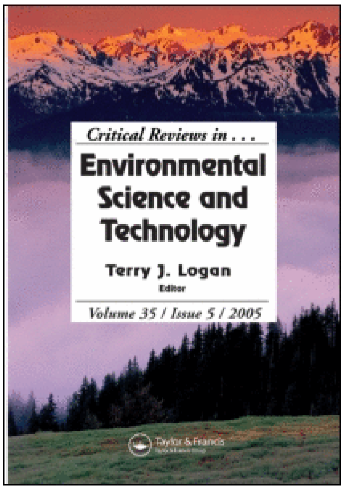

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Management of Concentrated Waste Streams from High-Pressure Membrane Water Treatment Systems

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The sustainable management of concentrated waste streams from high-pressure membrane-based water treatment processes are commonly the greatest limitations to the implementation of such processes. This applies to seawater desalination, brackish water desalination, groundwater softening, surface water treatment, and municipal water reclamation. This review provides an analysis of the potential environmental implications of concentrate disposal to marine, freshwater, and terrestrial environments. Although high-pressure membrane treatment plants generate a number of other waste streams of similar content and effect on the environment (such as spent pre-treatment filter backwash and spent cleaning chemicals used during periodic cleaning of reverse osmosis membranes), these waste streams are not discussed in detail herein. The focus is on Australian circumstances, but the issues raised are universal. Established management practices are critically reviewed, and a number of alternative practices canvassed. Given that large-scale high-pressure membrane water treatment plants are relatively recent developments in Australia, a significant amount of work has been undertaken. However, a considerable number of knowledge gaps are revealed, preventing a complete understanding of the risks associated with existing practices and the development

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of potentially more economically and environmentally sustainable concentrate management practices. As such, the review provides insight to current research needs and priorities.

KEY WORDS: reverse osmosis, desalination, membrane concentrate, brine disposal

INTRODUCTION

Integrated water supply systems are increasingly utilizing non-traditional water sources such as seawater, excessively hard or brackish groundwater, poorer quality surface waters, and wastewater. These sources commonly require treatment with membrane technologies before use in water supply systems. Membrane technologies including reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) can remove many chemical substances and microorganisms with impressive efficiency. RO and NF are generally considered to be the high-pressure membrane processes, operating at 5–100 bar, depending on the application. However the low-pressure processes, MF and UF (operating up to about 8 bar), often provide the important function of pre-treatment in RO and NF plants.

Membrane technologies operate by providing a physical barrier to impurities. These technologies generate waste streams that require disposal. The terms brine, brine reject, membrane reject, hypersaline discharge, discharge, and concentrate all refer to the concentrated waste stream of membrane treatment processes. They comprise materials rejected by the membrane, whether present in the original source water or added during pre-treatment, as well as substances used to clean, maintain, or optimize the performance of the membranes. The disposal (usually to land or receiving fresh or marine waters) of the membrane concentrates requires careful management to minimize environmental impacts. For seawater desalination plants, these impacts are mainly due to elevated salinity of the plant discharge. For groundwater softening and brackish water desalination plants, such impacts are most often related to elevated salinity and ion imbalance (i.e., significant difference in the ionic composition of the discharge and the receiving freshwater or seawater environment). For water reclamation plants, key environmental impacts are related to the elevated content of nutrients and anthropogenic pollutants such as endocrine disruptors, carcinogenic chemicals, and metals, as well as ion imbalance related toxicity and low salinity if the concentrate is to be discharged to the ocean.

Concentrate management is now one of the greatest concerns for water reuse and desalination. The United States Bureau of Reclamation has published a *Desalination and Water Purification Technology Roadmap,* citing concentrate management as one of the five major areas where research and development is required to accelerate the expansion of desalination and water reuse.[1] The respected wastewater engineering handbook published by Metcalf & Eddy states that "disposal of the concentrated waste streams produced by membrane processes represents the major problem that must be dealt with in their applications" (p. 1135).[2] A recent analysis by the US WateReuse Association reported that "new technical and regulatory approaches to concentrate disposal are desperately needed" (p. xvii).[3] Approval of a cost-effective concentrate management option is often a key factor for project viability. Demonstrated environmental due diligence, technical challenges, permitting and licensing of the discharge, and associated costs are all issues to address.

