An Environmental Literature Review and Position Paper for Reverse Osmosis Desalination Plant Discharges

– Contract No. CN-05-12269 –

29 April 2006

WATER CORPORATION
ABN 28 003 434 917

Sydney WATER

Water Consultants International

Project:	**Environmental Literature Review and Position Paper for Perth Seawater Desalination Plant Two and Sydney Seawater Reverse Osmosis Plant**
Client:	**Water Corporation of Western Australia**
WaterCi Project No.:	**1890**
WaterCi Primary Contact:	**John Tonner**
Date:	**4 April 2006**

Revision History

1st Draft	**Project Team**	**20 February 2006**
2nd Draft	**Project Team**	**5 March 2006**
QA/QC Review	**Dr C Robert Reiss**	**6 March 2006**
Peer Review	**Nikolay Voutchkov**	**7 March 2006**
Presentation	**Tom Pankratz and John Tonner**	**12, 13, 16 & 17 March 2006**
Final comment compilation	**Project Team**	**30 March – 5 April 2006**
Report Issued	**Project Team**	**28 April 2006**

Water Consultants Intl.
10201 N Concord Dr
Mequon WI 53097

Tel: +1 262 242 2502
Fax: +1 262 242 0835

www.WaterCI.com

Executive Summary

Seawater desalination has provided a reliable source of water for the Middle East and Caribbean since the 1950's. As traditional fresh water supply sources face increasing pressures, communities around the world have now begun to view seawater desalination as a necessary component of a diversified water supply portfolio. Over 3,000 seawater desalination systems have been installed, producing more than 37,000 ML/d of fresh water (IDA, 2004), including 4,700 ML/d of new capacity contracted in 2005.

Thermal desalination processes have traditionally been employed in many of these systems. However, today's membrane technology has shown that seawater reverse osmosis (SWRO) desalination can provide a cost-effective, drought-proof local water supply source. In fact, SWRO technology is proving so reliable and cost-effective, that it is now replacing aging thermal desalination plants in the Caribbean and Middle East.

Large-scale (i.e. >40 ML/d) SWRO projects are now being developed by coastal communities in the US, Europe, Africa, Asia, Australasia and Indian subcontinent. In each of these instances, desalination will be a part of an overall water management plan that includes reuse, conservation and water importation.

As the number and size of SWRO facilities increase, so does the potential for their impact on the environment. The challenge facing communities considering seawater desalination is to develop an environmentally responsible method of obtaining a seawater supply and returning concentrate back to the sea. Fortunately, there are numerous strategies that can be employed and it is possible to ensure that the seawater supply is responsibly abstracted and more importantly that concentrate returned to the sea is immediately dispersed and quickly equalized to normal seawater salinity.

The Water Corporation of Western Australia and Sydney Water understand the importance of environmental stewardship and have commissioned studies to confirm their respective seawater desalination plants reflect the state-of-the-art in environmental design and monitoring, and mitigate all potential environmental impacts, particularly with respect to SWRO concentrate discharge. This may include pre-treatment backwash water, diffusion of the seawater concentrate and system cleaning solutions.

This report is the culmination of an investigation which provides an international review of the policies and practices associated with seventeen of the world's largest SWRO plants. Information from dozens of smaller plants operating in environmentally sensitive locations has also been considered. More than 70 technical papers and numerous Environmental Impact Reports, Environmental Impact Assessments and books have been reviewed. Interviews were conducted with regulators, consultants, plant operators and project developers familiar with discharge disposal issues. The information evaluated includes data from plants approved and in operation since early 1989, to some plants that are still under development and whose Environmental Impact Assessments (EIA) have been submitted, assessed and/or defended.

Particular emphasis has been placed on SWRO discharges because they pose the greatest and most visible potential environmental risk. A March 2004 report by California's Coastal Commission – the planner and regulator of one of the world's most environmentally-sensitive seacoasts – concluded, "the most significant direct adverse environmental impact of seawater desalination is likely to be on marine organisms. This impact is due primarily to the effects of the seawater intake and discharge on the nearby marine life; however, these effects can be avoided or minimized through proper facility design, siting, and operation."

This study's findings have confirmed that concentrate discharge is/remains the most universal environmental concern associated with seawater desalination. It is also apparent that a complete lack of consistency in discharge designs, monitoring, assessments and regulations exists. These inconsistencies are due to reasons relating to the uniqueness of each plant and its location, including:

- varying degrees of the local environment's sensitivities,
- varying degrees of local environmental sensibilities,
- lack of reliable baseline environmental data available with which to evaluate impacts,
- differences in each waterbody's ability to assimilate a concentrate discharge,
- facilities that are being installed/considered in locations where there is an absence of historical data,
- recent increase in SWRO plant sizes for which limited relevant historical information is available,
- the fact that much of the published data available is based on thermal desalination and power plant discharges and is not necessarily relevant to SWRO.

Fortunately, the significant potential impact of SWRO concentrate discharge issues makes it the primary focus of environmental impact considerations, even in parts of Southeast Asia and the Middle East that are not known for their environmental concerns. Even in these locations, anecdotal evidence concerning environmental impacts was generally available. Detailed and quantified studies of the impact of desalination discharges on marine life surrounding Caribbean coral islands provides strong evidence of little or no impact, even when using unsophisticated discharge designs.

During the preparation of this report, the authors also reviewed environmental information provided by the Water Corporation of Western Australia and Sydney Water on their proposed facility's concentrate discharge systems. This information included planning studies, modelling reports, water quality management and test data, and baseline water and environmental studies. This information has been compared with that available from other facilities and the authors believe the Perth and Sydney projects have undertaken a more thorough job of evaluating and mitigating potential environmental impacts from SWRO concentrate discharges than any other SWRO facility evaluated. The Perth and Sydney concentrate discharge designs exceed the best current practice to ensure that the environment is protected from potential impacts of large-scale SWRO plants.

Table of Contents

1 Environmental Impacts of Seawater Desalination Plants

1.1 Introduction

As traditional fresh water supply sources face increasing pressures, communities around the world have begun to view seawater desalination as a necessary component of a diversified water supply portfolio. These growing supply pressures are occurring at the same time technological advances have reduced costs, further broadening the application of membrane desalination and making it one of the fastest growing segments of the water sector.

Reverse Osmosis (RO) systems now desalinate seawater at some of the world's largest desalination plants and the industry is facing a new era of large-scale (i.e. > 40 MLD) projects in areas where they were never before considered. As the number and size of these facilities increase, so does the potential for their impact on the environment.

This report provides an international review of the environmental impacts associated with seawater reverse osmosis (SWRO) plants. It will provide a review of relevant environmental literature, policies and practices. Particular emphasis has been given to the impact of the concentrate disposal from a SWRO facility.

This report will identify the normal desalination industry practice with regards to concentrate discharge and will document the impact mitigation measures employed at several large-scale SWRO plants around the world.

1.1.1 Literature Review Discussion

More than 70 papers and reports were reviewed in the preparation of this report. During the review process it was noted that a significant number of the 'technical' papers fell far short of expectations based on the level and amount of quantified environmental impact data that was provided. In many cases, the titles of publications created expectations for content that fell far short. Many papers offer very similar discussions of the potential environmental impacts of seawater desalination but contain no discussion of mitigation or management techniques, or present observed data.

One example can be found in the reference "Direct and Socially-induced Environmental Impacts of Desalination" (von Medeazza, 2005). The paper states *"…widely acknowledged that extensive brine discharge, as it constitutes a hypersaline layer that sinks towards the seabed due to its greater density has the potential to heavily affect local marine biota."* This is a very strong statement that, references Einav & Lokiec (2003) and Purnama (2003) despite the fact that neither reference provides field data (Puranama is a modeling study). von Medeazza goes on to reference Talvera (2001) as discussing possible mitigation techniques but does not mention this work included field measurements that showed complete mixing of the discharge occurred within the water column within a distance of 20m; a clear conflict with Einav/Puranama. von Medeazza further states that *"mitigation is dependant on local hydro-dynamic conditions (i.e. proportional to water column agitation)*" yet does not advise that Talavera's finding relate to calm conditions considered very conservative for local hydro-dynamic impacts.

This example may indicate that such an analysis is not wholly objective or scientifically valid.

Several published works discussed changes in certain physical properties of the receiving waterbody but failed to address quantified impact on biota. More than one paper identifies changes in heavy metal concentrations in the vicinity of a thermal desalination plant discharge but not a single species was studied for possible impact. Since no level above that of the background level is known to be non-toxic for most metals, these works missed an opportunity to quantify something that is currently unknown, even though it may not applicable to SWRO.

Many publications focused on particular aspects of potential impacts, such as plume mixing or measured changes in sea-grass meadows, but provided little detail of the prevailing hydrodynamic conditions and details of the discharge design (e.g. number/type of diffusers). Wherever possible, published data has been supplemented by interviewing facility owners, designers or operators. In some cases, conflicting information was provided through these interviews, although attempts were made to corroborate information whenever possible.

The best examples of references that quantified the environmental impact of SWRO concentrate were studies completed prior to the development of the Tampa Bay Florida SWRO project. The studies were performed in two phases. First, several SWRO facilities in the Caribbean were surveyed to find a location that was best suited for a more detailed, follow-up study, i.e. control over location, ideal for comparison to models, and limited anthropogenic impact from collateral sources. The second study performed a highly detailed baseline analysis of a virgin marine area that included an environmentally sensitive coral reef. An existing SWRO plant discharge was then diverted into the baseline area, which was then studied for quantified impacts on the benthic communities and other marine species which feed upon them. Although these studies (Blake et al, 1996; Hammond et al, 1998) were the most scientifically comprehensive to be reviewed as part of this report, the plants evaluated were relatively small. Nonetheless, the study authors consider the work to be valid and applicable to larger SWRO facilities and other marine locations,

1.2 Environmental impacts

SWRO is a generally ‘clean’ process that may be considered analogous to filtering salt from seawater. However there are potential impacts from the construction and operation of a SWRO desalination facility that must be considered and mitigation measures for each impact must be developed. Construction impacts are typical for those of coastal building projects and include some on or near-shore subsea works. A list of potential impacts and possible mitigation techniques, focused on operational issues is provided in Table 1. Over seventeen major SWRO facilities were surveyed to gather data for this report. A summary of the data is tabulated in the Appendices.

1.2.1 Concentrate streams

The RO desalination process produces two streams; a *product water* stream that is essentially “pure” water, and a *concentrate* stream whose salt content includes the salt that remains when the product water is produced. In a seawater desalination facility, the salt content of the concentrate stream may approach 7%, or approximately twice the concentration of seawater.

Seawater has the capacity to dissolve several times its normal salt concentration, and most seawater desalination facilities are able to discharge concentrate back to the sea where it is almost immediately diluted by the large volume of available water while marine life is left undisturbed. But, an in-depth characterization of the receiving water is a necessary first step, and it is important that the discharge be accomplished in a responsible, well-engineered manner to minimize its environmental impacts.

