue is implementation of indirect potable reuse. Indirect potable reuse is the process of proactively using recycled water to replenish an existing drinking water supply such as a groundwater basin or reservoir. The WateReuse Foundation has sponsored the development of a website, best practices, and tools that provide help in managing this sensitive dialogue and managing public perceptions. These tools can be found at the Foundation's website at http://www.watereuse.org/Foundation/resproject/WaterSupplyReplenishmt/index.htm.

In general, the need for the public dialogue arises because of changes in water supply demand and/or availability and the need for investment. Water agencies approach the community because there is a need to take action. Thus, the dialogue with the public can be summarized under the following components:

The Problem to be Solved. People invest and are willing to take risks to receive benefits or to solve a problem. In this way, the solved problem, or the benefits, is the critical context for the rest of the dialogue. Without this context of benefits, any amount of risk is arguably unacceptable. Therefore, it is important for the sponsoring agency to clearly identify the water supply problem to be solved, which provides the context for the community to accept risks and determine the appropriate level of investment. Comparing the cost of desalination to other supplies without understanding the problem to be solved, or the unique benefits of desalination, will lead to a confusing dialogue and will typically originate conflict.

Options for Solving the Problem. Consumers are used to having choices, and the same applies to investing in new water supplies. Understanding the different options and what actions have already been taken is important for deciding that desalination is an appropriate course of action. It is appropriate that the sponsoring water authority makes a recommendation, but communicating the options and the logic behind the recommendation is as important. Members of the community often expect that water agencies will first pursue other options such as water conservation and/or water reuse before proposing seawater desalination.

Managing Conflict. It is always best to avoid conflict that stems from confusing messages or incomplete information. Articulating the problem clearly and showing the options and logic supporting the recommended course of action are ways to avoid unnecessary conflict. Even with this clarity, there will still likely be some disagreements. However, a dialogue that constructively manages disagreement can lead to higher value outcomes.

Utility managers sometime establish an arbitrary limit on what the community is willing to pay for a highly reliable water supply and high standards of living. They may also assume that they have all the answers related to the features of a project. The utility needs to listen and consider altering the project based on the dialogue with the community. A collaborative approach to designing the project can dramatically reduce the permitting time.

Most communities have a history of disputes. Any new or interesting proposal has the potential to energize strained relationships. The utility should be aware of these issues and prioritize building relationships with those involved in these conflicts.

Ensuring a Good Policy Decision. One of the realities of investing in water is that the decision to invest will typically be made by elected officials. This means that utilities must reach the audience or community leaders that policymakers look to gage public support. These leaders or important audience often include the media, environmental groups, regulators, health officials, ethnic or social group leaders, or people involved in past conflicts in the community. Developing a strong foundation of support for investing in water and desalination among these key individuals will help ensure a favorable policy decision.

IMPORTANT ISSUES IN THE DIALOGUE ABOUT DESALINATION

Unlike indirect potable reuse, there appears to be no real stigma associated with desalination. Therefore, the key objective is for the utility or developer to convey the value of a desalination project. This will include how they address the negative impacts of desalination and how they develop an investment package that provides benefits and an overall increase in quality of life for the community. The value of desalination, how it is perceived, and how it is implemented will be determined by the following key parameters:

The Need for More Water. Desalination will be implemented when there is a strong need for more water and it is compelling when compared with other options.

The Economic Case for Desalination. Given a strong need for the water and limited options, cost will not be a deciding factor in implementation; communities will likely not "wait for the cost to drop." Running out of water is not an option. Evidence indicates that the trend in lower desalination costs has slowed. In fact, it is likely to see increases in costs due to increasing energy prices, which may affect material and construction costs, and the need to add more environmental features (e.g., being carbon neutral, and environmental restoration).

Options for Increasing or Extending the Water Supply. The value and need for desalination will be affected by the availability of other supplies including increased water use efficiency, recycled water, increasing stormwater capture, and others.

Environmental Impacts of Desalination. This can be a major part of the dialogue and significantly impact the permitting process. Key issues are the impact on aquatic life due to intakes and discharge, the plants energy use, and uses of coastal land. Growing awareness of climate change will continue to raise people's sensitivity to the environment and willingness to invest in preserving or enhancing the environment.

Public Opinion and Politics. Politicians and policy makers will have their own opinions about desalination, but public opinion will have a significant impact on their votes.

Privately Owned Desalination Plants. Privately owned desalination plants are a reality and the private model can change the dialogue in the community. A key question is whether a private company has more flexibility and creativity in how it proposes value to the community.

Technology and Water Quality Issues. Desalination is feasible. It has been implemented for many decades. Today, the technological debate tends to focus on environmental impacts, source water quality problems, acceptability of desalination water for the drinking water system, and increasing efficiency by reducing energy consumption. In general, the specific technology, unless it relates to specific energy or environmental benefits, is not a major component of the debate.

Permitting. The pace of the permitting process is considerably affected by how collaborative the public dialogue is, and how it changes or does not change the features of the proposed project. Being flexible and willing to change in response to public opinions will ease the time consuming permitting process.

SEAWATER DESALINATION AS A "VALUABLE" WATER SUPPLY OPTION

Seawater desalination is perceived as high capital and O&M costs. For many regions, the value of desalination project may overweight the costs. Seawater desalination has the following valuable features:

- It brings new water into the watershed. Conservation or water reuse apply to water already under management by water agencies
- It is not dependent on the climate, thus considered drought proof
- It is not limited by an amount of source water
- It is a locally controlled water supply, typically avoiding contentious water rights issues

Desalination can generate these important types of values, but the full range of values is often not well recognized and hard to measure. However it is important to clearly understand these features because seawater desalination will be compared to other options, and the features of desalination will significantly impact the public dialogue. All other water-supply options (including water reuse, conservation, building of reservoirs, and managing groundwater) address getting more value out of traditional water supplies, which ultimately come from precipitation or snow pack. Seawater desalination is very different in that it creates a new water supply that is not only equivalent to rain or snow pack, and does not depend on the climate.

SPECIFIC INSIGHTS AND CONCLUSIONS ABOUT THE OCEAN DESALINATION DIALOGUE

The following insights cover the need for more water, desalination, and the specific features of an ocean desalination project. These are the key components of the community dialogue. The insights below provide guidance on the conditions in the community and the features of a desalination plant. The guidance will lead to a streamlined process for evaluating and implementing seawater desalination.

Costs of Desalination. As mentioned above, utilities will likely not wait for costs to drop. They will propose desalination when the water is needed and the features of the desalination option are compelling. There is a tendency to conclude that "desalination is not yet cost effective", or suggest that desalination needs to be competitive with the cost of current supplies. This can be misleading and can leave the community without the benefits of a new water supply. In many communities the "low cost" supplies have been exhausted, and the cost of maintaining these traditional supplies is increasing. Also, comparing desalination to other alternatives as if they were equivalent does not take into account the unique features of desalination and the other options. The cost/price of desalination will be acceptable based on the severity of the need, the availability of other options, and positive externalities.

Desalination as Compared to other Options. The public dialogue and acceptance of desalination will go much smoother if the sponsoring water agency has or is aggressively pursuing increased water-use efficiency and recycled water. This idea extends to being good stewards of the resource, including reducing the amount of water that is wasted. Thames Water ran into this issue because of significant leakage in the water distribution system. Arguments against the desalination plant gained momentum because the amount of water to be produced by the desalination plant was significantly less than the excessive leakage in the system. During the Southern California case study, a conservation specialist was noted as saying that the best thing that has happened to conservation was proposing seawater desalination (Case study interview). This highlights the fact that the public will naturally want to see appropriate levels of success on water-use efficiency before pursuing desalination.

Environmental Features of Seawater Desalination Plants. Environmental impacts and environmental features of a proposed plant are a major part of the dialogue, and can significantly affect the permitting process. With growing public acceptance of climate change and growing sensitivity to environmental issues, future desalination plants will arguably be required to have more features that relate to the environment. Analysis of the impacts on marine life of both the intake structures and concentrate discharge are required (CCC 2004, Desalination Task Force 2003a). More environmentally friendly intake structures such as sub-surface intakes are being evaluated and may soon become the standard, especially if they prove to have both environmental benefits and benefits that relate to water quality (LBWD 2006, MWDOC 2007). Energy use and its impact on the climate is a sensitive issue. Several large desalination plants in Australian, and Thames Water desalination plant in UK, are purchasing renewable energy credit, or have announced to use renewable energy to power the plants. Poseidon Resources announced in 2007 that its Carlsbad plant will be "carbon neutral" (Poseidon Resources 2007c). These desalination projects have become the standard on future projects to reduce carbon footprint.

Private Desalination Plants. Desalination plants proposed by private companies can change the nature of the dialogue and bring into play different issues, including the well-known issue that water is so essential that it should be managed by a public agency. What may even be more interesting is that desalination proposed by a private company may allow a community to achieve water independence. One of the ways to define this independence is not being tied to a public water bureaucracy or the reliability issues associated with more traditional water supplies. Some public water agencies tout the benefits of a diverse water supply, and there are real benefits. However, these supplies will always have some reliability risk due to their dependence on climate. In fact, desalination can be a good addition to a mix of supplies to increase reliability. Since desalination's reliability relates almost entirely on the reliability of the plant and its processes, and a diverse supply is arguably not necessary, desalination can be very compelling to communities who wish to put the issue of water reliability to bed. Because of the reliability and water independence features, seawater desalination may be more suited to a private venture than other water supplies or privatizing the entire system.

Pace of Permitting. When dealing with regulatory issues and permits we are also dealing with people. Evidence shows that when the proposing agency enters into a collaborative dialogue with regulators and key stakeholders, the permitting process can go pretty quickly, especially if the proposing agency is willing to seriously consider the inputs of key stakeholders. There have been cases where permitting has taken many years or happened in just a few months.

UNIQUE FEATURES OF THE BRACKISH WATER DIALOGUE

It is useful to separate the issue of brackish water desalination from seawater desalination because the public dialogue is quite different. The primary difference relates to the fact that brackish water desalination does not have to contend with the issues of coastal land use and the marine environment. This means that the general public and arguably even key stakeholders will be paying much less attention.

However the implementation of inland desalination is facing the largest challenge of concentrate disposal. In inland areas, concentrate disposal options such as surface water discharge, sewer discharge, and land application, can contaminant the receiving waters and soils. Evaporation ponds often require large land area and are only appropriate in arid climates with high evaporation rate. Evaporation ponds also require impervious disposal areas to prevent contamination of fresh water supplies and soils. Deep well injection is often not geologically applicable or not permitted in many states. Even though it is applicable in some states such as Florida, New Mexico, and Texas, the injection is costly and requires permits, monitoring wells, and completions in deep contained aquifers to insure that fresh water supplies are not contaminated (Mickley 2006).