In Australia, federal, state, and local government may have a role in approving or licensing membrane treatment facilities. Despite the environmental impact analysis, review and studies associated with the recent implementation of large seawater reverse osmosis (SWRO) projects, there is little public information on how to assess options for concentrate disposal.

Most current proposals involving RO or NF plants in Australia propose to discharge concentrates to marine environments or waterways or to land for evaporation. However, such practices are not always technically or economically viable due to local site-specific environmental constraints or limited evaporation, mixing, or dispersion capacity.

Wastewater reclamation plants using high-pressure membranes in Australia currently rely exclusively on ocean discharge of concentrates, either directly or via municipal sewers. Inland water reclamation plants have tended to adopt alternative treatment technologies, which avoid the production of concentrates.[4] However, emerging plans for indirect potable reuse may present major new challenges, with inland cities such as Canberra seriously considering the construction of RO-based advanced water reclamation schemes.[5]

This paper provides an overview of issues and challenges for the management of membrane concentrate. A review of current practices for handling (including beneficial reuse or resource recovery) and disposal of membrane concentrates is presented, with examples given to illustrate the techniques. Knowledge gaps and opportunities for research and development that could guide the development of sustainable management practices are identified.

CHARACTERIZATION OF TYPICAL CONCENTRATE STREAMS

Membrane Processes

The fundamental principle of high-pressure membrane-based processes is the use of semi-permeable membranes to separate a purified component of the water from contaminants. The waste-stream produced during this process is thus a concentrated brine containing most (or, ideally, all) of the

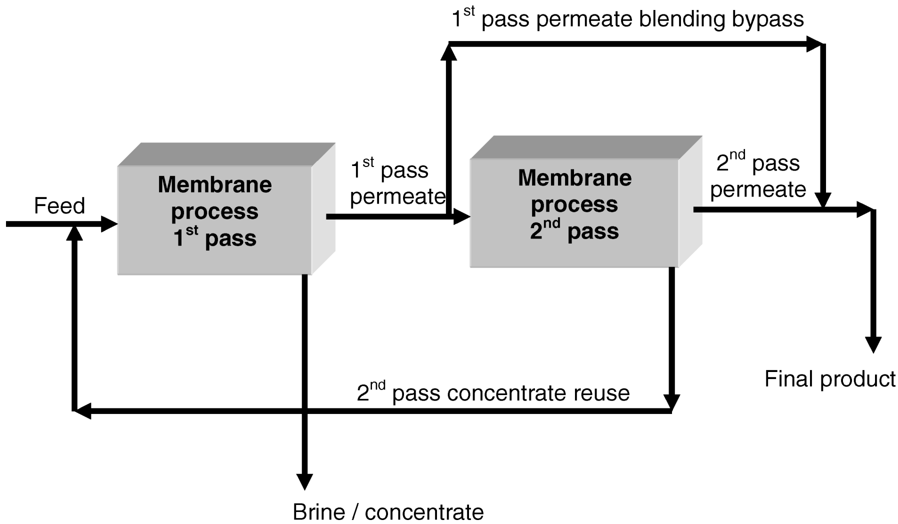

FIGURE 1. Representative schematic layout of membrane processes leading to concentrate production.

total dissolved solids (TDS) and other impurities of the source water in a fraction of the original volume.

Large, modern schemes often involve multiple high-pressure membrane process steps in series. Steps are commonly referred to as first pass, second pass, etc. The precise movement of permeates and brines between subsequent passes is determined by an optimization process considering end use requirements and energy efficiency targets.[6] The concentrated discharge may be a combination of concentrates produced from all passes. A typical membrane process layout is given in Figure 1.

The term *concentrate* (concentrated discharge) typically refers to the high-salinity (high-TDS) waste stream generated during the NF or RO separation process. However, other waste streams generated in high-pressure membrane treatment plants include spent waste backwash water from the source water pre-treatment processes (granular media or MF or UF filtration) and spent membrane cleaning solution generated during the periodic cleaning of the NF/RO membranes and any MF/UF membranes. These additional waste streams are not addressed in detail in this article.