To assess the environmental impacts of a concentrate stream(s) on the marine environment, information on the individual constituents of the discharge as well as the sensitivity of the accepting ecosystem is required. One approach is to individually evaluate the chemical concentrations in the reject stream with regard to their toxicity to marine organisms. Another is to estimate total discharge volumes and loads with regard to the carrying capacity of the coastal ecosystem in terms of dilution and degradation.

The expected environmental impacts of a plant will depend on the design of the desalination process including the pretreatment and discharge system, and the location of the facility including its intake and outfall. Concentrate can include traces of corrosion from desalination equipment and residual chemicals that may have been added for pretreatment, scale inhibition or cleaning purposes.

Approximately 60% of the world’s seawater desalination capacity is produced using thermal processes. While the salt concentration factor of thermal processes is very similar to SWRO, there are some important differences in the concentrate streams produced by thermal and membrane processes:

- Temperature; SWRO concentrate is essentially ambient temperature while thermal concentrate may be 8°C warmer than seawater.
- Volume; thermal plant concentrate includes a large cooling water flow and may be may times higher than that of a similar sized SWRO facility.
- Salinity; although the process concentration is similar for both processes, thermal plant concentrate may be diluted by the cooling water flow.
- Heavy metals; the type and quantity of materials used in the construction of thermal plants are more likely to corrode and appear in the concentrate.
- Chemicals; the chemicals used in thermal plants are significantly different than those used in membrane plants.
- This report will only consider SWRO plant concentrate and will not consider the potential impacts that are unique to thermal desalination plants.

Location	Area of Concern	Potential Adverse Impact(s) - some or all may apply -	Potential Impact Level	Possible Mitigation Measures - some or all may apply -	Duration of Mitigation	Mitigation Monitoring Frequency
On shore	Improper management of solid wastes	Risk of accidents Health hazards Poor aesthetics	L L L	Develop and implement solid waste management plan including recycling programs	C	P
On shore	Improper management of sludge wastes.	Risk of accidents Health hazards Poor aesthetics	L L L	Develop and implement solid waste management plan including recycling programs	C	P
On shore	Improper care of raw chemicals and hazardous wastes	Human health impacts Environmental contamination	L L	Implement waste management plan, provide designated containers/areas wastes accumulations, proper disposal, worker training	C	P
Offshore	Concentrate discharge	Increased salinity Increased turbidity Discoloration Density stratification	H L L L	Design for rapid dilution, reduce size of mixing zone, dilute prior to discharge, locate outfall in deeper waters away from the shoreline	C	P
Offshore	Pretreatment backwash streams	Chemical toxicity Altered biological functions Increased mortality Eutrophication Discolouration	M L L M M	Segregate the solutions. Pretreatment prior to blending with concentrate. Hold for continuous blending. Direct to sewer	I	P
Offshore	RO membrane spent cleaning solutions added to concentrate discharge	Chemical toxicity Altered biological functions Increased mortality Eutrophication	H M M L	Segregate the solutions. Pretreatment prior to blending. Hold for continuous blending. Direct to sewer	I	P
Offshore	RO membrane preservative solutions added to concentrate discharge	Chemical toxicity Altered biological functions Increased mortality Eutrophication	H M M L	Segregate the solutions. Pretreatment prior to blending. Hold for continuous blending. Direct to sewer	I	P
Offshore	Residual feedwater additive in the concentrate	Lowered pH Chemical toxicity Eutrophication Altered biological functions Increased mortality	L L L L L	Minimize use of chemicals, pretreat concentrate prior to discharge, use low impact chemicals, minimize pretreatment required by technology selection	C	P
Offshore	Discharge of corrosion by-products	Chemical toxicity Impacted biological functions Increased mortality	L L L	Use corrosion resistant pipes	C	P
Offshore	Discharge of disinfectants and their by-products	Chemical toxicity Impacted biological functions Increased mortality	M M M	Minimize disinfectant use, minimize disinfectant removal products, substitute non-chemical disinfection	I	P
Offshore	Discharge of intake screening	Aesthetic concerns Coastal pollution Contaminate intake	L L L	Appropriate screenings handling system, mitigate entrainment, action plan for algae bloom, jelly fish runs	C	P
C = Continuous, I = Intermittent, P = Periodic, L = Low, M = Medium, H = High						

Table 1 - Mitigation Measures

1.2.2 Determining Marine Sensitivity

The environmental sensitivity of coastal areas varies enormously. To characterize a site's ability to assimilate a desalination plant's concentrate, marine habitats have been subdivided into 15 categories reflecting their sensitivity to potential environmental impacts [Höpner et al]. These categories can be used to select the least sensitive location for a desalination plant, and/or are indicative of the degree of mitigation that is required.

1) *High-energy oceanic coasts, rocky or sandy, with coast-parallel current*. Energy input prevents local accumulations and oxygen and nutrient levels favor biodegradation.
2) *Exposed rocky coast.* Good water exchange, even in small niches.
3) *Mature shoreline.* Sediment mobility prevents local accumulations of matter.
4) *Coastal upwelling.* Greater danger of stagnant beach, near-water than 1, above; conditions change seasonally, sometimes containing nutrients and suspended solids.
5) *High energy soft tidal coast.* Large intertidal areas and sediment surfaces susceptible to accumulation; however, the water exchange and sediment mobility is high.
6) *Estuaries and similar systems*. Similar to 5, above, with high nutrient input. Turbidity and seasonal water quality changes not suitable for desalination plants.
7) *Low energy, sand-, mud- and beachrock-flats.* Sensitive because of high individual but low species numbers. Loads may accumulate because of large surface, evaporation and limited water exchange.
8) *Coastal sabkhas* (salt flats). Similar to 7, above, and flooded occasionally.
9) *Fiords.* Enclosed deep water bodies with limited water exchange. Danger of themoclines and oxygen deficits at depths; marine life shelter and breeding areas.
10) *Shallow low-energy bays and semi-enclosed lagoons*. Similar to 7, with lower exchange.. Consequences of load add to salinity, water depth and other stress factors.
11) *Algal mats*. Wide, intertidal areas at very low beach slopes. While not sensitive to salt, irradiation, dryness or oil, other sensitivities are unknown.
12) *Seaweed bays and shallows*. Similar to 10, and bears additional sensitivity of seaweed and animals that feed and live within.
13) *Coral reefs*. Species rich community, some of whom have highest sensitivities, e.g. fish schools.
14) *Salt marsh*. Sensitivity similar to 7, with the additional sensitivity of macrophytes (aquatic plants) and animals that inhabit salt marshes.
15) *Mangal* (mangrove flats). Sensitivity similar to 14, and rapid decline of mangrove areas argues for high sensitivity.

The topography and hydrodynamics of the location and the project specific design of the discharge must be considered alongside environmental sensitivity. Diffusers improve the mixing of the discharge into the receiving water by dispersing the discharge at velocity, with a specific direction and at multiple points. This is most important to improve mixing and water exchange at locations with low coastal currents or enclosed water bodies.

These factors are normally modelled using software that has been developed specifically for this purpose. The predictions of the software programs are calibrated by comparison with known real world conditions, often with locally tailored models that have been historically proven such as Environmental Fluid Dynamics Code. Localized models may better reflect other parameters such as the influence of prevailing winds on local currents and the resulting impact on mixing. Some of the software packages available include CORMIX, Visual Plume and Hamsom.

Modelling is normally performed for several environmental conditions (e.g. temperature, current, TDS) that may vary by season and for different operating capacities or configurations of the desalination plant. The calculations will consider the constituents of the discharge, it's physical properties and expected behaviour in the receiving body (i.e. is the discharge negatively buoyant and more dense than the seawater?). Two zones are usually considered.

The Zone of Initial Dilution, also known as the Near Field, is the area where all the parameters are determined by the design of the outfall and the quality of the water being discharged. The Far Field is the local area that is primarily affected by prevailing currents and other natural phenomena.

The objective of a properly designed discharge is to ensure the Near Field is as small as possible, and that within it there is minimal environmental impact. In highly sensitive locations, site-specific studies may be required to ensure targeted species are not adversely impacted. This can be mitigated by ensuring that discharge point(s) are not within the most sensitive zones, or that all parameters at the discharge point are within permissible limits.

A secondary objective is to ensure that mixing is complete and that there is no significant impact of the discharge in distant areas, nor any recycling of the discharge back towards the general outfall area, or the plant intake.

1.2.3 Physical properties

Salinity and temperature of the reject stream are the most prominent parameters in studies concerned with the environmental impacts of desalination plants (e.g. Ahmed et al., 2000; Höpner, 1999; Abdel-Jawad and Al-Tabtabaei, 1999; Morton et al., 1996; Mickley, 1995; Shams El Din et al., 1994; Del Bene et al., 1994; Altayaran and Madany, 1992). Both parameters depend on the desalination process used and the ambient seawater properties at the plant site and determine the density of the concentrate stream, which influences spreading of the plume beyond the discharge. Knowledge of the spreading behaviour (e.g. through hydrodynamic modelling) is essential for most impact assessments, as it affects the dispersal range and dilution rate of chemical constituents in the reject streams.

1.2.3.1 Salinity

Seawater is a chemically complex substance that may contain more than 70 chemical elements. The chemical composition of seawater varies somewhat, but "standard" seawater is considered to have a total dissolved solids (TDS, or *salinity*) concentration of 36,000 mg/L. Most elements are present only in trace concentrations, while more than 99% of the dissolved solids consist of the following eight constituents in the approximate quantities:

Cations	mg/L	Anions	mg/L
Sodium	11,035	Chloride	19,840
Magnesium	1,330	Sulfate	2,770
Calcium	420	Bicarbonate	146
Potassium	400	Bromide	68

Table 2 – Typical seawater constituents

During the desalination process, the water rejected by the RO membrane is typically concentrated to a salinity of 60,000 to 70,000 mg/L, although it can be as high as 90,000 in some "high recovery" applications. The concentrate is overwhelmingly characterized by the seawater chemistry rather than the chemicals added during the pretreatment or desalination process. In fact, the level of chemicals added during the desalination process usually totals less than 15 mg/L.

The impact of concentrate salinity on a receiving waterbody is highly site specific, but some species of marine flora and fauna can be impacted by an increase of less than 2% of the ambient seawater salinity[1]. Determination of a receiving water's response to a concentrate discharge can be determined by evaluating and monitoring its local biological community. The organisms evaluated are usually selected based on their ecological relevance, e.g. Posidonia oceanica, and sensitivity to changes in salinity, e.g. echinoderms (Fernandez-Torquemada).

The US EPA has used a threshold criterion of 10% above ambient salinity as an acceptable salinity increase in a concentrate discharge, and the Florida Department of Environmental Protection has considered an increase of up to 10% of chlorides as acceptable; essentially the same overall concentration increase as the US EPA value. These criteria have been used as good engineering practice..