Additional improvements in desalination efficiency/recovery, cost effectiveness, and concentrate disposal are still needed for desalination to become widely used as a long-term, environmentally friendly enhancement for fresh water supplies in inland areas.

To enhance the dialogue of brackish water desalination, the key components should include:

- **Value of Brackish Water Desalination.** Communicate clearly the need for investing in new water supply, water supply options, and the cost and benefits of desalting the brackish groundwater. Increasing water demands in inland areas have lead to some unsustainable water management practices. The consequences of these practices are groundwater mining, overdraft of aquifers, depletion of surface and ground water quality and availability, falling water tables with ground subsidence and associated building and utility damage. To meet the water challenges, it requires a combination of approaches including water conservation, recycling, and treatment of impaired water from nontraditional resources to "create" new water.
  As fresh water supplies become more limited, desalination of brackish water resources provide a new water source to supplement fresh water supplies for a wide range of industrial and domestic needs. In addition, many surface and ground water sources suffer from salt buildup and contamination caused by surface runoff, agricultural irrigation practices, urban uses, and evaporation. Desalination of these impaired water sources is becoming increasingly important to meet more stringent water quality standards for municipal water supplies.
  To bring a meaningful dialogue, it should be clear that desalination is only one of the alternative water supply options in sustainable water management portfolio. Other alternatives should be implemented, including water conservation, and reuse of currently available water.
- **Environmental and Regulatory Issues Associated with Concentrate Discharge.** To reduce the environmental impact of concentrate disposal, new research into areas such as concentrate volume minimization, beneficial reuse of concentrate, zero-liquid discharge, and salt sequestration technologies are needed to address.
- **Terminology.** Another approach to improve the brackish water dialogue is the terminology itself. “Desalination”, is described as a process in desalting water. This term may often be misguided by the public to focus only on seawater. There is much lower focus on brackish water desalination, as the public does not regularly observe inland water sources to be “salty”. Brackish water desalination should be considered as an approach to improve the quality of alternative water supply instead of merely desalting water.

SUMMARY

To summarize, key points that relate to managing the public dialogue about desalination are listed below:

- **The Problem and Need for Investment.** Clearly articulate the need for more water – How much and by when
- **Options for Solving the Problem.** Make a recommendation on the solution but outline the options for investing in new water supplies. Make sure there is a good case for demonstrating strong progress on water-use efficiency and implementation of water reuse

- **Meaningful Costs and Value.** Don't assume that desalination needs to cost a certain amount for it to be acceptable. Express the cost of desalination (and other options) in terms of their impact on water rates or fees
- **Collaborating with Community Leaders.** Lead a collaborative dialogue with the community members that policy makers look to gage public opinion. Listen, and be willing to alter the course of action based on inputs that are feasible and have strong support
- **Energy Consumption.** Consider launching the project with provisions for using renewable energy or even making the plant carbon neutral
- **Marine and Coastal Environment.** Be prepared to seriously consider different intake structures that reduce the impact on marine life and/or investing in other environmental mitigation or restoration
- **Technological Options** – Provide information on technological developments such as on concentrate treatment and disposal processes and beneficial use options.

CHAPTER 10
MULTIPLE-CRITERIA DECISION ANALYSIS FOR ASSESSING THE IMPLEMENTATION OF DESALINATION

DESCRIPTION OF ASSESSMENT METHODOLOGY APPLIED

Desalination has received increasing interest to augment regional and national water supplies. Implementing desalination, however, has raised a set of issues, in particular regarding location, energy use, intake infrastructure, greenhouse gas emission, entrainment/impingement, concentrate disposal, cost, water quality, and inducement of unwanted growth. A sustainable development of desalination requires strategies integrating technical, energy, economic, social, political, and ecological factors. A critical assessment of implementing desalination technologies should include a more comprehensive analysis of social, environmental, and economic impacts of implementing alternatives and requests a *full account* of the benefits and limitations of each approach.

A comprehensive evaluation of desalination projects can result in a vast amount of data, treatment alternatives often characterized with uncertain consequences, complex interactions, and identification of multiple stakeholders with conflicting interest. These evaluations require decision makers to weigh all these set of consequences to arrive at a preferred action. However, decision-making is often applied with subjective reasoning and different decision makers may have different values and priorities, and thus different preferred actions. The nature of multiple actions in decision making shows that there is much information of a complex and conflicting nature, often reflecting differing viewpoints and often changing with time (Belton and Stewart. 2002).

The use of Multiple-Criteria Decision Analysis (MCDA) aims at helping decision makers organize and synthesize such complex and conflicting information, such as in desalination. The analyses aid decision makers in determining their own and other's values and judgments, and guide them in identifying a preferred course of action (Belton and Stewart 2002). Thus, MCDA is an approach which examines a range of alternative actions and determines the main concerns or criteria of the multiple decision makers. Although MCDA is a common tool used for water resource planning, its application to desalination specific projects has been limited. MCDA have been applied regarding certain technical criteria specific to desalination (Mamoud et al. 2002, Young 1996) and to identify best available energy sources (Afgan et al. 1999, Akash et al. 1997, Voivontas et al. 2001).

Mahmoud et al. (2002) presented a MCDA methodology for locating and sizing desalination plants using criteria of demographics, distance to available freshwater sources, and political preference of desalination facilities. Likewise, Young (1996) considered multiple criteria in siting a proposed desalination plant in Marin County, California with factors including raw water source, constructability, service area, proximity, land availability, land use compatibility, existing intake/outfall, access to power, and environmental compatibility.

Akash et al. (1997) evaluated multiple alternative energy sources for use with desalination technology in Jordan. These alternative energy sources included hydropower, solar, wind, and nuclear energy and were assessed with water productivity and environmental sustainability criteria. Afgan et al. (1999) evaluated the sustainability of desalination plants based on resource, environmental, and economic indicators and assessed different energy sources to be used for the desalination process. Voivontas et al. (2001) also evaluated the combination of various desalination technologies with renewable energy sources to identify the optimum condition of a specific region based on a detailed financial analysis. The assessment compared energy flows and calculated water costs and expected revenues from selling water. An iterative approach was utilized to assess options in meeting regional water demand and economic viability of the renewable energy driven desalination technology.

The evaluations of the previously listed desalination studies have been based primarily on technical and economic criteria with limited scope on considering environmental and social needs. Little has been done in terms of encompassing a full range of factors for desalination implementation. Recently, MCDA method has been used to evaluate a variety of water resources management options including desalination in Queensland, Australia (Ove Arup & Partners Ltd. 2007).

The objective of this chapter is to provide an overview and to analyze the important components of a decision-making framework for sustainable development and critical assessment of implementing desalination technologies.

SUSTAINABILITY STRATEGIES

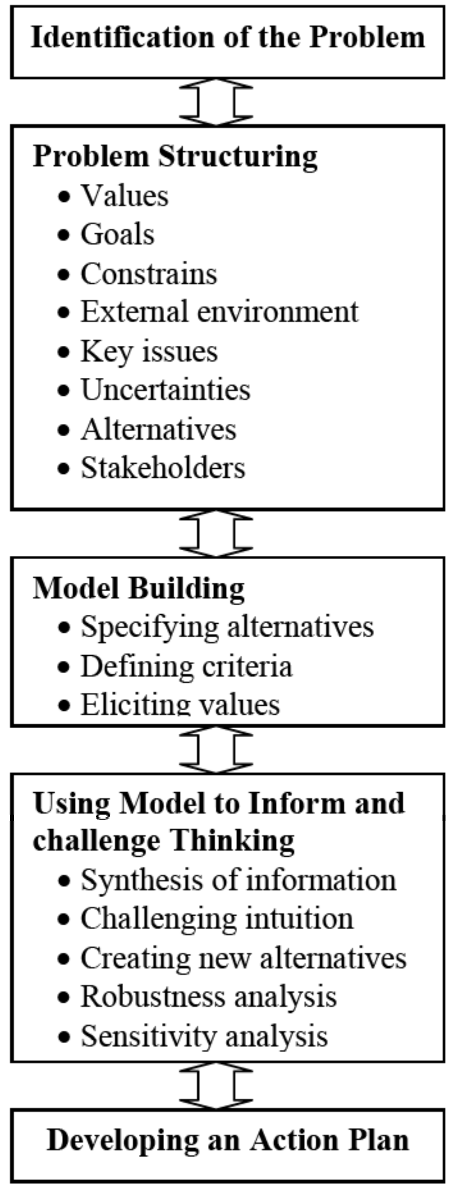
Water supply is an important part of sustainable development. Sustainable development defined by the Brundtland Commission is "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs" (WCED 1987). The definition incorporates the idea of natural capital, including water, and protecting it to meet the needs of the future. In *Sustainability, An Economists Perspective,* Robert M. Solow defines sustainable development in a similar manner and includes quality of life aspects, investment of man made capital and financial aspects. His definition states "…(sustainability) is an obligation to conduct ourselves so that we leave to the future the option or capacity to be as well off as we are" (Solow 1993). According to Holdren (2008), sustainable development means "doing so by means and to end points that are consistent with maintaining the improved conditions indefinitely". Economic, social, political, and environmental conditions and processes are indispensable and human well-being dependent on the integrity of all three pillars Holdren (2008).

The description of a sustainable system requires a multiple criteria decision analysis framework to ensure that all the important aspects of sustainability are addressed. There is general agreement that sustainability criteria include five categories (Lundin 1999, Mels et al. 1999, Ashley et al. 1999). In the urban water approach Hellström et al. (2000) formulated a set of sustainability criteria:

- Health and hygiene criteria (microbiological risk assessment as well as chemical risk assessment)
- Socio-cultural criteria (organizational capacity, implementation, user aspects)
- Environmental criteria (substance flow analysis, life cycle assessment)
- Economic criteria (investments from a business economic perspective as well as economic assessment on a societal level)
- Functional and technical criteria

MULTIPLE CRITERIA DECISION ANALYSIS

The MCDA processes have in common the need to define the alternatives to be determined, the criteria or objectives to guide the evaluation, and some measure of the relative significance of different criteria (Belton and Stewart 2002, Stewart and Scott 1995). Belton and Stewart. (2002) identified the process of MCDA in five stages which includes (1) identification of the problem, (2) problem structuring, (3) model building, (4) using the model to inform and challenge thinking, (5) and ultimately to determine an action plan. Each of the main stages includes a subset of stages which can be used for further analysis (Figure 10.1). To determine the best decision, there may be iterations between these main stages or their subsets. This iterative and interactive preference modeling procedure maintains the basis of the decision-support orientation of MCDA.