Source Water Characterization

Seawater salinity varies between regions, but in the open ocean typically ranges between 33 and 37 g/L (33–37 ppt).[7] Variations are usually due to relative rates of evaporation, precipitation, and freshwater influx. For example, high salinities are typical in poorly mixed waters with high evaporation rates,[8,9] while proximity to very large river mouths can have a significant diluting effect.[10] Regardless of these variations, the relative proportions of the major dissolved ions are very consistent. By mass, TDS in seawater is around 55% Cl^- and 31% Na^+. Other major ions include SO_4^{2-} (8%), Mg^{2+} (4%), Ca^{2+} (1%), K^+ (1%), HCO_3^- (0.4%), and Br^- (0.2%). Detailed descriptions of mass concentrations of major and minor constituents of seawater are available elsewhere.[7]

Ionic composition of groundwaters and surface waters are highly variable throughout the world and thus difficult to generalize. However, membrane treatment of groundwaters is typically employed to remove hardness (Mg^{2+} and/or Ca^{2+}),[11,12] excessive concentrations of specific ions such as fluoride,[13] or brackish salinity.[14,15] Membrane treatment of surface water is used to target high concentrations of organic matter, which would otherwise lead to excessive formation of disinfection byproducts.[16,17] There is also growing interest in surface water treatment for the specific purpose of targeting trace organic chemical contaminants.[18,19]

Wastewater (municipal and industrial) compositions depend on specific characteristics of the service area, the origin of the wastewater (domestic, industrial, agricultural), the quality of the individual water sources contributing to the wastewater effluent, as well as the nature and intensity of pre-treatment operations.

Process Chemicals

In addition to concentrated feedwater compounds, plant discharges may contain various chemicals used in pre-treatment for performance optimization and during intermittent chemical cleaning of the membranes.[20]

Antiscalants are used to prevent the formation of scale (usually carbonate and sulfate scale) within plant equipment and membranes. The major chemicals used as antiscalants are organic, carboxylic-rich polymers such as polyacrylic acid and polymaleic acid.[21] Other commonly used antiscalants include sodium hexametaphosphate.[20] and sulfuric acid.[8] Typically a dose rate of 0.5 to 2 ppm is added to the feedwater, which is then concentrated in the brine. Knowledge regarding the stability, residence times, and eco-toxicity of antiscalants is limited.[22]

Ferric chloride (or alternatively, ferric sulfate or aluminium sulfate), is sometimes used in the pre-treatment process as a flocculant to reduce silt derived from organics, small colloids, and other suspended material.[23] These flocculants form flocs of ferric oxyhydroxide ($Fe(OH)_3$) or aluminium hydroxide, which are washed from the MF or UF membrane modules in the filter backwash and combined with the RO concentrate before discharge. The ferric iron gives a distinct color to the backwash water that needs to be considered when determining disposal options. In most cases, the spent filter backwash water is settled prior to removal, and the sludge that contains the vast majority of the coagulant is either disposed of to the sewer or dewatered and disposed of to a landfill as solid waste. If the spent filter backwash water is discharged without treatment, ferric oxyhydroxide flocs may settle on the seabed or, more likely, be dispersed.[24] Coagulant aids such as cationic or anionic polyelectrolytes may also be used in some cases to enhance the capture of the destabilized particles.[8]

Chlorine is commonly used in membrane desalination and water reclamation plants to control biofouling.[21] However, modern plants often utilize polyamide NF and RO membranes, which are sensitive to strong oxidants such as chlorine. Accordingly, the chlorine is removed (pretreated water is dechlorinated) prior to the water entering the RO unit.[23] For this reason, chlorine is not typically measurable in RO concentrate. Sodium bisulfite solution is commonly used for dechlorination.[23]

Lime is used for pH and alkalinity adjustment and corrosion control, which can produce a further concentrated stream known as the lime sludge.[23] Lime sludge is typically mixed with membrane concentrates for disposal.[24] Lime sludge is generated in large quantities when lime is used for the pretreatment of the source water rather than the post-treatment of the NF or RO permeate. However, state-of-the-art lime feed systems used for corrosion control in SWRO permeate do not generate lime sludge. Similarly, many seawater desalination plants use calcite (calcium carbonate) contact filters for corrosion control and pH and alkalinity adjustment of the RO permeate, which also do not generate residual waste streams.