During planning, design and permitting phases, the normal practice is that the project proponent/developer undertakes numerous siting studies, collects baseline environmental data, and conducts computer modelling of alternative discharge arrangements. In most existing SWRO installations, one or more mitigation measures are employed to reduce salinity-related impacts. These include selection of a site with the lowest environmental sensitivity, outfall design to maximize mixing and/or dilution, commingling with cooling water or wastewater discharge, and segregation of toxic additives.

1.2.3.2 Temperature

Unlike thermal desalination processes, the temperature of RO concentrate is usually within 1°C of the ambient seawater temperature. Historically temperature changes of less than 2°C are not considered to have an environmental impact. Australia and New Zealand Environment and Conservation Council's (ANZECC) guidance require temperature increases to be within the 80th percentile of the natural background variation over the same period. This should be readily achieved by RO discharges which are not blended with other, warmer, outfalls.

SWRO discharges in which the concentrate is blended with power plant or industrial cooling water, or wastewater treatment plant effluent can be up to 8°C above ambient seawater values. In such cases it is recommended practice to perform testing to determine the upper temperature limit based on three known temperatures:

- Temperature for maximum species growth
- Maximum temperature for long term exposure
- Incipient lethal temperature

The testing normally involves multiple species and is recommended by USEPA and ANZECC but is not appropriate for unblended discharges of constant temperature rise of less than 2°C.

1.2.3.3 Dissolved Oxygen (DO)

Oxygen becomes less soluble in seawater with increasing temperature and salinity levels. The desalination process may therefore affect dissolved oxygen levels in seawater. However, the main

---

[1] Salinity increases are expressed as percentages rather than ppt, psu or mg/L values because, in general, sensitivity is proportional to changes relative to the background levels rather than an absolute, incremental rise.

influence on oxygen levels will be due to dosing of oxygen scavengers such as sodium meta-bisulfite (SMBS) to inhibit corrosion and/or remove residual chlorine from RO feedwater to prevent membrane damage by oxidation. Low oxygen levels may harm marine life if mitigation measures such as aeration or sufficient dilution prior to oceanic discharge are not implemented.

It has been considered that dissolved oxygen may be reduced in zones below a density or thermally induced stratification. Theoretically, this could result from the normal action of aerobic biota in a water volume that was not mixing or interacting with the full water body because of the stratification. No evidence of this was found in any literature reviewed, even when salinity strata were identified in areas up to 20m from the discharge.

1.2.3.4 Density

Desalination plant concentrate will have a higher density than seawater due to its higher salt concentrations. Without adequate mitigation measures, the discharge plume could easily sink to the sea floor and have a detrimental affect on benthic communities as a result of high salt concentrations and residual chemicals.

Transport direction and the impact range of a discharge plume is controlled by site-specific oceanographic conditions, such as currents, tides, water depth, bottom and shoreline topography. To predict plume spread and environmental dispersal of chemicals at a specific site, the environmental and operational conditions should be investigated by hydrodynamic computer models (e.g. Doneker and Jirka, 2001).

Theoretical studies indicate that brine tends to situate itself at the bottom once it is no longer affected by the effects of the of the discharge jets/diffusers. But data collected in one study (Talevara, Ruiz; 2001) shows that based on the dynamics of the waterbody, concentrate discharged in the thermocline is diluted in the whole column of water and can be reduced from 75 psu to 38.5 psu in only 20m.

Detailed studies of discharges in coral seas of the Caribbean (Hammond et al, 1998) showed no impact on seagrass meadows or the main fish species that grazed upon them. A weak but statistically significant correlation did exist between plume density and the coverage of one particular seagrass species. The study concluded that the brine discharges "had no detectable effect on the chlorophyll concentration (biomass) and numerical abundance of the benthic microalgal community in this area." The most abundant fish species and two species of macro-epiflora were repeatedly found within 2m of the discharge – "...no obvious stress or mortality was observed in the relatively long-lived and sedentary species such as soft coral… or in the hard corals". The study authors further state "the results of this study can be applied to other regions and be generally interpreted as indicative of elevated salinity impacts on benthic microalgal communities." Although most of the projects in this study included granular media filters for pretreatment, the study did not identify the use of coagulants or polymers or their presence in the discharge.

1.2.3.5 Heavy metals

Generally, any concentration of heavy metals that exceeds the natural background levels can be considered to be environmental pollution, even if biological consequences cannot be proven (Höpner; 1999).

Most of the heavy metals present in SWRO concentrate are those that occur naturally in the sea in trace concentrations. However, some metals may pass into the reject streams as a result of corrosion inside the desalination plants. Non-metallic and stainless steel materials predominate in SWRO desalination plants and may contribute trace amounts of iron, nickel, chromium and molybdenum from pretreatment chemicals or corrosion products. Intake screens may be of copper alloy construction, operate at ambient temperature, and could result in very minor increases in copper concentrations.

Heavy metals will adsorb to suspended matter and can sink to the bottom causing an accumulation in the sediment. Since the problem is one of load, rather than concentration, the consequences cannot be mitigated by simple dilution of the outfall. The load can be distributed over a larger area, but the question is difficult to answer whether a small, more impacted area is more acceptable than a larger, less impacted area.

Instances where heavy metal discharges have been associated with desalination plants are invariably related to dual purpose power/water facilities that incorporate thermal desalting processes (e.g. Abdel Jawad et al, 1999; Altayaran et al, 1992). Thermal desalination plants (distillers) operate at much higher temperatures (i.e., to 112°C) where corrosion is more likely to occur. To minimize corrosion, these distillers are fabricated from copper, nickel and zinc alloys as well as titanium and special grades of stainless steel. The fact that distillers operate at higher, more corrosive temperatures – with feedwater flows six to ten times greater a SWRO plant – and the water is in intimate contact with the metallic surfaces for a much longer period of time compared to a membrane plant means that distiller concentrate is likely to have significantly higher concentrations of heavy metals.

Even though several distillation plants have monitored heavy metals in their discharges, none of these have attempted to quantify whether or not marine biota was impacted (e.g. Arain et al, 2002).

Corrosion must also be mitigated within desalination plants, particularly SWRO, for non-environmental reasons. Heavy metals and other corrosion by-products can precipitate on membrane surfaces and be difficult to remove. Material selection and operation of SWRO facilities has been refined in the past 20 years to ensure membrane longevity meets economic targets.

1.2.4 Subsurface intakes and beachwells

Subsurface intakes use horizontal or vertical beach wells, infiltration galleries, or seabed filtration systems. In each of these designs, the open seawater is separated from the point of intake by a geologic unit. A subsurface intake can be used where geologic conditions beneath a surface water are of sufficient thickness and depth to support water extraction. In addition to providing some natural filtration, this arrangement has the advantage of separating most of the marine organisms from the water intake. In some cases, subsurface intakes may be evaluated and regulated as groundwater sources.

The use of subsurface intakes offers a distinct environmental advantage because the ecological impact associated with impingement and entrainment of marine life is virtually eliminated. However, subsurface designs should consider their potential negative impact on nearby fresh groundwater aquifers.

Subsurface intakes are often only technically or economically practical for SWRO production capacities of less than 50 ML/d (Pankratz; 2005), and one evaluation found the advantages of beachwell intakes diminish as plant capacities exceed 20 ML/d, and may actually impact a larger land area because of the number of wells/wellheads required (Voutchkov; 2004).

1.2.5 Pretreatment and resulting chemical constituents in reject streams

Some type of chemical pretreatment of the intake water is a necessity in most desalination plants to improve plant performance and to increase intervals between shutdowns for cleaning or replacement of system components.

In RO plants, the most vulnerable point of the system is the membrane, which is permeable for water but not for most dissolved and suspended materials that may accumulate on the membrane and cause fouling or scale deposits. Conventional pretreatment steps include scale and biofouling control.

The residuals and by-products of pretreatment and cleaning chemicals are often discharged along with the concentrate to the marine environment. Composition of the concentrate depends primarily on the quality of the intake seawater at the location of the plant, the desalination process utilized and the pretreatment and cleaning scheme.

1.2.5.1 Metal salts and Coagulants

Most existing SWRO plants use either ferric chloride ($FeCl_3$) or ferric sulfate ($FeSO_4$) as a primary coagulant or flocculant in the pretreatment system. When added to water, a hydrolysis reaction produces an insoluble ferric hydroxide precipitate that binds non-reactive molecules and colloidal solids into larger aggregations that can then be more easily settled or filtered from the water. The resulting ferric hydroxide floc is retained in the filter until the filter is flushed during a backwash process.

Of the 17 plants surveyed for this report, all but two currently discharge the filter backwash water along with the RO concentrate. Prior to blending filter backwash water with the RO concentrate, the two facilities first employ a sedimentation step where the filter backwash water is clarified and the settled sludge is thickened, dewatered, and disposed of in a landfill. In all other instances, it appears that the filter backwash water is immediately blended with the concentrate as each filter is backwashed.

Iron has a very low toxic potential. In fact, iron is a limiting nutrient in some seawaters and the additional amounts contained in some SWRO concentrate as a result of pretreatment has been considered beneficial when available for uptake by phytoplankton and other primary producers (Graham; 2004). Similarly ANZECC (2000) recognizes that no adequate toxicity data exists for marine species and suggests the nutritional iron deficiency needs to be considered (page 8.3-123).

However, the discharge of excess concentrations of iron may cause discolouration at the outfall and in surrounding sands. It may also result in an increase in turbidity that could reduce light penetration and/or could cover sessile benthic organisms (see Appendix for further discussion).

The regulatory position regarding iron discharges is not consistent. ANZECC provides guidance limited by an acknowledged lack of applicable data. It is not clear if the US EPA has data to support their de facto position that iron discharges are restricted by the anti-degradation regulations of the Clean Water Act according to the classification of each waterbody. These regulations are then subject to local state regulations. In Florida, for example, each water body must first adhere to a narrative requirement that a waterbody is not degraded by the discharge, and it must also adhere to a numerical limit for iron – as well as 52 other constituents – based on the classification of each specific waterbody. However, the influential California Coastal Commission has no numerical limit on iron discharges in its Ocean Plan. Rather, it relies on narrative language requiring that “no water quality degradation” be the overriding criteria and that it be applied on a case-by-case basis.

1.2.6 Biofilm control

Chlorination is the primary method of biofilm control, particularly for large-scale SWRO plants. Chlorine is frequently injected either as chlorine gas or added as hypochlorite (i.e. sodium hypochlorite, NaOCl) at the plant’s seawater intake. Typical chlorine doses range between 0.5-2 mg/L in desalination plants, which is comparable to the treatment often applied for power plant cooling waters. Most oxidative capacity is lost during the desalination process due to self-decomposition and the oxidant demand of the intake seawater.