Source: Adapted from Belton and Stewart 2002

Figure 10.1 General MCDA

Similar to the framework proposed by Belton and Stewart (2002), Lundie et al. (2005) proposed six phases in MCDA specific to water resources for the development of an Australian national guideline for evaluating sustainable options for water sensitive urban developments:

- Phase 1 Definition Objectives: define context specific objectives including human and environmental needs
- Phase 2 Generation of Options: creative options generation for water supply and wastewater services
- Phase 3 Selecting Sustainability Criteria: selection of primary and secondary criteria
- Phase 4 Screening of Options: reduce number of options by constraints-driven screening in agreement with stakeholders
- Phase 5 Perform Detailed Options Assessment: generation of performance matrix
- Phase 6 Recommend Preferred Options

Problem Identification and Structuring

Before any analysis occurs, stakeholders need to develop a common understanding of the problem, as well as the key factors with which the decisions are to be judged and evaluated.

Problem identification and structuring should be a process which reveals the relevant issues to the problem and identifies criteria specific for the evaluation of alternatives. It is thus necessary to take into account the views of different stakeholders and to consider alternative solutions. An evaluation of water issues in the Costal del Sol region of Malaga, Spain, revealed that stakeholders initially had very different perceptions about the problem facing the region. Water authorities defined the problem as water shortage with a need for additional infrastructure, while other stakeholders identified the issue as resource mismanagement (Paneque Salgado et al. 2008).

Identification of Stakeholders and Defining Issues

An important aspect to MCDA is identifying the stakeholders involved in the problem analysis and decision making, understanding their positions of interest, capacity to act, and their potential alliances with other stakeholders which may create weighted bias to their opinions (Paneque Salgado et al. 2008). Stakeholder participation is significant to (1) incorporate stakeholder values into decision, (2) improve substantive quality of the decision, (3) resolve conflict among competing interests, (4) build trust in institutions, (5) educate and inform the public, and (6) facilitate implementation (Beierle and Cayford 2002). Consulting stakeholders at an early stage, and through the project, makes it less likely they will oppose the project. Lundie et al. (2005) emphasize this importance by developing a participatory stakeholder involvement framework through all phases of MCDA analysis (Table 10.1).

Each desalination project has unique and specific environmental, social, political, and institutional settings. Involvement of the stakeholders is important in generating alternatives for the structuring of the problem. These alternative scenarios help identify the key factors which form the basis for MCDA evaluation. These key factors can be referred to variously as values, (fundamental) objectives, criteria, or (fundamental) points of view (Belton and Stewart 2002). Given the significant impact on the decisions to be made, it is important that the stakeholders agree upon setting the criteria which will be used in screening and assessing the performance of prioritized options.

Identification of Alternatives

A preliminary list of alternatives should include a broad range of conventional and unconventional options which might become attractive in the future under changed conditions. A diverse group of stakeholders should participate in this stage. Many options might have already been investigated by water utilities or water supply developers. However the brainstorming, new way of thinking, and backcasting of diverse stakeholders can improve options generation and help institutional development.

Sometimes the problem is not of generating alternatives, but of identifying an appropriate and manageable set of alternatives for detailed evaluation from a much larger set of possibilities, thus requiring a screening process (Belton and Stewart 2005, Hellstrom et al. 2000). This screening process may require iterative procedures to reduce the list of alternatives and to determine whether alternatives are reasonable.

Table 10.1
Objectives, processes, participants (by scale) for each phase in sustainability assessment for urban water systems

Phase	Objectives	Processes	Participants	Scale[a]
1. Define problem & objectives	•Determine objectives that are in harmony with (or at least acceptable to) the project proponent, broader policy framework, stakeholder groups, and local community	•Steering committee •Value management study •Market surveys •Public conversations •Reference to other studies, policies, planning controls, organizational goals, etc •Document all assumptions and value sets used	•Owner/developer •Water authority •Consent authority •[Future] resident community •Relevant government departments/Regulatory agencies •Relevant politicians •Relevant community, environmental groups	• A • A • M-L • M-L • M-L • L • M-L
2. Preliminary options	•Provide a reasonably diverse and comprehensive set of possible solutions •Any proposed option should be included at this stage	•Brainstorming •Lateral thinking •Backcasting •Workshops •Expert consultants •Collaboration of diverse group	•Any of the Phase 1 participants with an interest in participating •Water management experts (from industry / academia)	• A • M-L
3. Determine sustainability criteria & weightings	•Arrive at a consensus (or aggregate) of stakeholder values •Within the five primary criteria, aim to reduce the total number of secondary criteria, to limit complexity of assessment process	•Citizens' Jury •Deliberative Panel •Expert panel •'Value-tree analysis' •Public conversations •Etc.	•All stakeholders (i.e. see Phase 1)	• A
4. Screen options	•Reduce the number of options down to a number that can be thoroughly assessed (e.g. 4 or 5)	•Simple absolute yes/no decision based on qualitative assessment (or quantitative if values already known) against objectives and criteria already established •Identify if mitigation is possible, reassess	•Technical experts in consultation with the wider stakeholder group	• A refers to tech. experts
5. Detailed assessment	•Assess the impact of each of the options according to each of the criteria selected •Determine preferences on criteria	•Use whatever assessment tools are available: LCA, LCC, MFA, etc. •Surveys &/or focus groups •Identify if mitigation is possible, reassess •Ranking & normalization of criteria	•Only local engineers •Broader technical experts •Community participation for social impact assessment	• S • M-L • L
6. Recommend preferred option	•Arrive at one preferred option which is either implemented or recommended, depending on the degree of authority	•Critical review of options & uncertainties, which for M-L projects may utilize multi-criteria decision add tools, such as SMART and STRAD	•Senior engineer •Representative stakeholders well informed in the whole process (i.e. see Phase 1)	• S-M • M-L

Source: Lundie et al. 2005

LCA – life cycle assessment; LCC – life cycle cost; MFA – material flow accounting and analysis

[a]Scale letters refer to: S – small-scale decision (e.g. pump or valve replacement) within an organization; M – medium-scale decision (e.g. a major trunk main) involving external stakeholders; L – large-scale decision (e.g. a new subdivision with water/wastewater services in a large city); A – common to any scale.

Development of Criteria

A variety of criteria have been proposed to evaluate the sustainability of water resources management (Hellstrom et al. 2000, Lundie et al. 2005). The criteria that were developed for conventional water supplies, however, do not cover the full range of technical, environmental, economic, water quality, and social aspects associate with desalination. Based on the research findings from the previous literature review and case studies, a priority set of criteria and its associated planned analytical methods, was established as an initial evaluation for practical and operational purposes in assessing desalination project (Table 10.2).

The framework addressed the need for the decision making process to incorporate four basic criteria which encompass (1) functional and technical criteria; (2) environmental criteria; (3) economic criteria; and (4) social, political and institutional criteria.

It is important to highlight that the set of criteria is very preliminary and merely a guide and not a default set of decisions in all cases. Again, developing an evaluation criteria, screening alternatives, performing an assessment, and developing mitigation strategies in each MCDA analysis, require a close consultation with various stakeholders and potential iteration.

Perform Detailed Assessment - Building MCDA Model

After structuring the problem, generation of a set of alternatives, development of evaluation criteria, and screening available alternatives, a model is developed to represent decision maker preferences and value judgments. The model is used to compare the alternatives relative to each other in a systematic and transparent manner. The guidelines in modeling for MCDA may be segmented into three main points, which include input capabilities, preference modeling, and aggregation (Guitouni and Martel 1998). Input capabilities involved the data collection of the criteria and information required by the methodology. Preference modeling determines the relative weights of each of the criteria. Aggregation is the algorithmic assessment used to combine results from separate criteria to determine an overall ranking.

Models differ based on how the stakeholders express their preferences and how these preferences are captured in mathematical terms (Lundie et al. 2005). Several assessment tools and methods are available for the aggregation of the preferences including the Linear Additive model, Simple Multi-Attribute Rating Method (SMART), Strategic Advisor (STRAD), Analytical Heirarchy Process (AHP), Single Syntesising Criterion approach, and Synthesising using an outranking approach (Karrman et al. 2005). Other available MCDA specific tools also include programs such as ELECTRE, PROMETHEE, REGIME, NAIADE, SWARD, and STRAD (Karrman et al. 2005).

Table 10.2
Evaluation criteria, and mitigation strategies for sustainable development of desalination technology

Primary criteria	Secondary Criteria	Mitigation strategies to achieve sustainability, and comments
Functional/ Technical	Water supply reliability	Probability to meet water demands under defined drought or water shortage conditions; Design and build the system that provides an acceptable frequency of failure
	Water supply diversity	Ensure a diversity to mitigate the dependence on limited water sources
	Creation of new water	Desalination can create “new” water as compared to traditional water supplies
	Durability	Ensure the plant site, source water and selected technology are durable
	Process flexibility	Redundancy and flexibility should be considered during system design
	Process robustness	Ensure the system is robust, and it can recover rapidly from upsets by: preventive design of unexpected events, preventative maintenance, multiple barriers, using resilient equipment
	Raw water quality/quantity	Select intake location and type that can provide consistent quantity and good quality for pretreatment and treatment processes
	Product water quality	Quality complies with drinking water regulations and other water quality standards, particularly the risks of infection, and exposure to harmful substances
	Waste disposal	Quality of wastewaters, e.g. concentrate, chemical cleaning water, backwashing water, complies with discharge standards. Ensure there are available disposal options for the produced waste and wastewater
	Energy use	Ensure energy demand can be met; Employ high energy efficient technologies such as energy recovery devices, high efficient pump, centralized system design, energy saving membranes; Optimization of operating parameters; Co-location and co-generation
Economics/ Financing	Life cycle costs	Minimize the total life cycle costs including capital and operating costs
	Impact to water rate	Ensure the water rate is affordable
	Costs of alternatives	Compare the cost of desalination with other alternatives
	Willingness to pay	Ensure the water rate increase is lower than the willingness to pay for benefits from the project
	Financial approach	Ensure the financial mode will minimize the risks of project and reduce project costs

(continued)

Table 10.2 (Continued)