Membrane cleaning is usually undertaken three or four times per year, and the chemical products used are mainly weak acids and detergents (citric acids, sodium polyphosphate, and EDTA) and caustic alkali.[8,20,25] Water reclamation plants and desalination plants use the same types of chemicals for this periodic membrane cleaning. Often the spent membrane cleaning chemicals are disposed to sanitary sewers, rather than blended with the other waste streams and discharged to a water body.

Membrane Recovery

The composition of membrane concentrate streams will be primarily determined by the composition of the source water (feed) and the efficiency (fractional recovery) of the membrane treatment system.[26] The concentrate TDS can be calculated in terms of the feed and permeate TDS and the fractional recovery (Y)[27]:

$$\mathrm{TDS_{concentrate}} = \mathrm{TDS_{feed}}\left(\frac{1}{1-\mathrm{Y}}\right) - \frac{\mathrm{Y} \times \mathrm{TDS_{permeate}}}{100(1-\mathrm{Y})}$$

where

$$Y = \frac{\text{Permeate flow rate}}{\text{Feed flow rate}}$$

By neglecting the permeate TDS (usually about one percent of feed TDS for RO treatment of saline waters), the concentrate TDS can be more simply defined as:

$$TDS_{concentrate} = TDS_{feed}\left(\frac{1}{1-Y}\right)$$

The brine concentration factor is then defined as $TDS_{concentrate}/TDS_{feed}$. Because membranes will be more permeable to some chemicals than others,[28] variable concentration factors may apply for specific chemicals. Exactly how the brine concentration factor impacts the disposal of brines depends heavily on the means of disposal. In some cases, volume minimization (high brine concentration factor) will be preferred, whereas, in cases where the brine is to be discharged to waterways, low concentration may be more important than low volume.

If free from scalants, the concentration factor is primarily limited by the increasing osmotic pressure of the developing brine. For modern systems, this limit is typically around 65–75 g/L.[27] For some waters, particularly brackish groundwaters, solutes that lead to the development of scale on the membrane surface can significantly reduce the achievable brine concentration.[29] Scaling can sometimes be minimized by pre-treatment, such as lime softening to remove hardness,[29] or by the use of dual membrane systems, which enable the initial removal of divalent cations (typically by nanofiltration) before the monovalent ions are removed by reverse osmosis.[30]

The combined effect of membrane porosity and source water concentration typically renders the optimum fractional recovery from a single-pass system as low as 35–45 percent for seawater reverse osmosis plants. Consequently, concentration factors for single-pass seawater desalination processes are often around 1.5–1.8. Some of the most efficient (high-pressure) two-pass SWRO systems report recoveries as high as 60 percent.[31]

The largest SWRO plant outside the Middle East commenced operation in Perth (Western Australia) in November 2006.[23] The Perth Seawater Desalination Plant is a two-stage RO plant operating with a first pass recovery of 45 percent and a second pass recovery of 90 percent.[23] This corresponds to an overall brine concentration factor of approximately 1.7 times. Based on a source water TDS of 33–37 g/L, the plant produces an overall RO brine TDS of around 65 g/L. The ionic compositions of feed and concentrate streams of an SWRO plant in the Canary Islands (Spain) show a similar concentration factor of approximately 1.8.[25]

The considerably lower salt concentrations of surface waters groundwaters and municipal sewage effluents tend to allow for much greater fractional recoveries. For example, surveys undertaken in Oman and the United Arab Emirates revealed brackish groundwater RO plants operating with recoveries up to 75 percent, corresponding to a concentration factor of 4.0.[14,15,32] Groundwater softening plants tend to operate with recoveries of 80–90 percent (concentration factor 5–10 assuming complete TDS rejection).[12] Wastewater reclamation plants typically operate with recoveries of 80–85 percent for NF and 70–85 percent for reverse osmosis.[2] A large NF plant in France treats high organic carbon surface water with a recovery of 85 percent.[17]

Concentrate Characterization

Chemical composition of the concentrate is determined by the composition of the source water, including any process chemicals added.[26] Physical parameters such as temperature are also largely dependent on source water but are affected slightly by the high pressures and extensive physical shear involved in low-porosity membrane treatment operations.