As most RO plants operate on polyamide membranes, which are sensitive to oxidizing chemicals, residual oxidative capacity is typically neutralized (usually with sodium bisulfite, SBS) before the feedwater enters the RO units to avoid membrane damage. Consequently, most RO discharges are characterized by very low to non-detectable levels of residual oxidants. However, it is possible that non-oxidizing biocides are used and discharged along with the brine.

A pilot study for the Tampa Bay RO plant in Florida showed that total residual chlorine levels are below the detection limit of 0.05 mg/L at the point of discharge to the Bay (Florida Department of

Environmental Protection and S&W Water, 1999). In this facility, the feedwater is chlorinated/dechlorinated and the brine diluted with sufficient power plant cooling water prior to discharge. Therefore, it is expected that the discharge will also meet state Water Quality Standards of 0.01 mg/L. The facility will be equipped with instrumentation to monitor the removal of chlorine.

Many toxicological studies have shown that chlorine is highly toxic to many marine species, even at low concentrations. Reflecting the high toxicity of chlorine, a low short-term allowable maximum concentration (CMC) of 13 μg/L and a long-term exposure (CCC) concentration of 7.5 μg/L are recommended by the US EPA (1998) for seawater. In California, State regional water quality control boards do not permit chlorine or other biocides to be discharged directly into the ocean, so these chemicals would have to be neutralized before discharge. In Florida, State Water Quality Standards of 0.01 mg/L apply.

In addition to toxicity, a second drawback of chlorination is the formation of halogenated organics, which are problematic from an environmental point of view (see next section). There is also a third drawback; continuous chlorination has proven ineffective at most large RO facilities and have been replaced by only intermittent shock chlorination.

Chlorination is primarily practiced as an intermittent “shock” dose treatment with a corresponding dose of dechlorinant (such as SBS). SBS and similar dechlorination treatments rapidly react with free chlorine but have a much slower reaction with naturally occurring dissolved oxygen. The reaction chemistry involved also means that these chemicals can remove less oxygen from the seawater than the quantity of chlorine they are capable of removing.

The potential impact of dissolved oxygen does not appear to have been explicitly studied in the outfall of desalination plants. Studies of plume mixing based on salinity measurement provide some indication that lower DO levels (e.g. from excess dechlorination) may mix with the receiving body and return to background levels within 20m of the outfall (Talavera et al, 2001).

1.2.6.1 Halogenated organic compounds

The use of chlorine as a disinfectant can lead to reactions with natural organic seawater constituents. Trihalomethanes (THMs), such as bromoform are among the compounds that can be created from naturally present precursors.

As only a small fraction of total added chlorine will be recovered as halogenated by-products – and the by-product diversity is high – the environmental level of each substance will be comparatively low (Abarnou and Miossec, 1992). If one takes dilution and evaporation of these highly volatile substances into account, environmental levels will unlikely have acute toxic effects with regard to relatively high LC50 values of test organisms. A more detailed discussion on this topic is included as an Appendix.

1.2.6.2 Shock treatment with biocides

Shock treatment almost universally uses chlorine (from a variety of sources) especially for the largest desalination plants. Other biocides are used for small-scale plants or have been considered for large scale facilities. A further general discussion of this topic is included as an Appendix.

1.2.6.3 Methods of chlorine neutralization

Several chemicals can be used for neutralization, of which sodium bisulfite is most commonly used in RO plants. Alternatives such as sulfur dioxide and hydrogen peroxide have been suggested to treat thermal plant reject streams (Shams El Din and Mohammed, 1998).

1.2.6.3.1 Sodium bisulfite

Sodium bisulfite (SBS, $NaHSO_3$) is a strong reducing agent. It reduces hypobromous acid (HOBr) to hydrobromic acid (HBr) and is in turn oxidized to sulfate. Although the reaction products are non-hazardous, overdosing should be avoided as SBS may cause oxygen depletion which is also toxic to marine life.

1.2.6.3.2 Sulfur dioxide

Sulfur dioxide (SO_2) reacts with hypobromite to hydrobromic acid (HBr) and sulfuric acid (H_2SO_4). Overdosing should be avoided as both products may cause a pH reduction, but low amounts are probably of no concern because seawater has a good buffering capacity and low amounts of acid will be immediately neutralized.

1.2.6.3.3 Hydrogen peroxide

Hydrogen peroxide (H_2O_2) forms water, oxygen and bromide. Overdosing should be avoided as H_2O_2 is also a biocide, although weaker than chlorine.

1.2.6.4 Antiscalants

Antiscalants may be added to feedwater in RO plants to prevent scale formation on the membranes. The term usually refers to polymeric substances with different chemical structures. In general, four groups of polymers can be distinguished: polyphosphates, phosphonates, polymaleic acids and polyacrylic acids. In addition, mineral acids such as sulfuric acid are frequently used to inhibit scaling. Polyphosphates and mineral acids are in limited use in RO plants, and are increasingly substituted by phosphonates, polymaleic acids and polyacrylic acids, which are generically used as 'polymer' antiscalants.

Problems of eutrophication near the outlets of plants could clearly be attributed to the use of polyphosphates (Shams El Din et al, 1994; Abdel-Jawad and Al-Tabtabaei, 1999). Polymer antiscalants can be assumed to have some similar properties to natural seawater constituents such as humic matter. Both have high molecular weight, multiple carboxylic groups, metal ion binding capacity and a high stability. Toxicity of antiscalants is relatively low (FMC, 1994; BASF, 1994), but biodegradation tests reveal that biodegradation of polymaleic and polyacrylic acid is rather slow (18% and 52% in 35 days, respectively, Wilcock and Finan, 1994; FMC, 1994; BetzDearborn, 2000). In seawater, the complexing properties of antiscalants, which are important for inhibiting scale formation, could interfere with natural element cycles. Metal complexes are generally less available for marine organisms than dissolved metal ions, so that uptake of essential nutrients (e.g. iron) or toxic heavy metals (e.g. copper) could be reduced.

1.2.7 Alternative pretreatment systems

1.2.7.1 Membrane pretreatment

As RO membranes may not be exposed to chlorine or other oxidizing chemicals, non-chemical pretreatment methods such as pre-filtration with low pressure membranes, beach-well intakes or infiltration galleries have proven effective and are believed to be more widely applied in the future instead of chemical or "conventional" pretreatment (Ebrahim et al., 2001).

Integrated, or dual membrane systems combine lower pressure microfiltration (MF) or ultrafiltration (UF) membranes with reverse osmosis units. MF removes suspended material including bacteria and algae, whereas UF also filters viruses from the RO feedwater (Ebrahim et al., 2001), but both are not capable to treat dissolved organic and inorganic substances (Redondo, 2001).

MF/UF materials should be chlorine-resistant to withstand periodic disinfection (Redondo and Lomax, 1997), as the biofouling problem is likely to be transferred from the RO to the prefiltration membrane. Although frequent backwashing (e.g. every 15 minutes) with permeate water counteracts accumulation of suspended solids and bacteria, chemically enhanced backwashing may become necessary intermittently to restore the membrane's performance. For this purpose, acid treatment (pH 2-2.5) and hypochlorite dosing can be carried out several times a day.

As an alternative to liquid backwashing, high-pressure air can be used to remove foulant accumulations in some MF/UF systems. Air-assisted cleaning has the advantage of not requiring disinfection chemicals and this method was also classified as the most singularly effective means to control biofouling in the Orange County Water District, Water Factory 21 membrane pretreatment evaluation from 1993-95 (Durham and Walton, 1999).

Furthermore, no coagulation chemicals may be necessary (Ebrahim et al, 2001), although ferric chloride can be added to the UF/MF feedwater to improve removal of dissolved and suspended materials (Redondo, 2001; van Hoof et al, 2001). If severe fouling occurs, MF/UF membranes may be cleaned with chemicals similar to those used for cleaning RO membranes.

MF/UF systems have not yet been widely applied as pretreatment for large-scale SWRO plants. The largest plants to utilize this technique are approximately 10 ML/d. This is expected to change.

1.2.8 Cleaning chemicals (RO plants)

RO cleaning intervals typically range from three to six months depending on the quality of the intake water and the efficiency of the pretreatment scheme. The cleaning procedure depends on the type of membrane fouling.

Effluent parameter	RO Concentrate Property
Salinity	typically 60 – 70 psu
Temperature	ambient seawater temperature + 1°C
Plume density	negatively buoyant
Oxygen	May be intermittently decreased as a result of chlorine neutralization (using sodium bisulfite)
Chlorine	neutralized
Coagulants (Fe^{3+}, Al^{3+})	1 – 30 mg/L
Coagulant/filter aids	0.2 – 4 mg/L
Antiscalants	1 – 2 mg/L
Acid (H_2SO_4)	pH 6 – 7
Heavy metals	Copper, iron, chromium, nickel, molybdenum
Cleaning chemicals	alkaline (pH 11-12) or acidic (pH 2-3) solutions containing detergents, complexing agents, oxidants and biocides

Table 3 - Typical effluent properties of RO plants

Alkaline solutions (pH 11-12) are used to remove silt deposits and biofilms from membranes, while acidic solutions (pH 2-3) are applied to dissolve metal oxides or scales. Cleaning solutions often contain additional chemicals to improve membrane cleaning. Common additives in alkaline solutions are detergents (e.g. dodecylsulfate, dodecylbenzene sulfonate) or oxidants (e.g. sodium perborate, sodium hypochlorite). Both are considered harmful to aquatic life, either by disturbing the intracellular membrane system of organisms in the case of detergents (Höpner, 1999), or by being capable of oxidizing organic tissue. Furthermore, alkaline and acidic cleaning solutions often contain complexing agents such as EDTA (ethylenediamine tetraacetic acid) to improve the removal of biofilms, scale and metal deposits from membranes. EDTA is poorly degradable and therefore rather persistent in the marine environment, where it could interact with dissolved metal ions like iron, copper, zinc, or calcium by complex formation.

After cleaning or prior to storage, membranes are typically disinfected. For this purpose, either oxidizing biocides such as chlorine and hydrogen peroxide or, more commonly, non-oxidizing biocides like formaldehyde, glutaraldehyde or isothiazole can be applied to the membrane. All biocides are highly effective substances and hazardous to aquatic life if discharged to the marine environment.

1.3 Other potential environmental impacts of desalination plants

Like other coastal development projects, a desalination plant will affect and change the environmental properties of the site where the plant is located and adjacent areas. This may encompass effects on landscape properties, air quality, marine and terrestrial site properties and biological resources.

Impacts may occur temporary during construction works for buildings, intakes and outfalls or supporting infrastructure (e.g. connecting roads, power lines, etc.), intermittently during plant operation or maintenance operations, or can be of a long-term or permanent nature.