Primary criteria	Secondary Criteria	Mitigation strategies to achieve sustainability, and comments
Environmental	Extraction of water sources	Ensure the water source is not negatively affected, and the environmental flow requirements (or for groundwater minimum water level) are met
	Land use and disturbance	Select site that has less impact on land use, or offset harm by purchase of substitute land, or rehabilitate degraded land off-site
	Impingement and entrainment (e.g. fish killed lbs/kgal, entrainment mortality)	Choose a location with relatively low conservation significance; Use subsurface intakes; Use advanced screens and behavior barriers for open intake; Conduct restoration strategies such as enhancement of fish hatchery; Use variable speed drives to reduce flow in response to water demand
	Benthic damage (e.g. area of seabed affected)	Use existing intake system; Minimize the excavation, construction and installation of collecting wells, pipes, tunnels or seabed filter; Sediment restoration
	Biodiversity	Offset temporary losses by rehabilitiation; offset permanent losses by purchasing natural habitats for long-term protection, rehabilitate degraded land elsewhere or create new habitats (eg wetlands).
	Greenhouse gas emissions [ton CO_2-eq./year]	Low carbon intensity sources of power; Renewable energy
	Ecotoxicity to terrestrial, marine, and freshwater aquatic system	Ensure that environmental and tissue toxin concentrations from concentrate disposal remain below those harmful to terrestrial, freshwater and marine organisms; Post-treatment of concentrate, and minimize concentrate disposal or zero liquid discharge; Beneficial use of concentrate
	Resource/ Material flow [t/year]	Purchase products with the highest resource-use efficiencies and with 'cradle-to-grave' recycling guarantees by their manufacturers
	Benefits to ecosystem and over-allocated watershed	Replace water lost from other sources and relieve drought conditions Replace water that can be used for river and stream ecosystem restoration Reduce groundwater overdraft and restore use of polluted groundwater
	Aesthetics and noise	Involve public to identify the issues related to truck traffic to/from the facility, transport of chemicals, aesthetics, noise, health and safety issues associated with facility construction and operation. Set acceptable limits and develop neighborhood program

(continued)

Table 10.2 (Continued)

Primary criteria	Secondary Criteria	Mitigation strategies to achieve sustainability, and comments
Social, political, and institutional	Affordability	Water rate should be affordable for the community
	Acceptability, public understanding, awareness and trust	Timely and open engagement of the community, interest groups, politicians, and regulatory agencies is essential to maximize acceptability of proposals, as is establishing an agreed framework for assessing sustainability Have an open and transparent dialogue with public; Develop environmental friendly technologies; Recruit and retain the best staff; Develop and maintain trust and credibility; Invest in strategic and scenario planning; Invest in emergency preparedness
	Distribution of responsibility	A clear, fully accountable and fully funded governance model is essential for the good ongoing management of new assets, particularly for DB/DBO and DBOOT projects where is the responsibility divided and shared between public agencies and private entities,.
	Political and institutional risks	Timely and open provision of information to political and regulatory authorities, and being flexible and willing to change, are essential to maximize acceptability of proposals
	Employment	Long-term employment opportunities are created

Weighting the criteria and assessing the performance of alternatives against the criteria are two of the most important and most difficult aspects of applying the MCDA methodology and are potential sources of considerable uncertainty (Roy and Vincke 1981, Larichev and Moshkovich 1995, Hyde et al. 2004). It is often difficult for stakeholders and experts to provide precise numbers for the criteria weights (CWs) and criteria point values. There may exist some imprecision, contradiction, arbitrariness, and/or lack of consensus concerning the value of the parameters used in MCDA (Mousseau et al. 2003). CWs indicate a criterion's relative importance and allow stakeholders' views and their impact on the ranking of alternatives to be expressed explicitly. Many CW elicitation methods have been proposed in literature (Moshkovich et al. 1998, Kheireldin and Fahmy 2001), and various studies have found that the same stakeholder may elicit different CWs using diverse approaches and that no single approach can guarantee a more accurate result (Moshkovich et al. 1998, Kheireldin and Fahmy 2001). Additional uncertainty and additional loss of information may occur when the CWs obtained from multiple actors are averaged or aggregated to a single CW for a final ranking of alternatives, as occurred in studies undertaken by Choi and Park (2001), Moshkovich et al. (1998), and Netto et al. (1996).

A value must also be assigned to each decision criterion for each alternative, which indicates its relative performance and is determined by expert judgment and/or mathematical models (Kheireldin and Fahmy 2001). Criteria point values may not be fixed or known exactly due to variability in the data available (e.g., water salinity records may range between 10,000 and 15,000 mg/L), limited data availability, or because the alternatives to be assessed are generally based on predicted future events. Values may be qualitative (e.g., excellent to poor) or quantitative; however, it is necessary to transform all criteria point values into one common measurement scale when value-focused MCDA techniques are utilized (e.g., outranking methods do not require all point values to be in commensurable units).

The often subjective, ambiguous, and imprecise nature of assigning the CWs and point values ultimately results in uncertainty in the outcomes of the decision analysis, which appears to have been largely disregarded or inadequately assessed in applications of MCDA to water resource allocation problems reported in the literature (Tecle et al. 1988, Netto et al. 1996, Flug et al. 2000, Kheireldin and Fahmy 2001). The CWs and point values are generally treated as deterministic, which enables rankings of alternatives to be obtained; however, no information is provided to the decision makers with regard to how likely it is that a reversal of the rankings of the alternatives will occur as a result of a change in input parameters. The uncertainty in the input parameters has been found to influence the resultant ranking of alternatives and therefore should be taken into consideration as part of the decision-making process (Wolters and Mareschal 1995).

Development of Action Plan

The purpose of modeling MCDA is to construct a view or perception of decision maker preferences consistent with a certain set of assumptions, therefore giving coherent guidance to the decision makers in the search for the most preferred solution (Belton and Stewart 2002). Ultimately, the goal of MCDA is the implementation of results that translates the analysis into specific plans of actions. It should be emphasized that MCDA does not "solve" the decision problem and should not be viewed only in terms of technical modeling and analytical features, but also to give support and insight to implementation (Belton and Stewart 2002).

SUMMARY

The MCDA is a method commonly used in water resources decision-making as it facilitates stakeholder participation and collaborative decision. The advantages of the MCDA include:

- Facilitating the understanding and structuring of the problems characterized by multidimensional evaluations of a desalination project
- Contributing to clarification of the nature of conflicts and creating the conditions necessary to find a preferred option
- Promoting active participation in all the phases of the decision-making process, and enable stakeholders to acquire knowledge of each other and their respective positions
- Promoting the formulation of innovative alternatives and make it possible to progress
- Not requiring assignment of monetary values to environmental, social, political aspects of a project
- Allowing assessment in combination of quantitative and qualitative criteria

Weighting the criteria and assessing the performance of alternatives against the criteria are the most difficult aspects of applying the MCDA methodology. It is often difficult for stakeholders and experts to provide precise numbers for the criteria weights and criteria point values. Due to the subjective, ambiguous, and imprecise nature of assigning the values, the uncertainty in the input parameters can result in imprecision, contradiction, arbitrariness, and/or lack of consensus concerning the ranking of the alternatives. This may lead to the failure of the MCDA approach.

To make the decision management approach viable and successful, future research work should include:

- Conducting case studies with water agencies to field test the framework. It will help to identify how water agency may handle the multi-dimensional and multi-stakeholder situation, apply the framework to assist in decision making processes, and validate the MCDA method in a project-specific setting
- Conducting research to improve the MCDA method, particularly in identification of evaluation criteria, weighting the criteria and assessing the performance of alternatives against the criteria, development of approaches to evaluate the uncertainty in criteria and weight estimation.

CHAPTER 11
CONCLUSIONS AND RECOMMENDATIONS

The overall objective of the study was to identify and evaluate the full range of water quality, energy, environmental, economic, social, political, institutional, and regulatory aspects of implementing desalination technologies. This study was designed to focus on seawater and brackish water desalination using membrane-based technologies because of its increasing prevalence as the preferred desalination treatment method in the United States and other regions.

The study included comprehensive literature review, international utility surveys, expert workshop and interviews, case study analysis, and development of a multiple criteria decision analysis framework. This report documents a wide range of information pertinent to planning and implementing desalination technologies from feed water intake, product water distribution, energy use and carbon footprint, to concentrate management. The study focuses on challenges, risks, risk-mitigation strategies, failures and barriers, and unforeseen issues associated with implementation of desalination. The case studies cover diverse areas of the U.S., Europe, Asia, and Australia. The major conclusions and recommendations for water professionals are summarized below.

CONCLUSIONS

Feedwater Intake and Pretreatment

Feed water intake and pretreatment processes are critical to the operation and performance of desalination plants; they control and dictate water quality and quantity, process reliability, costs, and environmental impact. Intakes can be broadly categorized as open surface intakes (stand-alone or co-location with a power plant) or as subsurface intakes where water is collected via groundwater wells, beach wells, or infiltration galleries. The type of intake facility strongly influences the selection of pretreatment process and consequently the stability and efficiency of membrane desalination processes. The most appropriate type and location of the intake structure can be determined only after a thorough site assessment and careful environmental evaluation. The following are major pros and cons identified for each of the sub-components of intake structures:

Open Intakes

- Flexible capacity, employed primarily by large desalination facilities
- Reliable in providing designed water quantity
- Often provide inferior water quality as compared to subsurface intakes, and therefore, more complex pretreatment is needed
- More susceptible to the adverse impacts of algal blooms, biological growth, and many common and accidental pollutions
- Impingement and entrainment of aquatic life are the biggest environmental concerns associated with open intake facilities
- The adverse environmental impacts of intake systems can be reduced through appropriate siting of the intake and employing advanced screening techniques and other restorations strategies

Co-location with Power Plant

- Reduced construction cost through elimination of a dedicated intake and/or outfall for concentrate disposal; yet, uncertainty exists about future use due to the potential phase out of once-through-cooling (OTC) system at coastal power plants
- Decrease in the pressure requirement to operate RO systems as a result of higher feed water temperature: yet, product water quality can be negatively affected
- Increase in propensity of membrane biofouling as a result of higher feed water temperature, especially in the presence of nutrients and organic matter
- Reduction of impingement and entrainment by using cooling water as feed water source instead of extracting water directly from surface water body
- Impingement and entrainment of a co-located desalination plant should be evaluated as a stand-alone plant for the environmental impact assessment
- Complex coordination with the operation, maintenance, and upgrade of power plants

Subsurface Intakes

- Feed water capacity is site-specific, usually employed by small to medium size plants
- Yield good water quality and require minimal pretreatment
- Minimize impingement and entrainment
- Might require significant size of seabed
- Might cause benthic damage due to construction and operation
- Beach wells require appropriate hydro-geological conditions
- Require extensive geological survey and pilot-testing
- Naturally occurring scaling of the well collectors and beach erosion may shorten the useful life time of subsurface intake facilities

Pretreatment

- Control of RO membrane fouling is challenging for both membrane and conventional pretreatment when using an open intake system
- Membrane pretreatment can produce a more consistent filtrate quality than conventional pretreatment, in particular during challenging source water conditions such as high turbidity, high TOC, and algal blooms. During upset events, the operation of membrane pretreatment is more challenging than conventional pretreatment due to MF/UF membrane fouling.
- Disinfection and oxidation of feed water can reduce and control biological growth; however, chlorination followed by dechlorination was found occasionally to contribute to RO fouling. Chlorination may break down organic material into assimilable organic carbon, which acts as a food source for the re-growth of bacteria on RO membrane surface.