An Australian brackish groundwater desalination scheme is in operation in Dalby, a small country town in South East Queensland. Details of the feed and concentrate constituents from an analysis of this plant are provided in Table 1.[33] These data show a concentration factor of about 4 for most constituents, but it is worth noting that the following parameters do not follow this pattern: total iron (concentration factor = 2.3); calcium (6.6); magnesium (0.1); free carbon dioxide (1.6); and sodium adsorption ratio (2.0). Allowing for some variability in analytical reproducibility, these results suggest either significant variation in permeability between chemical species, or that significant species transformation (in the case of free carbon dioxide, volatilization) is occurring in the concentrate. The very low concentration factor for magnesium is surprising, as this divalent cation would be expected to be concentrated to a similar (considerable) degree as calcium. Notwithstanding the possibility of analytical error, it may also be possible that magnesium had become so concentrated that precipitation was initiated, leading to excess removal of this species from solution as scale. Because of variable species rejection and the possibility of subsequent species transformation, it should not be presumed that simple concentration factor calculations will consistently deliver accurate concentration predictions for all chemicals. As a result, precise concentrate characterization may require pilot scale evaluation for new schemes.

Chemical composition of brines produced from up to nine inland brackish water RO plants on the Arabian Peninsular (Oman, United Arab Emirates [UAE], and Saudi Arabia) have been compiled.[15] The data are also presented in Table 1. These data indicate that these plants tend to produce more concentrated brines with respect to conductivity and total dissolved solids

TABLE 1. Feed and concentrate concentrations for a variety of parameters at Dalby (QLD) BWRO scheme.[33] and up to nine plants on the Arabian Peninsular.[15]

Parameter	Dalby (Australia) plant.[33] Feed	Dalby (Australia) plant.[33] Concentrate	Arabian Peninsular plants.[15] Concentrate
pH	7.6	8.0	4.1–8.0
Conductivity (mS/cm)	3.2	10.4	12.9–127.4
Total hardness (mg/L $CaCO_3$)	403	1650	1730–4041
Total alkalinity (mg/L $CaCO_3$)	371	1480	380–945
Molybdate reactive silica (mg/L)	32.5	133	—
Total iron (mg/L)	0.04	0.09	0.05–65.5
Total manganese (mg/L)	<0.01	0.01	0.01–22.6
Calcium (mg/L)	98.0	650	173–923
Magnesium (mg/L)	38.5	5.7	207–510
Sodium (mg/L)	552	2180	1433–6206
Potassium (mg/L)	2.9	10.4	51–264
Sulfate (mg/L SO_4)	119	453	1537–4197
Chloride (mg/L)	788	3080	1457–8946
Nitrate (mg/L NO_3)	9.8	29.1	5–143
Phosphate (mg/L PO_4)	0.30	1.04	—
Temporary hardness (mg/L $CaCO_3$)	371	1480	—
Bicarbonate alkalinity (mg/L $CaCO_3$)	371	1480	—
Carbonate alkalinity (mg/L $CaCO_3$)	<2	<2	—
Hydroxide alkalinity (mg/L $CaCO_3$)	<2	<2	—
Free carbon dioxide (mg/L)	18.6	29.7	—
Total dissolved ions (mg/L)	2060	8220	—
Total dissolved solids (mg/L)	1860	7440	6920–18300
Figure of merit	0.3	0.3	—
Saturation index	0.56	2.38	—
Residual alkalinity (meq/L $CaCO_3$)	Nil	Nil	—
Sodium adsorption ratio	12.0	23.4	19–27

than the Dalby plant. This is presumably related to feed water characteristics and variable plant operational parameters such as membrane selection and flux.

Depending on regional geochemistry, groundwater softening plants concentrate dissolved minerals such as calcium, magnesium, sodium, potassium, chloride, sulfate, silica, fluoride, nitrate and iron.[12]

Concentrate streams from surface water and wastewater reclamation plants can be expected to be considerably more variable than those from desalination facilities due to the greater variation in wastewater composition, pre-treatment (i.e., conventional wastewater treatment processes), and membrane operational parameters. However, wastewater concentrates will generally contain hardness, heavy metals, high molecular weight organics, microorganisms, and often sulfide gas.[2] Depending on nutrient removal at the sewage treatment plant, reclaimed wastewater concentrates will contain nutrients including phosphorus and nitrogen, and some of the nitrogen is likely to be present as ammonia, which is toxic to many aquatic species.[34]

Trace organic contaminants such as natural and synthetic hormones, pharmaceuticals, cosmetics, and dioxins are also concentrated in wastewater concentrates.[35,36] Due to high concentration factors, these anthropogenic pollutants, metals, and potentially carcinogenic volatile organic compounds may be present at levels several times higher than those in the wastewater treatment plant influent.