The project may further have cumulative effects with other proposed and existing developments in the region, ‘transboundary’ effects which go beyond the immediate vicinity of the plant (e.g. due to the dispersal of pollutants or impacts on migratory species), or secondary effects that can occur as a result of a primary interaction between the project and the project environment.

These issues should be of the same order of magnitude as other water or wastewater facilities.

1.3.1 Impacts on landscape and natural scenery

A desalination facility might affect the characteristic landscape properties and natural scenery of the coastal site where the plant is located due to noise generation, obstruction or alteration of scenic views, production of glare, or any effect that substantially alters the existing character of the area.

This should be no different from other water or wastewater facilities, and can be mitigated by careful design, and the use of noise enclosures.

1.3.2 Impacts on air quality and climate

Desalination of seawater requires energy and thus has an impact on air quality and climate if fossil fuels are used to produce this energy. Air quality may be affected by emission of acid rain gases (NOx, SOx) and particulate matter in the vicinity of power plants as well as greenhouse gases (i.e. carbon dioxide) that contribute to global warming. These effects can be mitigated by the use of renewable generation techniques (such as those proposed by Perth and Sydney), they can also be managed by adopting carbon trading techniques.

A minor factor may also be the emission of exhaust gases from construction and transport vehicles that may impair air quality locally.

A thorough comparison of the net energy difference between desalination (which is usually close to the point of water demand) and that of traditional water sources (which are usually remote) must be carried out.

During the thermal desalination process, dissolved gases are stripped from the feedwater and vented. However, most dissolved gasses pass directly through SWRO membranes into the permeate stream. In some cases – most commonly when the seawater feed originates from an anaerobic seawater aquifer – it may be necessary to strip hydrogen sulphide from the pemeate. When this is practiced, the gas is normally discharged into the concentrate stream where it is reabsorbed.

1.3.3 Impacts on terrestrial and marine site properties

A desalination project may affect soil and sediment properties as well as ground- and surface water properties of the coastal site where the plant is located. In specific, a desalination project may have effects on:

- topography and geomorphology (e.g. through erosion, land sliding),
- soil and sediment properties (e.g. through disturbance, re-suspension, compaction, permanent surface sealing),
- ground- and surface water quality (e.g. through saltwater intrusion into aquifers, seepage of contaminants, chemical spills, waste water, site run-off and contamination of rainwater);,
- ground- and surface hydrology (e.g. changes to flow directions, currents, water density layers, mixing).

Should be no different from other water or wastewater facilities, however traditional water treatment facilities are less likely to be on the coastline.

1.3.4 Impacts on terrestrial and marine biological resources

A desalination project may affect the fauna and flora in the vicinity of the site during construction, operation, maintenance and decommissioning. Impacts may be of a direct or indirect nature, include secondary effects via the food chain, and may harm single organisms, species or biodiversity and thus the intactness of coastal ecosystems. Impacts on fauna and flora may be particularly due to:

- surface sealing, leading to loss of habitat for plants and sessile animals,
- visual and acoustic disturbance, leading to behavioural changes or loss of habitat, e.g. feeding, resting, or breeding grounds for native animals, or disturbance of pathways and resting habitats for migratory animals,
- pollution of air, soil and water through exhaust gases, waste waters or spills, leading to uptake and bioaccumulation of pollutants, acute toxic or long-term chronic effects;
- disturbance of soils and sediments, changes to hydrology etc., affecting the distribution and settlement patterns of plants and animals, or causing the death of animals due to mechanical impacts or impingement and entrainment of animals.

Should be no different from other water or wastewater facilities, however traditional water treatment facilities are less likely to be on the coastline.

1.3.5 Socio-economic implications

The use of desalination to augment or diversify a community's or region's water supply may have demographic, cultural, socio-economic and human health implications. A brief overview is given in the following:

1.3.5.1 Population and community structure

The availability of desalinated water may affect demographic development and community structure, for example by stimulating relocations of people from disadvantaged areas (in terms of water availability, environmental quality, economic prospects etc.) to more favourable areas, with secondary effects on settlement and community structure.

1.3.5.2 Economic growth and development activities

The availability of desalinated water may affect the economic activities and development prospects of a region, and thus the importance of different activities for the local population as an employment opportunity and economic base. Different market sectors such as tourism, agriculture, aquaculture and fisheries, or producing industries may benefit differently or may be negatively affected by a desalination project.

1.3.5.3 Environmental and public health

Environmental health encompasses the potential health risks due to the exposure of a population to environmental hazards, as well as socio-economic, and psycho-social changes, related directly or indirectly to the desalination project. Environmental health risks should be balanced against the benefits provided to the population by the desalination project. The socio-economic and psycho-social impacts of water shortage if desalination or other water sources are not implemented must also be considered.

1.3.5.4 Site uses and human activities

A desalination plant may conflict with other recreational, commercial or nature conserving activities in the project site. For example, the plant may impair environmental quality and natural scenery or restrict public access to beaches, so that the recreational value of the site or the value of adjacent residential properties is reduced. Maritime structures like intakes or outfalls could interfere with navigation, access to harbours or other activities like commercial fishing or aquaculture. Alterations to the environmental quality can have potential impacts on the ecological value of a project site as a habitat for terrestrial and marine species. By changing the ecological value of a site through development, it may loose its present status or may no longer be eligible for becoming a protected area in the future. Sites utilized or studied may prove to have some cultural or historical significance.

1.3.6 Monitoring

Monitoring requirements are also ad hoc and are not uniform. In the developing world monitoring is driven by process control and operational considerations. In the developed world (and where Public, Private or Development Financing is involved) monitoring is required at the discretion of the Regulator. To date the only quantified base line monitoring programs have been performed for projects in the USA, most of which are still in development, and in Israel. Other monitoring reports appear lack scientific quantification.

The Perth and Sydney projects have conducted and continue to develop baseline studies similar to Israeli and USA projects. The level of continuous, online monitoring of key environmental parameters planned for the Perth desalination plant does not exist on any other SWRO project reviewed for this study.

1.3.7 Regulation

This review found that there appear to be no environmental regulations in place that apply specifically to desalination plants in any major jurisdictions. Ad hoc application of the most appropriate laws are applied and enforced. In some cases this results in potential over regulation but there may be a trend to improve and simplify this. Currently the US EPA has no specific category for RO concentrate. By default, it has been categorized as an industrial waste – resulting in special handling requirements, onerous permitting requirements, and restrictions on disposal techniques. This has now been recognized and accepted as inappropriate with revisions to classifications considered necessary by some. This could result in a new classification for concentrate that will improve the logistics and economics of concentrate disposal.

There are no consistent, process-specific regulations for SWRO concentrate discharges. Because of the increasing number and size of plants being considered/installed, this appears to be changing.

2 Environmental Literature Review; Search Results

This list reflects those papers that have the most relevance to this study.

Abarnou, A. and Miossec, L. (1992); Chlorinated waters discharged to the marine environment chemistry and environmental impact. An overview; The Science of the Total Environment, 126: 173-197.

Abdel-Jawad, M. and Al-Tabtabaei, M. (1999); Impact of Current Power Generation and Water Desalination Activities on Kuwaiti Marine Environment,; IDA World Congress, San Diego 1999, 3: 231-240.

Ahmed, M., Shayya, W., Hoey, D., Mahendran, A., Morris, R. and Al-Handaly, J. (2000); Use of evaporation ponds for brine disposal in desalination plants; Desalination, 130: 155-168.

Ali, M. and Riley, J. (1986); The distribution of halomethanes in the coastal waters of Kuwait; Marine Pollution Bulletin, 17: 409-414.

Altayaran, A. and Madany, I. (1992); Impact of a Desalination Plant on the Physical and Chemical Properties of Seawater, Bahrain; Water Research, 435-441.

Arain, R.A., Shahzad, K., Hamoud A.A. (2002); Desalination plant effluents analysis; IDA World Congress, Bahrain 2002

Blake Norman J., et al (1996); Effects of Disposal of Seawater Desalination Discharges on Near Shore Benthic Communities; Phase 1 Report; Southwest Florida Water Management District, 2379 Broad Street, Brooksville, FL 34609-6899

Bou-Hamad, S., Abdel-Jawad, M., Ebrahim, S., Al-Mansour, M. and Al-Hijji, A. (1997); Performance evaluation of three different pretreatment systems for seawater reverse osmosis technique; Desalination, 110: 85-92.

Burashid, K. (1992); Bahrain's Seawater Intakes and Pretreatment Systems; Desalination and Water Reuse, 22: 44-49.

Chang, C.-Y., Hsieh, Y.-H., Hsu, S.-S., Hu, P.-Y. and Wang, K.-H. (2000); The formation of disinfection by-products in water treated with chlorine dioxide; Journal of Hazardous Materials, B79: 89-102.

Cohen, T. (1997); Environmental issues of seawater desalination in California: An overview of the 1990s; Conference on California and the World Ocean

Del Bene, J., Jirka, G. and Largier, J. (1994); Ocean brine disposal; Desalination, 97: 365-372.

Doneker, R. L. and Jirka, G. H. (2001); CORMIX-GI systems for mixing zone analysis of brine wastewater disposal; Desalination, 139: 263-274.

Edlinger, R. and Gomila, S. (1996); Ibiza seawater RO - special design features and operating data; Desalination, 105: 125-134.

Einav, R. (2003); Checking today's brine discharges can help plan tomorrow's growth; Desalination and Water Reuse Quarterly vol 13/1;

Einav, R., et al (2002); The footprint of desalination processes on the environment; Desalination 152; 141-154;

Einav, R., Lokeic, F. (2003); Environmental aspects of a desalination plant in Ashkelon; Desalination 156; 79-85.

El-Yakubu Jibril, B., Ibrahim A.A. (2001); Chemical conversions of salt concentrates from desalination plants; Desalination 139 (2001)

Elabar, M., Elmabrouk, F. (2005); Environmental impact assessment for desalination plants in Libya. Case study: Benghazi North and Tobrouk desalination plants; Desalination 185; 31-44.

Equator Principles. (2003); An industry approach for financial institutions in determining, assessing, and managing environmental and social risk in project financing. 4 June 2003; Equator Principles

Farinas, M., et al (2005); Javea Desalination Plant: Environmental Study on the Brine Discharge. International Desalination Association World Congress; IDA World Congress, Singapore 2005.

Fernandez-Torquemada, Y. et al (2005); Preliminary results of the monitoring of the brine discharge produced by the SWRO desalination plant of Alicante (SE Spain); Desalination 182; 395-402

Florida Department of Environmental Protection and S&W Water (1999); Fact Sheet for application for a permit to discharge reverse osmosis reject water to waters of the state. Permit Number FL0186813, Application Date 1999; Florida Department of Environmental Protection, 2600 Blair Stone Road, Tallahassee, Florida 32399-2400; S&W Water, LLC, 5445 Mariner Street, Tampa, Florida 33609.