Product Water Quality and Post-treatment

Using highly purified water from unconventional water sources, including desalinated water for domestic and agricultural irrigation, is a relatively new practice in many regions. Yet, there are mounting concerns about the quality of desalinated water; particularly the presence of disinfection byproducts, algal toxins, and mineral constituents such as boron, calcium, magnesium, and sulfate in the product water. Post-treatment of desalinated water is required to protect public health, including disinfection and mineral replenishment, and to safeguard the integrity of water distribution systems (e.g., corrosion control). The following are major findings identified for water quality and post-treatment:

- Formation of brominated and iodinated DBPs, and loss of chlorine residual due to presence of bromide and iodide in desalinated water can adversely affect disinfection processes that use chlorine.
- SWRO is highly efficient in removal of bio-toxins during algal blooms.
- Second-pass RO can be used to meet boron standards for drinking water and agricultural irrigation; yet, current assessment by the WHO of boron toxicity to human health will likely result in higher maximum contaminant level; this might eliminate the need for second pass RO for drinking water application.
- The recent Israeli experiences show the need for modification of water-quality parameters of desalinated water. Key micro-constituents such as calcium, magnesium, and sulfate should be added in post-treatment prior to supplying water for agricultural irrigation.

Concentrate Management

Concentrate disposal and the associated environmental concerns represent the largest challenges to implementing desalination technologies, especially for inland facilities where the disposal options are limited by permitting requirement, and geographical and geological availability. Concentrate disposal may require careful consideration, including effects on receiving water bodies, soils, crops/vegetation, and effects on the operation of wastewater treatment plant if sewer discharge is applied. The approaches that may help mitigate the disposal challenges include:

- Beneficial use of concentrate, such as salt extraction, wetland restoration, or irrigation
- Developing technologies to improve water recovery, and in the extreme leading to ZLD
- Regional concentrate management
- Watershed concentrate management

Energy

High energy intensity and its associated greenhouse gas emission is one of the major hurdles to implementation of desalination technology. A variety of approaches have been developed to improve the energy efficiency and reduce the carbon footprint of desalination plants.

- Among various factors, energy recovery devices play a key role in reducing energy consumption of membrane technologies. The positive displacement technologies (e.g., pressure exchanger) and centrifugal devices (e.g., Pelton turbines) can achieve net energy transfer efficiency as high as 98 percent and 80 percent, respectively.
- Renewable energy such as wind, solar, and biodiesel provides an opportunity for desalination plants to be carbon neutral, more environmentally friendly, and favorable from public and political perspectives.
- Currently, wind energy is a favorable renewable energy source and has been used in coastal areas such as in Spain and Australia.
- With the decrease in cost of renewable energy and increase in cost of conventional energy sources, the use of renewable energy in desalination will be more attractive.

Economics

Desalination cost is a key consideration in planning and gaining public's acceptance of a proposed desalination project.

- The costs of desalination plants have decreased significantly due to advances in technologies, increasing plant size, and improvement of production efficiency. Desalination cost is site specific, and is a strong function of the level of plant utilization.
- It is important to identify and highlight the external benefits and values of desalination project. Thereby, the project may be presented and perceived as an investment rather than comparing it to equivalent costs of conventional water supplies.
- The partnership between public utilities and private firms has the advantages of transferring risks and responsibilities of asset ownership, operation, maintenance, and replacement to the private sector. The public agency might also have risks of losing control of the treatment process and need to deal with problems if the private party fails to perform.

Social, Political, and Institutional Aspects

Social, political, and institutional issues are playing a key role in the regulatory and permitting process, and are often the most significant hurdle in implementing desalination technologies. One focus of the research was to investigate and understand these aspects under different social, political, economic, geographic, and climatic settings. A better understanding of the issues would help water utilities identify and develop potential options and strategies to address these challenges.

- Environmental concerns, energy use, carbon footprint, cost, and growth inducement are the key issues that affect the social, political, and institutional justification of desalination.
- Political opposition proves to be a major challenge for desalination. Although the public and interest groups have influence on the permitting process, political leaders have a much more direct role on policy such as refusing proposals. Such refusals can lead to costly delays.

- The degree of a water crisis (quantity and quality) and long-term climate conditions can significantly change the public perception and political decision on implementing desalination.
- The implementation of desalination projects is a multilateral process and requires a meaningful dialogue among communities, regulators, and water agencies.
    - It is important that water agency remain flexible and collaborative in addressing the barriers to implementing a desalination project.

RECOMMENDATIONS

This study provides a guidance document to water utilities to identify the challenges and mitigate the barriers related to implementing desalination technologies, particularly focusing on intake, water quality, energy use, and concentrate disposal. Besides the detailed recommendations described in the chapters, the following is a brief summary addressing the general issues for planning and implementing desalination:

- Conduct thorough feasibility study to identify the items such as
    - The need for water and the alternatives for meeting this need
    - Costs and benefits, financing approaches, and potential partners
    - Plant siting and capacity
    - Handling of residuals
    - Permitting requirement
- Conduct extensive pilot testing to
    - Select process from intake, through pretreatment and desalination process, to post-treatment
    - Optimize operation and performance and provide experiences for full-scale plant design and operation
    - Assess the processes performance in site-specific conditions (including variability of source water quality over time)
    - Evaluate the impact of product water on distribution system
    - Demonstrate and certify technology efficacy such as water quality and energy use
    - Providing information to regulatory agencies
    - Offer opportunities for operator training
- Address early and effectively environmental concerns including
    - Impingement and entrainment
    - Greenhouse gas emission and carbon footprint
    - Concentrate disposal
    - Land use
    - Benthic impact
    - Aesthetic, noise, and traffic issues
- Lead an open dialogue with community leaders and other stakeholders to communicate the need for water, alternatives, and solutions for solving problems
- Be flexible and willing to alter the course of action based on inputs that are feasible and have strong support

- Provide information on comparison of technology options such as intake structures, concentrate disposal, approaches to reduce energy use and carbon footprint
- Involve public to identify the nuisances related to traffic to/from a desalination facility, transport of chemicals, aesthetics, noise, and health and safety issues associated with facility construction and operation. Develop neighborhood program and set acceptable limits to the nuisances
- Use mutli-criteria decision making approach to evaluate the alternatives, criteria, and uncertainties

APPENDIX A INTERNATIONAL UTILITY SURVEY

Table A.1
Survey Results of Seawater Desalination Plants

	Water Utility	Desalination Plant/Project	Status	Co-location	Water Quality
1	VID Desalination Company Ltd., Kadima, Israel	87.2 mgd Ashkelon Seawater Reverse Osmosis Plant	Operating since 2005	Y-Power Plant	TDS 40.7 g/L, 15-30°C
2	Tampa Bay Water, Tampa Bay, FL	25 mgd Tampa Bay Seawater Desalination Plant	Operating since 2007	Y-Power Plant	TDS 30 g/L (16-32 mg/L), 29-30°C
3	Water Corporation of Western Australia, Leaderville, Australia	38 mgd Kiwana (Perth I) Seawater Desalination Plant	Operating since 2006	Y-Power Plant	TDS 35-37 g/L , 16-24°C
4	Long Beach Water Department, Long Beach CA	9 mgd Long Beach Seawater Desalination Project	0.3 mgd Prototype Plant operating since May 2006	not likely	TDS 34 g/L, 15.2-17.5 °C
5	Marin Municipal Water District, Corte Madera, CA	5-15 mgd MMWD Seawater Desalination Project	Completed pilot testing	N	TDS 21.7 g/L (2.5-29 g/L), 10-21 °C
6	West Basin Municipal Water District, Carson, CA	20-40 mgd WBMWD Seawater Desalination Project	Pilot testing 40 gpm since 2002	Y-Power Plant	TDS 34.5 g/L, 14-23 °C
7	Poseidon Resources, Carlsbad, CA	50 mgd Carlsbad Seawater Desalination Project	Pilot testing	Y-Power Plant	TDS 33.5 g/L
8	Municipal Water District of Orange County, Fountain Valley, CA	26.4 mgd Dana Point Ocean Desalination Project	Proposing Phase 3 pilot plant testing and water quality testing	N	Anticipated 33 g/L
9	Texas Water Development Board, Austin, TX/Brownsville Public Utilities Board, Brownsville, TX	25 mgd Brownsville Seawater Reverse Osmosis Desalination Project	Demonstration-scale testing	N	TDS 36.1 g/L (29.4-41.4 g/L), 23.9°C (7.9-31.1°C)

(Continued)

Table A.1 (Continued)

	Water Utility	Intake	Pretreatment*	Membrane Treatment	Cleaning Frequency	Recovery
1	VID Desalination Company Ltd., Kadima, Israel	Open ocean intake	Coagulation ($FeCl_3$ and polymer), dual media filtration, cartridge filters	4-pass RO	<4/year	Approx. 45%
2	Tampa Bay Water, Tampa Bay, FL	Open intake cooling water	Coagulation ($FeCl_3$), sand filtration, diatomaceous earth filters, cartridge filters	2-pass RO if needed	Monthly	56.8%
3	Water Corporation of Western Australia, Leaderville, Australia	Open ocean	Floculation/filtration (Cl_2, H_2SO_4, $FeCl_3$)	Partial 2-pass RO		49%
4	Long Beach Water Department, Long Beach, CA	Pilot plant using cooling water, also testing subsurface intake	300 um strainer and MF	2-pass NF		40%
5	Marin Municipal Water District, Corte Madera, CA	Open ocean intake	Testing 3 pretreatment trains in parallel: conventional *vs* MF *vs* UF	2-pass RO	Anticipated 3/yr using MF/UF, 4-5/yr conventional	40-50%
6	West Basin Municipal Water District, Carson, CA	Open intake cooling water	Pilot testing two pretreatment trains 100 um screener UF *vs* 70 um-MF	RO		
7	Poseidon Resources, Carlsbad, CA	Open intake from cooling water	Pilot testing two pretreatment trains coagulation/floculation-media filtration *vs* MF	RO	Anticipated 2/year	50%
8	Municipal Water District of Orange County, Fountain Valley, CA	Slant wells	TBD due to initial high Fe and Mn concentration from groundwater aquifer	RO	TBD	50%
9	Texas Water Development Board, Austin, TX/Brownsville Public Utilities Board, Brownsville, TX	Open intake from channel	Pilot testing 4 pretreatment trains in parallel: 2 UF *vs* MF *vs* 1 conventional	Partial 2-pass SWRO/BWRO	TBD	40%

Note: The commonly used pH adjustment and addition of antiscalant and antifoulant are not included in the pretreatment process.