ENVIRONMENTAL IMPACTS OF CONCENTRATE DISPOSAL

The management and disposal of concentrate from high-pressure membrane plants presents a number of environmental issues that require careful consideration. Each receiving environment is unique, and indigenous aquatic species in the area of discharge vary in their susceptibility to deleterious effects.

The following sections describe some specific impacts of elevated salinity discharges from high-pressure membrane concentrates to some marine, freshwater, and terrestrial environments. While specific constituents, such as heavy metals, can present significant environmental concerns, only impacts relating to total dissolved solids (TDS) in general are discussed in detail. Nutrients are briefly mentioned where they are most relevant, but specific environmental impacts relating to other individual components of concentrates are not discussed. While there is a significant amount of knowledge and practical experience related to discharging concentrate from seawater and brackish water desalination plants, understanding of the environmental impact of the discharge of concentrate from water reclamation plants to fresh water bodies or the sea is very limited and detailed information not readily available.

Marine Environments

The environmental impacts of concentrate discharge into marine environments is a key issue for coastal desalination plants.[37–39] However, the majority of current international knowledge relates specifically to a few heavily impacted and relatively enclosed water bodies, including the Mediterranean Sea,[40–43] the Red Sea,[21] and the Persian Gulf.[39,44]

Many marine organisms are highly sensitive to variations in salinity[45] Simple marine organisms such as plants and invertebrates are usually "osmotic conformers," meaning that they have no mechanism to control osmosis so their cells conform to the same salinity as their environment. Large decreases in salinity cause water to enter the cells of these organisms, which eventually leads to cell rupturing (lysis). Increases in salinity can lead to cell dehydration, which can also result in cell death.

Studies from the Mediterranean have shown that Mediterranean Posidonia seagrasses and their associated ecosystems appear to be highly sensitive to increases in salinity.[40–42] For example, salinities of 45 g/L may lead to 50 percent death of some Posidonia species and 50 g/L may cause 100 percent death in as little as 15 days.[42] On the other hand, the seagrass species, *Posidonia australis* and *Amphibolis* found in Perth's coastal waters and at Shark Bay (a sheltered embayment with naturally elevated salinity compared to seawater), display maximum growth rates at a salinity of 42.5 g/L, and densest covers are found within a salinity range of 40 to 50 g/L.[46–48] Echinoderms, which are osmo-conforming organisms, appear to have been severely impacted in an area close to a Mediterranean SWRO discharge.[41]

Osmotic regulators are able to control the salt content and hence osmotic potential within their cells, despite variations in external salinity. Most marine fish, reptiles, birds, and mammals are osmotic regulators and employ a variety of mechanisms to control osmosis. Salinity tolerances of marine organisms vary, but few shellfish (scallops, clams, oysters, mussels, or crabs) or reef-building corals are able to tolerate salinities greater than 40–45 g/L.[49]

Concentrate disposal may also have impacts other than direct changes in salinity. In some circumstances, brine plume density may lead to increased stratification, reducing vertical mixing.[50] This may reduce dissolved oxygen levels, with ecological implications.[50] This possibility was raised as a particular concern during the planning and assessment for the Perth Seawater Desalination Plant discharging into Cockburn Sound, a large semi-enclosed embayment. However, detailed modeling and site investigation concluded that the anticipated concentrate discharge is unlikely to contribute to the exacerbation of low-oxygen conditions in this case.[49] Nonetheless, an ongoing dissolved oxygen monitoring program has been instated since construction of the plant.[38]

Ferric oxyhydroxide flocs, formed from the use of ferric flocculants, possess a very high surface area and thus are excellent adsorbents for a wide range of chemical species, including phosphorus and metals. As such, the discharged flocs may act to concentrate the adsorbed species, but with subsequent possible release if anoxia occurs and ferric ion is reduced to the much more soluble ferrous form. The possibility also exists that injection of iron into coastal waters may stimulate the growth of microorganisms including cyanobacteria, which is often controlled by iron availability.[51] The Perth Seawater Desalination Plant process removes the ferric oxyhydroxide flocs from the backwash water (via a centrifuge and subsequent disposal of the concentrate to landfill) to prevent possible staining of the white beaches of Cockburn Sound.