Graham, Jeffrey B., PhD (2004); Evaluation of a Report on Receiving Water Chemistry and Quality issues Related to the Operation of a Reverse Osmosis Desalination Facility at the Huntington Beach Power Generating Station;

Grebenyuk, V., Mazo, A., and Linkov, V. (1996); New ecological problems of desalting and water re-use. ; Desalination 105' 175-183.

Hall, L., Burton, D., Graves, W. and Margrey, F. (1981); Effect of dechlorination on early life stages of striped bass (Morone saxatilis); Environmental Science and Technology, 15: 573-578.

Hammond Mark A., et al (1998); Effects of Disposal of Seawater Desalination Discharges on Near Shore Benthic Communities; Phase 1 Report; Southwest Florida Water Management District, 2379 Broad Street, Brooksville, FL 34609-6899

Höpner, T and Windeelberg, J. (1996); Elements of environmental impact studies on coastal desalination plants. ; Desalination, 108: 11-18.

Höpner, T. (1999); A procedure for environmental impact assessment (EIA) for desalination plants; Desalination, 124: 1-12.

Hose, J.E., King, T.D. and Stephens, J.S., Jr (1984); Effects of dechlorinated seawater on fish behavior. ; Marine Environmental Research, 11: 67-76.

HSDB (2001); Hazardous Substances Databank (HSDB), a database of the National Library of Medicine's TOXNET system, http://toxnet.nlm.nih.gov. Record quoted in the text: Sanders J.G.; Environ Sci Technol 18 (5): 383-5 (1984)

Iso, S., Suizu, S., and Maejima, A; (1995); The lethal effect of hypertonic solution and avoidance of marine organisms in relation to the discharged brine from the desalination plant; International Desalination Association World Congress, Abu Dhabi 1995.

Jenkins, S.A. and Wasyl, J. (2004); Hydrodynamic modeling of source water make-up and concentrated seawater dilution for the ocean desalination project at AES Huntington Beach Power Station. A report prepared for Poseidon Resources.; Poseidon Resources

Jenner, H., Taylor, C., van Donk, M. and Khalanski, M. (1997); Chlorination by-products in chlorinated cooling water in some European coastal power stations; Marine Environmental Research, 43: 279-293.

Khordagui, H. (1992); Conceptual approach to selection of a control measure for residual chlorine discharge in Kuwait Bay; Environmental Management 16, 3: 309-316.

Latorre, M. (2005); Environmental impact of brine disposal on Posidonia seagrasses; Desalination 182; 517-524.

Lattemann, S. and Höpner, T. (2003); Seawater Desalination - Impacts of Brine and Chemical Discharges on the Marine Environment; Desalination Publications, L'Aquila, Italy, 142p.

Leynen, M., Duvivier, L., Girboux, P. and Ollevier, F. (1998); Toxicity of ozone to fish larvae and Daphnia magna; Ecotoxicology and Environmental Safety, 41: 176-179.

Loizides, L. (2004); The Cost of Environmental and Social Sustainability of Desalination; MEDRC International Conference on Desalination Costing, Cyprus 2004.

Mahi, P (2001); Developing environmentally acceptable desalination plants. Desalination 138; 167-172;

Maugin, G. and Corsin, P. (2005); Concentrate and other waste disposals from SWRO plants: characterization and reduction of their environmental impact. ; Desalination 182; 353-364

Meerganze von Medeazza (2005); "Direct" and socially-induced environmental impacts of desalination; Desalination, 185; 57-70

Mickley M. (1995); Environmental Considerations for the Disposal of Desalination Concentrates; Desalination and Water Reuse, 54: 56-61.

Mohamed, K., Odeh, M., and Areiqat, A. (2005); Environmental impact assessment on a plant located inside a lagoon; Desalination 185; 45-56.

Morton, A., Callister, I. and Wade, N. (1996); Environmental impacts of seawater distillation and reverse osmosis processes; Desalination, 108: 1-10.

Murrer, J. and Rosberg, R. (1998); Desalting of seawater using UF and RO - results of a pilot study; Desalination, 118: 1-4.

Oldfield, J. and Todd, B. (1996); Environmental aspects of corrosion in MSF and RO desalination plants; Desalination, 108: 27-36.

Pankratz, T.M. (2004); Seawater Intake & Outfall Cost Considerations; Middle East Desalination Research Centre Intl. Conference on Desalination Costing,Cyprus

Perrot, J. and Baron, J. (1995); The disinfection of municipal wastewater by ultraviolet light: A French case study; Water Science and Technology, 32: 167-174.

Purnama, A., Al-Barwani, H., and Smith, R. (2005); Calculating the environmental cost of seawater desalination in the Arabian marginal seas; Desalination 185; 79-86

Redondo, J. (2001); Brackish-, sea- and wastewater desalination; Desalination, 138: 29-40.

Redondo, J. and Lomax, I. (1997); Experiences with the pretreatment of raw water with high fouling potential for reverse osmosis plant using FILMTEC membranes; Desalination, 110: 167-182.

Rice, R. and Wilkes, J. (1992); Fundamental aspects of ozone chemistry in recirculating cooling water systems: Data evaluation needs. ; Ozone-Science and Engineering, 14: 329-365.

Saad, M. (1992); Biofouling prevention in RO polymeric membrane systems; Desalination, 88: 85-105.

Sadhwani, J., Veza, J., and Santana, C. (2005); Case studies on environmental impact of seawater desalination; Desalination 185 (2005); 1-8

Scott, G. (1983); Physiological effects of chlorine-produced oxidants, dechlorinated effluents and trihalomethanes on marine invertebrates. In: Water chlorination: environmental impact and health effects, Jolley, R.L., Brungs,W.A., Cotruvo, J.A., Cumming, R.B., Mattice, J.S. and Jacobs, V.A., ; Ann Arbor Science, Ann Arbor, Michigan, pp. 827-841.

Shams El Din, A. and Mohammed, R. (1998); Kinetics of reaction between hydrogen peroxide and hypochlorite; Desalination, 115: 145-153

Shams El Din, A., Aziz, S. and Makkawi, B. (1994); Electricity and water production in the Emirate of Abu Dhabi and its impact on the environment; Desalination, 97: 373-388

Sommariva, C., Hogg, H., Callister, K. (2004); Environmental impact of seawater desalination; relations between improvement in efficiency and environmental impact; Desalination 167 (439-444)

Talavera, J.L.P and Ruiz, J.J.Q. (2001); Identification of the mixing processes in brine discharges carried out in Barranco del Toro Beach, south of Gran Canaria (Canary Islands); Desalination, 139: 277-286.

Tanaka, S., Numata, K., Kuzumoto, H. and Sekino, M. (1994); New disinfection method in RO seawater desalination systems; Desalination, 96: 191-196.

Thompson, John D., Arnold John, Moch Irving Jr. (2005); Three years operation of the 27.6 MIGD (125,530 m3/d), desalination plant, Point Lisas, Trinidad and Tobago; IDA World Congress, Singapore 2005.

Tsiourtis, N. (2001); Seawater desalination projects. The Cyprus Experience.; Desalination 139; 139-147.

Turner, D.R. and Hunter, K.A. (2001); The Biogeochemistry of Iron in Seawater; Wiley and Sons, ISBN: 0-471-49068-7

United Nations Environmental Programme, Mediterranean Action Plan (UNEP/MAP) (2003); Seawater desalination in the Mediterranean, Assessment and Guidelines.; UNEP MAP Technical report series no. 39.

(US) EPA (1998); National recommended water quality criteria; U.S. EPA, National Center for Environmental Publications and Information, 11029 Kenwood Road, Cincinnati, Ohio 45242, USA, http://www.epa.gov/ost.

van Hoof, S., A.Hashim and Kordes, A. (1999); The effect of ultrafiltration as pretreatment to reverse osmosis in wastewater reuse and seawater desalination applications. ; Desalination, 124: 231-242.

van Hoof, S., Minnery, J. and Mack, B. (2001); Dead-end ultrafiltration as alternative pretreatment to reverse osmosis in seawater desalination: a case study; Desalination, 139: 161-168.

Verschueren, K. (1996); Handbook of Environmental Data on Organic Chemicals, 3rd ed., New York; Van Nostrand Reinhold Co., 333p.

Voutchkov, N. (2004); Thorough study is key to large beach-well intakes; Desalination and Water Reuse Quarterly,Vol 14/1 pg 16.

Wilcock, J. and Finan, M. (1994); Ensuring the safety of additives used in desalination plants to produce potable water: The role of independent approval agencies and comprehensive toxicological and ecotoxical product profiles. ; Desalination, 97: 443-451.

Wilf, M. and Klinko, K. (1998); Effective new pretreatment for seawater reverse osmosis systems; Desalination, 117: 323-331.

World Bank (1998); Pollution Prevention and Abatement Handbook. Effective July 1998; World Bank

3 Appendices

Survey results
Mitigation of metal salts and coagulants
Halogenated organic compounds
Shock treatment with biocides
Alternative treatment methods for biofouling control
Glossary

3.1 Survey Results

Plant Location	Caribbean I	South Europe I	South Europe II	South Europe III	South Europe IV	Asia I	South Europe V	South Europe VI
Total capacity, m3/d	119,000	42,750	120,000	65,000	65,000	136,360	54,000	40,000
Date Commissioned	Mar-02	Oct-89	Jul-02	2000	Under Const	Sep-05	May-01	Jun-09
RO product recovery, %	50.0%	50.0%	45.0%	45.0%	53.0%	38.5%	50.0%	50.0%
Feedwater TDS, mg/L	29,000	38,300	39,000	*39,000*	*39,000*	35,000	36,000	40,570
Intake description	Open intake	Open intake	Open sea, 150m offshore, -13m	Horizontal DD well	Open intake	Open sea, offshore	Open sea, offshore	Open sea, offshore
Pretreatment description	Floc/settle, deep bed gravity filter	DM Gravity Filter Precoat Filter	Degrit DM Pressure filter	1-stage horiz pressure filter	2-stage pressure filter	DAF, Gravity filter	DM Gravity Filter	DM Gravity Filter
Pretreatment primary coagulant	$FeCl_3$	$FeCl_3$, DE	$FeCl_3$	$FeCl_3$	$FeCl_3$	$FeCl_3$	$FeSO_4$	$FeCl_3$
Brine Flow	119,000	42,750	146,667	79,444	57,642	217,822	54,000	40,000
Concentration factor	2.00	2.00	1.82	1.82	2.13	1.63	2.00	2.00
Concentrate TDS, mg/L	58,000	76,600	70,909	70,909	82,979	56,911	72,000	81,140
Dilution water source	Industrial plant cooling water	none	Power plant cooling water	none	none	none	none	none
Dilution water volume, m3/d	n/a	0	n/a	0	0	0	0	0
Final discharge TDS, mg/L	n/a	76,600	n/a	70,909	82,979	56,911	72,000	81,140
Discharge distance offshore	at shoreline			4650m	5100m	120m	1500m	250m
Discharge Elevation m	0					≈ -3	-18	-3.5
Discharge Description	Filter b/w settled, sludge to landfill; conc blended, discharge to ship channel		Concentrate & filter b/w blended with PP cooling water	Subsea outfall with multiple diffusers	Subsea outfall with mulitple diffusers	DAF float, filter b/w with conc; pipe laid on seabed, discharge angled for better mixing		10 uni-directional diffusers, pipe buried/laid on seabed
Pretreatment backwash blended with concentrate discharge	Y	Y	Y	Y	y	y	y	y
Pretreatment solids/sludge blended with concentrate	N	Y	Y	Y	Y	Y	Y	Y
Is discharge plume visible	N/R	N/R	N/R	N/R	N/R	Infrequently	No	Infrequently
Energy Consumption, kWh/m3	3.8	6.16	4.08	4.25	4.3	4.34	4.5	5.3
Power/Energy source	Grid	Grid	Grid	Grid	Grid	Grid	Grid	Grid
Receiving body type	Bay	Open sea	Open Sea	Open Sea	Open Sea	Open Sea	Open Sea	Open Sea