(Continued)

Table A.1 (Continued)

	Water Utility	Post-treatment	Energy use	Cost
1	VID Desalination Company Ltd., Kadima, Israel	Lime remineralization and stabilization	13.2-13.7 kWh/kgal (3.5-3.62 kWh/m^3), with Double work exchanger energy recovery (DWEER) devices	Capital cost US$212M, total water cost 2.96 NIS/m^3 ($0.66/m^3, $2.50/kgal)
2	Tampa Bay Water, Tampa Bay, FL	Mixing lime and CO_2 for stabilization, and NaOCl for disinfection	14 kWh/kgal, RO feed pumps have energy recovery units which may cut plant energy costs and boost pump horsepower approximately 30-40%	Initial cost of $110M and remediation cost of $48M. Total water cost $3.19/kgal for the 1st year and will reduce to $2.85/kgal upon receipt of $85M in co-funding. Electrical cost $1.13/kgal
3	Water Corporation of Western Australia, Leaderville, Australia	lime, chlorine and fluoride	15.1-22.7 kWh/kgal (4.0-6.0 kWh/m^3), using ERD (Isobaric PX from ERI) and wind power	Capital cost AUS$387M, total water cost AUD$1.17/m^3 (approximately US$3.86/kgal)
4	Long Beach Water Department, Long Beach, CA	NaClO, blending, and NaOH and CO_2 addition	11-12 kWh/kgal (2.9-3.2kWh/m^3), using ERD (PX from ERI)	
5	Marin Municipal Water District, Corte Madera, CA	CO_2 and lime/calcite stabilization and disinfection	10-14 kWh/kgal (2.9-3.70 kWh/m^3), using ERD (PX)	Total water costs $6.21-9.19/kgal depending on pretreatment
6	West Basin Municipal Water District, Carson, CA			
7	Poseidon Resources, Carlsbad, CA	Disinfection by chloramines and remineralization by lime and CO_2	13.5kWh/kgal, carbon neutral through replacing imported water, ERD (PX ERI) recover 25% energy, REC, Solar PV project, etc.	Initial sale price $861/AF($2.64/kgal), MWD subsidies $250/AF, Energy cost estimated $1.1/kgal
8	Municipal Water District of Orange County, Fountain Valley, CA	CO_2 and limestone stabilization and disinfection	Anticipated 10-12 kWh/kgal with 90% energy recovery	Estimated capital cost $136-176M, total water cost $1287-1584/AF ($3.95-4.86/kgal)
9	Texas Water Development Board, Austin, TX/Brownsville Public Utilities Board, Brownsville, TX			$2.36/kgal ($768/AF)

(Continued)

Table A.1 (Continued)

	Water Utility	Disposal	Issues/Challenges
1	VID Desalination Company Ltd., Kadima, Israel	Ocean discharge blending with power plant cooling water at 1:10 ratio	Bioactivity in open intake, biofilm grows 1inch/year in intake pipelines
2	Tampa Bay Water, FL	Ocean discharge blending with cooling water at 1:70 ratio. Backwash water goes through coagulation, flocculation, and clarification process, and recycles back into the plant pretreatment process. Sludge follows into a belt filter press and disposed of offsite.	Contract risks and availability, system design, pretreatment, regulatory.
3	Water Corporation of Western Australia, Leaderville, Australia	RO concentrate, dechlorinated and neutralized. RO cleaning water and filtration backwash discharge to the sound through nozzles. Salinity increase<1% in the receiving water	Environmental impact due to concentrate disposal and energy use
4	Long Beach Water Department, Long Beach, CA	Current discharge to river, chemical cleaning solution was hauled from site	Optimization of energy recovery, subsurface intake design and testing
5	Marin Municipal Water District, Corte Madera, CA	RO concentrate ocean discharge with WWTP effluent, chemical cleaning solution neutralized and disposed of by discharge to WWTP. Solids wastes landfill.	Membrane fouling/scaling, concentrate disposal
6	West Basin Municipal Water District, Carson, CA	Blending ocean discharge	Feed water quality challenged by red tide event
7	Poseidon Resources, Stamford, CT	RO concentrate disposal: blending with power plant cooling water discharge to ocean; Cleaning waste was neutralized and discharge to sewer	I&E, co-location, regulatory and public perception
8	Municipal Water District of Orange County, Fountain Valley, CA	TBD	High Fe and Mn concentration in the slant well affected the selection of membrane pre-treatment
9	Texas Water Development Board, Austin, TX/Brownsville Public Utilities Board, Brownsville, TX	RO concentrate ocean discharge through channel. Filtrate and sanitary wastes, cleaning and flushing solutions discharge to WWTP. Sludge landfill.	

Table A.2
Survey Results of Brackish water Desalination Plants

	Water Utility	Desalination Plant/Project	Status	Source Water	Water Quality
10	Inland Empire Utilities Agency (IEUA) /Chino	14.2 mgd Chino I Desalter	Operating since Aug. 2000, expanded in July 2005	Groundwater	TDS 240-1300 mg/L, 20-280 mg/L nitrate
11	Basin Desalter Authority, Chino, CA (2 facilities)	10 mgd Chino II Desalter	Operating since 2006, plans for expansion by 2010	Groundwater	
12	Eastern Municipal Water District, Perris, CA (3 facilities)	3 mgd Menifee Desalter	Operating since 2003	Groundwater	TDS 2100 mg/L (1970-2220 mg/L), 22°C, Silica 63 mg/L
13		5 mgd Perris Desalter	Operating since 2005	Groundwater	
14		3 mgd Perris II Desalter	In design	Groundwater	
15	City of La Junta, CO	6.6 mgd BWRO	Operating since 2004	Groundwater	TDS 1200-1500 mg/L
16	City of Brighton, CO	6.65 mgd BWRO	Operating since 1993, expanded in 2002 and 2004	Groundwater	TDS 604 mg/L with high nitrate
17	City of Cape Coral	13 mgd BWRO	Operating since 1977	Groundwater	TDS 2000 mg/L
18	City of Fort Myers, FL	12 mgd BWNF	Operating since 1992	Groundwater	TDS 585 mg/L
19	City of Pompano Beach, FL	10 mgd BWNF	Operating since 2002	Groundwater	TDS 457 mg/L
20	City of Dunedin, FL	9.5 mgd BWNF	Operating since 1992	Groundwater	TDS 580 mg/L
21	City of Hollywood, FL	2 mgd BWRO, NF	Operating since 1999	Groundwater	TDS 2200 mg/L
22	City of Port St. Lucie, FL	9 mgd BWRO	Operating since 2001	Groundwater	TDS 2248 mg/L
23	El Paso Water Utility, TX	27.5 mgd BWRO	Operating since July 2007	Groundwater	TDS 600-1000 mg/L
24	City of Abilene, TX	6 mgd Hargesheimer RO WTP (BWRO)	Operating since 2003	Surface water	TDS 1183 mg/L
25	Thames Water, London, UK	39.6 mgd Thames Gateway WTP (BWRO)	Final planning permission granted in May 2008	Combination of seawater and surface water	

Note: None of the surveyed brackish water desalination plants c-located with power plants. The Thames Gateway Water Treatment Plant is collocated with the Beckton wastewater treatment plant, and considers an onsite biodiesel combined heat and power (CHP) plant using biogas (methane) from sludge digestion, which may be obtained from the adjacent Beckton Sewage Treatment Plant to power the CHP engines.

(Continued)

Table A.2 (Continued)

	Water Utility/Plant	Intake	Pretreatment	Membrane Replacement	Cleaning frequency	Recovery
10	Chino Basin Desalter I, CA	groundwater well	Cartridge filter	2-4 years		78.8%
11	Chino Basin Desalter II, CA	groundwater well	Cartridge filter	2-4 years		83.3%
12	EMWD Menifee Desalter, CA	groundwater well	Cartridge filter	5 years	4/year	71%
13	EMWD Perris Desalter, CA	groundwater well	Cartridge filter		2/year	70%
14	EMWD Perris II Desalter	groundwater well	Cartridge filter			
15	City of La Junta, CO	groundwater well	Cartridge filter	No replacement	Annually	80% (RO) 91.4% (overall with blending)
16	City of Brighton, CO	groundwater well	Cartridge filter	No replacement	3/year	80%
17	City of Cape Coral	groundwater well	Cartridge filter	10 years	Annually	75% for Plant 1 and 85% for Plant 2
18	City of Fort Myers, FL	groundwater well	Cartridge filter			88%
19	City of Pompano Beach, FL	groundwater well	MF	5 years	2/year	83%
20	City of Dunedin, FL	groundwater well	Prechlorination to oxidize H_2S, $KMnO_4$/Mn greensand filtration for Fe removal, H_2SO_4 pH adjustment, cartridge filtration	5 years	2/year	80%
21	City of Hollywood, FL	groundwater well	Cartridge filter	No replacement	Never cleaned	75%
22	City of Port St. Lucie, FL	groundwater well	Cartridge filter	>8 years		80%
23	El Paso Water Utility, TX	groundwater well	Cartridge filter	TBD		83%
24	City of Abilene, TX	Open intake	Coagulation/floculation, MF			70%
25	Thames Water, London, UK	Open intake	Coagulation/floculation, clarification, sand filtration, MF/UF	TBD		

Note: The commonly used pH adjustment and addition of antiscalant and antifoulant are not included in the pretreatment process.