Co. loc = co-located with a power plant Grid = Grid power connection Captive = dedicated generation facility

DM Dual Media, PP Power Plant, b/w backwash, SM Single Media, DE Diatomaceous Earth *Estimated values*

3.1 Survey Results

Plant Location	Mid East I	North America I	North America II	North America III	North America IV	Mid East II	Mid East III	Mid East IV
Total capacity, m3/d	170,465	108,820	189,250	189,250	75,700	326,144	56,800	56,800
Date Commissioned	May-04	not comm.	Proposed	Proposed	Proposed	Apr/Dec-05	Apr-89	Mar-94
RO product recovery, %	43.0%	41.8%	50.0%	50.0%	45.0%	40.7%	35.0%	35.0%
Feedwater TDS, mg/L	40,000	32,000	*34,000*	33,520	*34,000*	40,679	43,300	43,300
Intake description	Open sea, offshore	Open intake	Open sea, 550m offshore	tbd	tbd	Open sea, 1000m offshore	Open intake	Open intake
Pretreatment description	DM Gravity Filter	Floc, SM Gravity Filter, Precoat filter	tbd	tbd	tbd	DM Gravity Filter	DM Gravity Filter	DM Gravity Filter
Pretreatment primary coagulant	$FeCl_3$	$FeSO_4$, DE	tbd	tbd	tbd	$FeSO_4$	$FeCl_3$	$FeCl_3$
Brine Flow	225,965	151,515	189,250	189,250	92,522	475,193	105,486	105,486
Concentration factor	1.75	1.72	2.00	2.00	1.82	1.69	1.54	1.54
Concentrate TDS, mg/L	70,175	54,983	68,000	67,040	61,818	68,599	66,615	66,615
Dilution water source	Power plant cooling water	Power plant cooling water	Power plant cooling water	Power plant cooling water	Power plant cooling water	none	Power plant cooling water	Power plant cooling water
Dilution water volume, m3/d	1,409,160	8,553,600	480,700	1,022,000	4,640,000	0		
Final discharge TDS, mg/L	44,170	32,400	43,604	38,757	34,544	68,599	66,615	66,615
Discharge distance offshore	at shoreline	at shoreline	518m	at shoreline	1370m	at shoreline		
Discharge Elevation m	0	0	-10	0		0		
Discharge Description	Blend with PP cooling water, discharge from channel at shoreline	Filter b/w settled, sludge to landfill; concentrate blended with PP cooling water	Pipe buried under seabed, single port discharge	Discharged with power plant cooling water	Pipe laid or anchored to seabed, 10+ omin-directional diffuesers	Filter b/w and concentrate discharge at shoreline adjacent to PP cooling water	Concentrate & filter b/w blended with PP cooling water	Concentrate & filter b/w blended with PP cooling water
Pretreatment backwash blended with concentrate discharge	y	y	y	y	y	y	y	y
Pretreatment solids/sludge blended with concentrate	Y	N	Y	Y	Y	Y	Y	Y
Is discharge plume visible	No	N/R	N/A	N/A	N/A	Infrequently	N/R	N/R
Energy Consumption, kWh/m3	<5.3	2.96				3.9	8.4	
Power/Energy source	Co-loc./Hybrid	Co-located	Co-located	Co-located	Co-located	Captive	Co-located	Co-located
Receiving body type	Open Sea	Bay	Open Sea	Open Sea	Open Sea	Open Sea	Open Sea	Open Sea

are italicized

3.1 Survey Results

Plant Location	Mid East V	Mid East VI	Asia II
Total capacity, m3/d	90,900	127,500	50,000
Date Commissioned	Jan-01	Jun-98	Mar-05
RO product recovery, %	35.0%	35.0%	60.0%
Feedwater TDS, mg/L	45,000	43,764	35,000
Intake description	Open sea	Open sea, offshore	Infiltration gallery
Pretreatment description	DM Gravity Filter	DM Gravity Filter	Sprialwound UF
Pretreatment primary coagulant	$FeCl_3$		n/a
Brine Flow	168,814	236,786	33,333
Concentration factor	1.54	1.54	2.50
Concentrate TDS, mg/L	69,231	67,329	87,500
Dilution water source			Wastewater plant effluent
Dilution water volume, m3/d			33,000
Final discharge TDS, mg/L	69,231	67,329	61,382
Discharge distance offshore			360m
Discharge Elevation m			
Discharge Description	Filter b/w blended with concentrate discharged to sea		Blended with wastewater plant effluent onshore, gravity discharge to sea via multiport diffuser.
Pretreatment backwash blended with concentrate discharge	y	y	y
Pretreatment solids/sludge blended with concentrate	Y	Y	Y
Is discharge plume visible	N/R	N/R	N/R
Energy Consumption, kWh/m3	7.5	7	5.5
Power/Energy source	Co-located	Co-located	Grid
Receiving body type	Open Sea	Open Sea	Open Sea

3.2 Mitigation of metal salts and coagulants impacts

Section 1.2.5.1 of this report discusses the use of use metal salts – specifically ferric coagulants – in SWRO pretreatment systems, and it is noted that most plants discharge pretreatment filter backwash water by immediately mixing it with RO concentrate. The report goes on to describe potential impacts and explain the lack of clear, consistent regulatory controls for the practice.

One of the predominant effects of discharging backwash water containing ferric coagulants is the reddish colour that it may impart on the discharge plume and its surroundings an extreme example of which is shown in Photo 1, below.

In addition to the discolouration at the outfall, the iron could also cause an increase in turbidity that could reduce light penetration and/or could cover sessile benthic organisms

This Eastern Mediterranean SWRO plant reported significant discolouration of concentrate at its shoreline outfall during periods that the filters are being backwashed. In this example, feedwater is continuously dosed with ferric sulphate at a rate of 3 mg/L and filters are sequentially backwashed so that approximately 30% of the total concentrate discharge volume consists of backwash water for 10 to 15 minutes per hour, causing the discolouration pictured.

Rani Amir,
Marine and Coastal Environment Division, Head
Ministry of the Environment, State of Israel. Nov 2005

Photo 1 - "Red brine" event

Since this photo was taken, the severity of these events is understood to have been mitigated by collecting filter backwash in a retention tank and then slowly blending it with the concentrate discharge rather than immediately discharging, as pictured). Other facilities that do not perform this mitigation step have not reported discolouration in the plume to the extent shown here, although most of those facilities employ an offshore, submerged intake.

The need for mitigation is a function of project-specific parameters that affect the ferric coagulant dose and frequency of backwash.

While this mitigation technique resolves the aesthetic aspects of "red brine" events and reduces (or removes) the potential impact of higher turbidity, it does not reduce the total amount of iron discharged, only its concentration. This could be a concern if iron is not a limiting nutrient in the local environment.

An alternative, but more costly method of mitigating such an impact is to employ a sedimentation step in which the filter backwash water is clarified and the supernatant is discharged with the concentrate. The settled sludge can then be thickened/dewatered prior to disposal in an appropriate landfill.

3.3 Halogenated organic compounds

Halogenated organics are compounds having a halogen-carbon bond and which are by-products from chlorination or the use of other strong oxidants. Chlorine reacts rapidly with any reducible compound present in seawater. Oxidative (disinfecting) capacity is thereby transmitted from chlorine to other chemical compounds, while chlorine is reduced to chloride, the major ion in seawater (Abarnou and Miossec, 1992). In seawater, most of the chlorine is consumed by naturally present bromide ions, which are instantaneously oxidized to bromine and hydrolyzed to hypobromous acid. The method of "chlorine" pretreatment has proven very effective in seawater applications (Redondo and Lomax, 1997), however, due to many possible reactions of chlorine and bromine with organic seawater constituents, the number of halogenated by-products can hardly be determined.

Precursors of natural origin will predominantly lead to the formation of trihalomethanes (THMs), mainly bromoform (Saeed et al., 1999). Very few studies investigated coastal THM concentrations near distillation plants. In two cases, increased levels up to 9.5 µg/L near the outlet (Ali and Riley, 1986) and up to 83 µg/l (Saeed et al., 1999) were reported. These findings are in line with bromoform levels observed in effluents from coastal power stations (around 15-20 µg/L). Concentrations of other halogenated hydrocarbons are considerably lower and usually in the nanogram per litre range. Components of anthropogenic origin such as those from oil pollution in coastal waters may give rise to compounds like chlorophenols or chlorobenzenes (Saeed et al., 1999; Allonier et al., 1999; Jenner et al., 1997; Abarnou and Miossec, 1992).

As only a small fraction of total added chlorine will be recovered as halogenated by-products – and the by-product diversity is high – the environmental level of each substance will be comparatively low (Abarnou and Miossec, 1992). If one takes dilution and evaporation of these highly volatile substances into account, environmental levels will unlikely have acute toxic effects with regard to relatively high LC50 values of test organisms. Although adult mortality seems unlikely, sensitive life stages like eggs or larvae may not survive or sensitive species may respond to chronic concentrations. Also, sufficient evidence exists that some halogenated by-products have mutagenic and carcinogenic properties, so that probably no threshold value can be established (Verschueren, 1996; Abarnou and Miossec, 1992).

Formation of halogenated organics is usually a problem associated with thermal plant reject streams, as the water is not dechlorinated as in the RO process. However, a certain level of concern should also be given to RO reject streams, as it was shown by some studies that dechlorinated seawater is still toxic to fish at sensitive development stages. For example:

Eggs and larvae of striped bass (*Morone saxatilis*) showed increased mortality and this was postulated to result from the formation of halogenated organics during seawater chlorination. SO_2 for neutralization ranged from 0.06-2 mg/L, but did not influence mortality (Hose et al., 1984 after Hall et al., 1981).

Marine phytoplankton growth was inhibited in aged seawater that had been initially chlorinated, but that was free of residual chlorine at the time of exposure (HSDB, 2001).

Chronic effects were also reported for adult oysters in dechlorinated water and again attributed to the formation of halogenated organics: at bromoform concentration of 16-19 µg/L, respiration rates were increased and feeding rates and size of gonads were reduced (Scott, 1983).

It can be concluded that residual chlorine in the discharge will provide a significantly higher acute toxicity to aquatic life than elevated concentrations of THMs or other chlorination by-products. Consequently, negative impacts from residual chlorine can be effectively controlled by dechlorination. Dechlorination will reduce the likelihood that chlorination by-products are formed, but may not eliminate these substances completely (Scott, 1983).

3.4 Shock treatment with biocides

Another major disadvantage of chlorination is the breakdown of high molecular dissolved organics into nutrients, i.e., assimilable organic matter (AOC). In addition, microorganisms subject to low levels of biocides often exude extracellular polysaccharides as a protective biofilm that increases their survival rate. Both, the availability of surplus nutrients and the survival of some microorganisms can cause a heavy re-growth in desalination systems following chlorination.

To control regrowth, shock treatment is common practice in many desalination plants, particularly SWRO plants. Biocide concentrations are increased during normal operation on a periodic basis, which can be as often as once or several times a day (Redondo and Lomax, 1997; Abdel-Jawad and Al-Tabtabaei, 1999). Chlorine doses can be as high as 6-8 mg/L in distillation plants (Burashid, 1992; Khordagui, 1992) but non-oxidizing biocides must be applied in RO plants. Sodium bisulfite is most commonly used for this purpose, e.g. 500-1,000 mg/L for 30 minutes, which reduces bacterial numbers by oxygen depletion and is therefore only effective against aerobic microorganisms (Redondo and Lomax, 1997). Consequently, the concentrate will either contain higher residual chlorine levels or be deprived of dissolved oxygen. To avoid toxic conditions to non-target organisms, the reject streams should be dechlorinated or deaerated prior to blow-down during shock treatment.

3.5 Alternative treatment methods for biofouling control

Due to environmental and health problems caused by residual chlorine and disinfection by-products, several alternative pretreatment methods have been considered to replace chlorine in industrial and municipal applications. The following chemicals were considered in recent literature as replacement for chlorine treatment. Although these methods can be successful, none has gained wide acceptance over chlorine, especially in thermal plants that require large amounts of disinfectants. Khordagui (1992) compared several alternative pretreatment methods for distillation with regard to their environmental and health impacts, effectiveness, technical feasibility and costs, but none superseded chlorination-dechlorination using SO_2.

3.5.1 Ozone

A major advantage of ozone (O_3) treatment in *freshwater* systems is that no chlorination by-products are formed (Gordon and Bubnis, 2000). Furthermore, free ozone decomposes very rapidly and has a very short half-life – in the range of minutes to seconds – and the rate of decomposition increases with the organic content of water (Leynen et al., 1998 after Rice and Wilkes, 1992).

In *seawater*, ozone is automatically depleted as it converts bromide to hypobromous acid (HOBr), which is also the main oxidant produced by chlorination of seawater. The substitution of chlorine by ozone will therefore produce similar chemical compounds and similar environmental concerns as chlorination (Khordagui, 1992).

Because ozone is an even stronger oxidant than chlorine, de-ozonation must be performed to prevent permanent damage of polyamide membranes by oxidation (Redondo and Lomax, 1997).

3.5.2 Monochloramine

Monochloramine (NH_2Cl) has been proposed by some membrane manufacturers as a disinfectant instead of chlorine. It can be produced by adding chlorine gas or hypochlorite to ammonium-enriched feedwater. At higher ammonia concentrations, bromine is no longer the dominant oxidant species in seawater. The complex equilibrium between chlorine, bromine and ammonia will be displaced toward the formation of monochloramine. For example, it has been suggested that this transformation can be achieved by mixing seawater with treated effluents from a sewage treatment facility after chlorination due to higher ammonia levels in the sewage (Abarnou and Miossec, 1992).

A major advantage of monochloramine is that it will less likely break down high molecular organics dissolved in seawater into AOCs; smaller fragments, which may become assimilable nutrients for microorganisms (DuPont, 1994; Filmtec, 2000). Also, chlorination by-products such as THMs in seawater and RO permeate are less likely formed (Tanaka et al., 1994).

Although laboratory tests show that monochloramine can be used as a disinfectant, field-testing of chloramine failed to yield conclusive positive results in some major Middle-Eastern surface seawater plants (Saad, 1992) Although chloramine has apparently weaker oxidizing properties than chlorine/bromine, de-chloramination is required in RO plants.

3.5.3 Chlorine dioxide

Chlorine dioxide (ClO_2) is a strong oxidant but polymeric membranes were found to have a greater tolerance to chlorine dioxide than to chlorine, so that concentrations of 1 mg/L or less could be used to sanitize the membranes without damage (Adams, 1990). Chang et al. (2000) reported the formation of disinfection by-products like THMs at relatively high chlorine dioxide dosage (up to 30 mg/L), which is far above disinfection levels in desalination plants.

It can be assumed that ClO_2 does not readily form THMs if it is added in small amounts to the feed stream (Gordon and Bubnis, 2000), which is a major advantage over chlorine use. Therefore, environmental impacts are somewhat lower than for chlorine (Khordagui, 1992) but like other biocides, ClO_2 will also affect non-target organisms in coastal waters if residual levels are not neutralized.

3.5.4 Copper sulfate

Copper sulfate has been recommended by membrane manufacturers at levels of 0.1-0.5 mg/L (Filmtec, 2000). Although copper sulfate does not cause membrane damage by oxidation, it might foul the membrane by precipitation in the form of carbonates or hydroxides. Furthermore, it is not an effective bactericide and primarily limits algal growth, although successful operation was reported for some large desalination plants in the Red Sea (Saad, 1992). Environmental concerns and strict discharge regulations limit the large-scale use of copper sulfate in many countries today.

3.5.5 Ultraviolet light

Ultraviolet light at 254 nm may be considered as a non-chemical method to remove microganisms from the RO feedwater. This method is more expensive than biocide dosing but has been found to be an effective method, practical in small, fully automated systems (Saad, 1992).

Positive aspects are that UV-light does not require storage and handling of chemicals. The physical and chemical parameters of the water are not altered and no toxic by-products are formed (Perrot and Baron, 1995). However, high turbidity decreases UV-transmission and may interfere with disinfecting properties, so that this method is limited to relatively clear waters (Redondo and Lomax, 1997).

3.6 Glossary

aerobic – Condition characterized by the presence of free oxygen.

anaerobic – Condition characterized by the absence of free oxygen.

anoxic – Condition characterized by the absence of free oxygen.

benthic – Relating to the bottom environment of a water body.

biofoul – Undesirable presence and growth of organic matter in a water system.

brine – Water saturated with, or containing a high concentration of salts, usually in excess of 35,000 mg/L.

chloramines – Disinfecting compounds containing nitrogen, chlorine and hydrogen formed by the reaction between hypochlorous acid and ammonia and/or organic amines in water.

chlorine – An oxidant commonly used as a disinfectant in water and wastewater treatment. Chemical formula is Cl2.

coagulant – A chemical added to initially destabalize, aggregate, and bind together colloids and emulsions to improve settleability or filterability.

concentrate – The water containing the dissolved solids removed during desalination.

concentration factor – A number indicating the number of times a solution has been concentrated from its initial condition.

cooling water – Water used, usually in a heat exchanger, to reduce the temperature of liquids or gases.

desalination – The process of removing dissolved salts from water.

diffuser – A device used at the end of a pipe to promote the diffusion of a discharged liquid.

dilution – (1) Lowering the concentration of a solution by adding more solvent. (2) The engineered mixing of discharged water with receiving water to lessen its immediate aesthetic and/or biochemical impact.

dilution ratio – The volumetric ratio of solvent to solute.

dissolved oxygen – (DO) The oxygen dissolved in a liquid.

dissolved solids – Solids in solution that cannot be removed by filtration with a 0.45 micron filter. See “total dissolved solids”.

distillation – The process of boiling a liquid solution, followed by condensation of the vapor, for the purpose of separating the solute from the solution.

DO – See “dissolved oxygen”.

eutrophication – Nutrient enrichment of a water body, causing excessive growth of aquatic plants and eventual deoxygenation of the water.

evaporation – The process in which water is converted to a pure vapor that can be condensed.

far field – The area away beyond the ‘near field’ where mixing and diffusion are primarily influenced by the natural parameters such as currents, tides etc.

feedwater – Water that is fed to the treatment or desalination plant.

heavy metals – Metals that can be precipitated by hydrogen sulfide in an acid solution, and which may be toxic to humans above certain concentrations.

intake – The works or structure where water is drawn from the sea to feed a desalination plant.

mg/L – Milligrams per litre.

ML – Megalitre; one million litres.

ML/d – Megalitres per day

near field – The initial mixing zone which is primarily influenced by the physical characteristics of the discharge outlet or diffuser..

nozzle – A device used at the discharge point on a pipe to promote mixing, usually with an accompanying increase in velocity.

outfall – The location where a storm or sanitary sewer or effluent is discharged into a receiving water body.

permeate - The liquid that passes through a membrane.

polyelectrolyte – A compound consisting of organic molecules used as coagulants or coagulant aids.

polymer – Common term for ‘polyelectrolyte’.

post chlorination – Addition of chlorine after completion of other treatment processes.

pretreatment – The initial water treatment process(s) that precedes a reverse osmosis primary system.

product water – The desalinated water produced by a reverse osmosis plant.

recovery – In a reverse osmosis process, recovery indicates the amount/percentage of product water recovered from the feed stream.

reject – The water containing the dissolved solids removed during desalination.

reverse osmosis – (RO) A method of separating water from dissolved salts by passing feedwater through a semipermeable membrane at a pressure greater than the osmotic pressure caused by the dissolved salts.

salinity – The concentration of dissolved salts in water.

salt – class of ionic compounds formed by the combination of an acid and a base, of which sodium chloride is one of the most common examples.

seawater – General term for sea or ocean water, with a typical total dissolved solids concentration of 35,000 mg/L.

sedimentation – The removal of settleable suspended solids from water or wastewater by gravity in a quiescent basin or clarifier.

SWRO – Seawater reverse osmosis.

TDS See “total dissolved solids”.

thermal desalination – The process of desalinating seawater through evaporation and condensation of the resulting vapours.

total dissolved solids – (TDS) The weight per unit volume of all volatile and non-volatile solids dissolved in a water or wastewater after a sample has been filtered to remove colloidal and suspended solids.

Zone of Initial Dilution – The area where a discharge from an outfall first mixes with the receiving water.