(Continued)

Table A.2 (Continued)

	Water Utility/Plant	Post-treatment	Energy use	Cost
10	Chino Basin Desalter I, CA	CO_2 degasing, blending and NaOCl disinfection		Capital $53M; expansion $20,341,246. Total water cost $2.09/kgal
11	Chino Basin Desalter II, CA	CO_2 degasing, blending and NaOCl disinfection		Capital $51,939,704. Total water cost $2.09/kgal
12	EMWD Menifee Desalter, CA	Decarbonation, pH adjustment, disinfection, blending	2.7 kWh/kgal (0.71 kWh/m^3)	Total capital costs $1.91/kgal, O&M cost $1.85/kgal
13	EMWD Perris Desalter, CA	Decarbonation, pH adjustment, disinfection, blending	2.7 kWh/kgal (0.71 kWh/m^3)	Total capital costs $3.8/kgal, O&M cost $2.08/kgal
14	EMWD Perris II Desalter, CA			
15	City of La Junta, CO	Degasing, pH adjustment, blending, disinfection	3.16 kWh/kgal (0.83 kWh/m^3)	Capital $9.1M and total water cost $2.4/kgal
16	City of Brighton, CO	Degasing, pH adjustment, fluoridation, blending, disinfection, corrosion control	2.01 kWh/kgal (0.53 kWh/m^3)	Energy and material costs $0.47/kgal
17	City of Cape Coral		7.26 kWh/kgal (1.92 kWh/m^3)	Operating cost $0.9/kgal
18	City of Fort Myers, FL	Degasing, pH adjustment, blending, disinfection, corrosion control		operating cost $0.55/kgal
19	City of Pompano Beach, FL			Capital cost $20M
20	City of Dunedin, FL			Capital cost $11M
21	City of Hollywood, FL	Degasing, NaOH pH adjustment, Chloramines disinfection, fluoride, Blending		
22	City of Port St. Lucie, FL	Degasing, pH adjustment, blending, disinfection, corrosion control	3.89 kWh/kgal (1.03 kWh/m^3)	Capital cost $24.5M, and total water cost $3.49/kgal
23	El Paso Water Utility, TX			Capital cost $87M
24	City of Abilene, TX			
25	Thames Water, UK	Remineralization by lime and CO2, GAC, disinfection	Use Pelton turbines, estimated 7.28 kWh/kgal (1.92 kWh/m^3)	

(Continued)

Table A.2 (Continued)

	Water Utility/Plant	Disposal	Issues/Challenges
10	Chino Basin Desalter I, CA	Regional brine inceptor to WWTP	Membrane fouling/scaling
11	Chino Basin Desalter II, CA	Regional brine inceptor to WWTP	Membrane fouling/scaling
12	EMWD Menifee Desalter, CA	Regional brine inceptor to WWTP	Severe membrane fouling/scaling due to inadequate pretreatment, and limited available capacity of concentrate disposal
13	EMWD Perris Desalter, CA	Regional brine inceptor to WWTP	Severe membrane fouling/scaling due to inadequate pretreatment, and limited available capacity of concentrate disposal
14	EMWD Perris II Desalter, CA		
15	City of La Junta, CO	Surface water disposal blending with treated wastewater, chemical cleaning solution sewer discharge	RO concentrate disposal due to more stringent surface discharge regulations on selenium and uranium
16	City of Brighton, CO	Surface discharge, chemical cleaning solution sewer discharge	RO concentrate disposal due to more stringent surface discharge regulations on nitrate
17	City of Cape Coral	surface disposal after treatment, chemical cleaning solution discharge to sewer	
18	City of Fort Myers, FL	Deep well injection	
19	City of Pompano Beach, FL	Deep well injection, cleaning water using sewer disposal	
20	City of Dunedin, FL	Brine and cleaning waste both WWTP	
21	City of Hollywood, FL	WWTP	
22	City of Port St. Lucie, FL	Deep well injection, cleaning water using sewer disposal	Membrane fouling/scaling
23	El Paso Water Utility, TX	Deep well injection	
24	City of Abilene, TX	Sewer disposal	
25	Thames Water, London, UK	RO concentrate and cleaning solution co-discharged with treated WW in WWTP outfall.	Political opposition, carbon footprint

APPENDIX B FEDERAL AND STATE REGULATIONS ON DESALINATION PROJECTS IN THE US

Regulations and permitting for public health and environmental health is an essential necessity for desalination plants. The regulatory and permitting process is critical to ensure that the implementation of the desalination plant occurs on a timely manner. Concerns over the cost, time, and the uncertainties in desalination permitting processes may be potential significant issues (Desalination Task Force 2003b). It may be difficult to identify all the regulation requirements and varying regulations present each desalination project with its own unique set of issues, and would have to be assessed individually. A coordinated effort is needed in addressing the regulatory framework involved in desalination projects.

Agencies on the federal, state, and local levels all administer desalination projects with the responsibility over environmental resources, water rights, land use, water use, and supply. Regulatory and permitting processes are involved in several aspects of implementing and operating desalination plants including construction of facility structure, water source intake, product water quality, and concentrate and waste disposal. Of the regulating agencies, state and local agencies may have variations in regulatory requirements and would have to be addressed on a case by case basis. Regardless of who regulates which operations, it is important that permitting issues be addressed in the early planning stages of project development to ensure proper timing and coordination among agencies.

FEDERAL AGENCIES

On the federal level, policies are reviewed through the National Environmental Policy Act (NEPA), which provides the initial regulatory framework for desalination planning with an environmental assessment (EA) and, if necessary, an environmental impact statement (EIS) and/or environmental impact report (EIR). The EA addresses the purpose and need for the facility, alternative considerations, affected environment, and their environmental consequences (Watson *et al.* 2003). The preparation of EA and EIS/EIR take many regulatory issues into account and are reviewed by a multitude of government agencies. The following federal agencies address regulations relevant to desalination projects.

U.S. Environmental Protection Agency (USEPA) – The United States Environmental Protection Agency (USEPA) protects public health and the natural environment. The USEPA is responsible for the enforcement of the Clean Water Act (CWA) and the Safe Drinking Water Act (SDWA). The CWA sets the basis for regulating pollutant discharge from point sources to waters of the United States and establishes the National Pollution Discharge Elimination System (NPDES) permits. Although administered by the USEPA, the CWA is often delegated to state governments to issue, administer, and enforce NPDES permits. Such permits include brine and concentrate disposal addressed in Section 402, discharging heated water into receiving water in Section 316(a) for co-location projects, and marine life entrainment and impingement of intake structures in Section 316(b) (Younos 2005). Requirements for obtaining an NPDES permit include determination of membrane concentrate quality and quantity. Prior to issuance of an NPDES permit, reporting guidelines to the regulatory agency need to be determined (Jordahl 2006).

Also administered by the USEPA is the Safe Drinking Water Act (SDWA) which maintains the safety of the drinking water supply. Desalination plants treating brackish or seawater for public consumption are administered under the SDWA through the Public Water System Supervision (PWSS) program which enforces drinking water standards and monitors the quality of the product water from desalination plants. Furthermore, desalination plants that may discharge or inject concentrates into a groundwater source that may have potential to be used for public consumption are administered under the SDWA through the Underground Injection Control (UIC) program (Younos 2005).

U.S. Army Corps of Engineers (ACOE) – The U.S. Army Corps of Engineers (ACOE) regulates activities involving the nation's waters under Section 404 of the CWA and Section 10 of the Rivers and Harbors Act. Section 404 of CWA addresses disposal of dredge or fill materials to U.S. navigable waters. Section 10 of the Rivers and Harbors Act regulates obstruction to navigable waters, including any dredging or disposal of dredged materials, excavation, filling, rechannelization, or any other modification of a navigable water of the United States (CCC 2004). This would include intake and discharge structures of desalination facilities. Depending on the issue, ACOE permits may be reviewed by other agencies, including the U.S. Coast Guard, U.S. Fish and Wildlife Services, and the National Oceanic and Atmospheric Association National and the National Marine Fisheries Association.

U.S. Coast Guard (USCG) – The U.S. Coast Guard (USCG) ensures the safety and security along the coast and consults with ACOE under the CWA Section 404 and Section 10 permitting process to assess potential navigation hazards associated with intake and outfall structures.

U.S. Fish and Wildlife Services (USFWS) – The U.S. Fish and Wildlife Services (USFWS) also consult ACOE under Section 9 of the Endangered Species Act (ESA). The ESA ensures that desalination facilities do not harm such federally listed species and their habitat. USFWS can require a desalination plant to prepare a formal biological opinion if the plant operation may impact any endangered species (Younos 2005).

National Oceanic and Atmospheric Association National Marine Fisheries Service (NMFS) – Similar to the USFWS, the National Marine Fisheries Service (NMFS) is responsible for marine species covered under the ESA. The NMFS assess if there may be potential impacts on essential fish habitat.

STATE AND LOCAL AGENCIES

Federal agencies may often delegate authority to states and some local agencies. To name a few examples, the USEPA delegates NPDES permitting authority to the Texas Commission on Environmental Quality in Texas, the Florida Department of Environmental Protection in Florida, and the State Regional Water Quality Control Board in California. States thus may have similar approaches towards regulations and permitting, as they are often based on federal guidelines. Despite similar approaches, states and local governments may significantly vary in specific permitting and regulatory requirements and would require site specific assessments. To illustrate the similarities and differences in local regulation of desalination plants between states, the following three states, Florida, Texas, and California are presented in detail. These states were selected because Florida has extensive desalination experience, Texas's recent involvement in brackish water desalination, and California's investments in seawater desalination (Jordahl 2006).

Florida

In Florida, local agencies mainly address construction operations including site plan review, building permit, tree and tree removal permit, erosion permit, right-of-way use permit. Some communities also have special permit requirements for on-site wastewater treatment facilities and potable water treatment. Private railroad companies such as CSX Rails or the Florida East Coast Railways may also issue permits for pipelines relating to desalination that cross any railroad properties or tracks (RW Beck 2002a). In addition to local and federal agencies, Florida requires relatively few state agencies to administer desalination projects. These state agencies are listed below:

Florida Department of Environmental Protection (FDEP) – Delegated by the USEPA, the FDEP issues the majority of permits for desalination projects in Florida. Its jurisdiction is derived from the state code Section 62 and addresses permitting process, quality assurance, operation permits for major sources of air pollution, surface water and water quality standards, environmental resource permitting and procedures, groundwater classes, standards and exemption, groundwater permitting and monitoring, construction for public works, underground injection control, drinking water standards monitoring and reporting, reclaimed water and land applications, water quality based effluent limitations, and industrial wastewater facilities.

Florida Fish and Wildlife Conservation Commission (FFWCC) – The FFWCC provides comments to FDEP on possible effects of a desalination plant to marine life, particularly the West Indian Manatee. FFWCC also comments on Section 404 permits under review by ACOE.

Florida Public Service Commission – May regulate the rates charged by water utilities and may monitor the safety and reliability of desalination product water.

Florida Department of transportation (FDOT) – The FDOT issues a permit if the transmission main crosses any right of way.

Even with these limited agencies, permitting applications may still be extensive. The Tampa Bay desalination plant required a total of 24 environmental and construction permits from local, state, and federal agencies (AWA 2005). Its NPDES permit alone underwent a 16 month review process and was one of the most thorough ever conducted by the FDEP (Ramirez and Lee 2004).

Texas

In Texas, a desalination project requires permits focusing on facility construction, feed water, and residual management. Similar to Florida, local city and county most often administer permits relating to construction such as building permits, tree removal permits, erosion permits, and right-of-way use (RW Beck 2004). In addition to local and Federal agencies, Texas requires only a few state agencies to administer desalination projects. Like Florida, there are relatively few state agencies to consider:

Texas Commission of Environmental Quality (TCEQ) – The Texas Commission on Environmental Quality (TCEQ) is the delegated authority by the USEPA and it provides the majority of the permitting activities including approvals for construction of public works, construction of petroleum storage tanks (if applicable), air emission, water rights, reviewing well construction, drinking water compliance, concentrate disposal permits which include underground injection discharge permits and surface water discharge permits.

Texas General Land Office (TGLO) – The Texas General Land Office (TGLO) approves easement of coastal, miscellaneous, upland surface and commercial leases, and submerged lands.

Texas Department of Transportation (TDOT) – Approves work along a Texas department of transportation roadway or right of way use.

Texas Historical Commission (THC) – The Texas Historical Commission (THC) assess impacts to historic and prehistoric resources under Section 106 of National Historic Preservation Act.

Railroad Commission of Texas (RRC) – A desalination project may require a permit from the Railroad Commission of Texas (RRC) for easement of utilities and pipelines affecting railroad crossings.

Perhaps the most difficult permits to obtain may be permits for concentrate disposal. This difficulty is reflected in Authorization to Construct (ATC) permits issued by the TCEQ. An ATC permit is required before a concentrate disposal structures may be constructed, while construction of the desalination treatment structures does not require such an ATC (Puente 2005). Depending on the disposal method, various permits are required. A Texas Pollutant Discharge Elimination System (TPDES) permit is required for surface water discharge, an UIC permit is needed for underground injection, or a Texas Land Application Permit (TLAP) is needed for use of the concentrates for irrigation or surface impoundment evaporation. No permits are required by TCEQ however if concentrates are discharged to publicly owned treatment works (Jordahl 2006, Puente 2005).

California

California has significantly more agencies associated with desalination projects than other states. A seawater desalination plant in California may require permits from up to 15 state agencies in addition to federal and local government involvement. Multiple reviews have addressed California agencies and regulations (Cooley et al. 2006, CCC 2004, DWR 2003, Desalination Task Force 2003b, California Desalination Planning Handbook 2008) and their relation to desalination projects. Such California agencies are briefly addressed in relation to desalination projects below:

California Coastal Commission (CCC) – The California Coastal Commission (CCC) regulates development along California coastlines under the California Coastal Act. It determines coastal consistency and issues a coastal development permit which addresses environmental policies, growth inducement, coastal dependency, and feasibility studies. Desalination plants built along the coast are under the CCC jurisdiction.

Office of Historic Preservation (OHP) – The Office of Historic Preservation (OHP) assess impacts to historic and prehistoric resources under Section 106 of National Historic Preservation Act.

California State Land Commission (CSLC) – The California State Land Commission (CSLC) manages the state's tidelands and land lying under coastal waters. Under the California Public Resource code, the CSLC may need to issue a land lease permit if desalination intake and outfall structures lay over SLC jurisdiction.

California Department of Fish and Games (CDFG) – The California Department of Fish and Games (CDFG) reviews projects for any biological impacts to species and habitat in California Endangered Species Act listing. The CDFG may issue permits on any stream alterations for activities within inland waters and some bays and estuaries. The CDFG consults with ACOE under Section 10 of the Rivers and Harbors Act and CCC under the Coastal Development Permit. It also reviews NPDES permits and EIR/EIS under California's Environmental Quality Act (CEQA).

California Public Utilities Commission (CPUC) – The California Public Utilities Commission (CPUC) regulates water service rates and service area. Under the Public Utilities Act, the CPUC may establish water rates and limit where water may be sent by the desalination facilities.

California Department of Health Service (CDHS) – The California Department of Health (CDHS) administers provisions relating to regulations of drinking water to protect public health under the California Safe Drinking Water Act. The CDHS specifies performance standards and treatment processes for approval of drinking water.

California Department of Transportation (CalTran) – The California Department of Transportation (CalTran) may require an encroachment permit for utilities affecting state highway right of ways.

State Regional Water Quality Resources Board (RWQCB) – The State Regional Water Quality Resource Control Board (RWQCB) is responsible for allocating water rights within California and responsible for the state's water quality certification requirements which includes discharge standards for NPDES permitting

California Department of Parks and Recreation (CDPR) – The California Department of Parks and Recreation (CDPR) requires approval from Department of Parks and Recreation if desalination facility is within or near a state park, which includes one-third of California's scenic coastlines.

California Department of Water Resources (CDWR) – Desalination projects may require approval from California Department of Water Resources (CDWR) for use of state distribution and conveyance facilities for water transfers.

California Department of Boating and Waterways – Reviews documents and EIR for impacts on boating safety relating to intake and discharge structures.

California Energy Commission (CEC) – The California Energy Commission (CEC) reviews effects of desalination facility and proposed changes to power plants including energy use and transmission lines. The CEC and also reviews CEQA.

California Ocean Protection Council (COPC) – The California Ocean Protection Council (CPC), under the California Ocean Protection Act helps coordinate and improve the protection and management of California's ocean and coastal resources. This would apply to desalination intake and outfall structures and facilities developed along California's coast.

San Francisco Bay Conservation and Development Council (BCDC)– State Coastal Management agency responsible for San Francisco Bay area protection and enhancement. The BCDC issues permits for placing fill materials, dredging or extracting materials, substantially changing the use of any structure or area, constructing, remodeling or repairing a structure, or subdividing property or grading land within BCDC jurisdiction.

South Coast Air Quality Management District (AQMD) – The South Coastal Air Quality Management District (AQMD) is responsible for controlling emissions, which includes emissions during construction of a desalination plant.

REGULATORY CONCERNS

Such a broad range of authorities and regulating agencies, particularly in California, may make coordination between agencies difficult and allows potential hindrance in the application of desalination projects. Many such regulations may be interrelated, though it may not always be apparent (Watson et al. 2003). For example, construction of an outfall structure in California would require permits from the State and Regional Water Quality Control Board, U.S. Army Corps of Engineers, California Coastal Commission, California Department of Fish and Games, U.S. Fish and Wildlife Service, National Marine Fisheries Service, local agencies, completion of the California Environmental Qualities Act, an Endangered Species Act evaluation, and consultation with the State Land Commission (Jordahl 2006). Concerns are further compounded by the fact that there has been only one large scale desalination facility developed in the United States (in Tampa Bay) and thus limits hindsight on the regulatory process (Ramirez and Lee 2004). In addition, permitting schedules may be long and arduous. It is estimated that a seawater desalination plant may require 21 months for the permitting process and perhaps even longer for inland brackish water facilities due to water rights permits (RW Beck 2004).

Despite potential confusion, there have been efforts to coordinate and set up guidelines in permitting processes. California has established a Desalination Task Force which comprises of 28 different organizations and agencies on all levels to address key issues in desalination including permitting and regulations (Members List for Water Desalination Task Force). In Texas, the Texas Water Development Board has been proactive in coordinating with different agencies. They have also commissioned studies for implementing seawater desalination and established a guidance manual for a desalination permitting process which includes a decision model using a set of decision tree analysis (RW Beck 2004). Certain regions in Florida have also commissioned feasibility studies for seawater demineralization which included rules and regulation issues in desalination (RW Beck 2002a).

General consensus of these studies have emphasized that permitting should be a priority during the desalination planning stages to allow ample permit processing time. Also, the regulatory and permitting process needs to develop agency guidelines for coordination and consistency of review for desalination facilities.

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ABBREVIATIONS

ADC	Affordable Desalination Collaboration
AF	acre-feet
AI	aggressive index
aMW	average megawatt, 1 aMW = 1 MW x 8760 hours/year = 8,760 MWh
AUD	Australian Dollar
BOT	Build, Operate, and Transfer
BWRO	brackish water reverse osmosis
CAP	Central Arizona Project
CCC	California Coastal Commission
CCPP	calcium carbonate precipitation potential
CF	concentrate factor
CHP	combined heat and power
CMSA	Central Marin Sanitation Agency
CW	criteria weight
CWQCC	Colorado Water Quality Control Commission
DBO	Design, Build, Own (**used once)
DBOOT	Design, Build, Own, Operate, Transfer
DBP	disinfection by-product
DO	dissolved oxygen
DOE	Department of Energy
DWEER	double work exchanger energy recovery
DWI	deep well injection
DWR	California Department of Water Resources
EA	UK Environment Agency
ED	electrodialysis
EDI	electrodionization
EDR	electrodialysis reversal
EfOM	effluent organic matter
EIR	environmental impact report
ERDs	energy recovery devices
ETM	Empirical Transport Model
FAS	Floridan Aquifer System
FPLC	Florida Power and Light Company
g/l	grams per liter
GL/year	gigaliter per year
gpm	gallons per minute
gpm/ft^2	gallons per minute per square foot
IEUA	Inland Empire Utilities Agency
kgal	1000 gallons
kWh	kilowatt hour
LADWP	Los Angelos Department of Water and Power
LBWD	Long Beach Water Department
LR	Larson ratio

LSI	Langelier saturation index
m^3	cubic meter
m^3/d	cubic meters per day
MCDA	multi-criteria decision analysis
MCM	million cubic meters
MED	multi-effect distillation
MF	microfiltration
mgd	million gallons per day
ML/d	million liters per day
MRET	Mandatory Renewable Energy Target
m/s	meter per second
MSF	multistage flash
MMWD	Marin Municipal Water District
MWD	Metropolitan Water District of Southern California
MWDOC	Municipal Water District of OrangeCounty
NaCl	sodium chloride
NDMA	N-nitrosodimethylamine
NF	nanofiltration
NGO	nongovernmental organization
NOM	natural organic matter
NPDES	National pollutant discharge elimination standard
Ofwat	Office of Water Services
O&M	operation and maintenance
OTC	once-through cooling
ppb	parts per billion
ppm	parts per million
PV	photovoltaic
REC	renewable energy credit/renewable energy certificate
RO	Reverse Osmosis
SAR	sodium adsorption ratio
SARI	Santa Ana Regional Interceptor
SDCWA	San Diego County Water Authority
SDI	Silt Density Inxex
SFWMD	South Florida Water Management District
SNWA	Southern Nevada Water Authority
SRP	Salt River Project
SWRO	seawater reverse osmosis
TDS	total dissolve solids
TGWTP	Thames Gateway Water Treatment Plant
TOC	total organic carbon
TSS	total suspended solids
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
VC	vapor compression
VSEP	vibratory shear process
USGS	Untied States Geological Survey

WBMWD	West Basin Municipal Water District
WET	whole effluent toxicity
WHO	World Health Organization
WTP	water treatment plant
WWTP	wastewater treatment plant
ZLD	zero liquid discharge
μg/L	microgram per liter
€	Euro
£	British pound

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