A marine ecological assessment for a planned seawater desalination plant in Sydney concluded that because the dense, hypersaline plume will tend to sink and disperse slowly, biota likely to be affected are bottom-dwelling or non-mobile species that live on or are physically attached to the reef.[52] These include fan corals, sponges, stalked and sessile ascidians, anemones, and attached algae. At present, there is little information available on the salinity tolerances of these species or their responses to chemicals contained in the discharge plume. The impacted zone for a 500 ML/day plant under quiescent conditions is assumed to be about 0.5 hectares.[24]

The Water Corporation of Western Australia conducted an extensive macrobenthic investigation into Cockburn Sound prior to the commencement of operations as a benchmarking investigation.[53] These data will be compared with new data to be gathered in a post-operations investigation. However, given the number of industries using Cockburn Sound and the mixing achieved by the diffuser (45 times dilution within 50 m), the establishment of a strong cause–effect link to the desalination plant seems scientifically unlikely and complex.

A comprehensive study on the effect of the disposal of seawater desalination plant discharges on near shore communities in the Caribbean was completed by the Southwest Florida Water Management District and the University of South Florida.[54] This study involved a detailed analysis of the environmental impacts of the discharges from seven existing SWRO plants in the Caribbean with plant capacities between 170 KL/day and 6 ML/day and discharge salinities between 45–56 g/L. All of the plants had been in operation for at least four years prior to the completion of the study. The study found no statistically significant impact from discharges on local benthic marine life, seagrasses, microalgae, or micro- and macro-invertebrates.

Recently, a novel method was reported for the assessment of the salinity tolerance of marine organisms on seawater desalination plant discharges.[55] This method was used for the evaluation of the environmental impact of the discharge of the 200 ML/day Carlsbad and Huntington Beach seawater desalination plants located in Southern California. The testing concluded that TDS discharge concentration of 40 g/L or less has no measurable effect on the marine environment in the vicinity of the discharge.[55] Chronic toxicity testing of the concentrate using topsmelt (a fish inhabiting the area of the discharge and used as a standard chronic toxicity-test organism) indicated that this species can withstand salinities of up to 50 g/L.

Freshwater Environments

Key factors determining the environmental impacts of concentrate discharge to freshwater environments include salinity and, for the case of water reclamation plants, nutrient concentration.[34]

The excessive discharge of nutrients such as nitrogen and phosphorous to freshwater environments can contribute to profligate algal growth and subsequent deoxygenation with devastating consequences to susceptible waterways.[56]

Very few studies have examined the effects of small increases of salinity on microbial organisms in Australian fresh water ecosystems.[57] The available information indicates that small salinity changes may have little deleterious effect on the important biological processes of bacteria.[58] This is due to the ability of freshwater bacteria to adapt to small salinity changes as well as the community replacement of freshwater species with otherwise similar saltwater bacteria.

There has been a similarly limited study of the salinity-tolerance of many macrophytes and microalgae in Australian rivers and streams.[57] Available evidence suggests that many species are salt-sensitive and that as salinity rises, the number and diversity of species falls.[59] Salinity increases up to around 1–2 g/L can be expected to be lethal to a large proportion of macrophytes found in Victoria.[58] Sublethal effects, such as reduced growing vigor, will occur at lower salinities.[57]

Many of the aquatic plants associated with lowland rivers in Victoria are known to be salt-sensitive. Adverse effects on a number of species have been reported to occur at salinities above 2 g/L.[58] There are variations in sensitivity, not only between species, but also between populations of the same species from different locations. Salt sensitivity can also differ between the seeds and seedlings of a species.

Aquatic invertebrates comprise a large and diverse range of species. Accordingly, their tolerance of salinity is comparatively diverse, but they appear to include some of the most sensitive of the freshwater animals.[58] Adverse effects are considered likely for some species at salinities in excess of 0.8 g/L.[59] Reviews of the literature have concluded that salinity impacts invertebrate fauna in a variety of ways and through several physiological mechanisms, resulting in negative effects on both species abundance and diversity.[57] Toxic effects would be particularly expected for simple multicellular organisms due to their lack of osmoregulatory capabilities.[58] It has also been suggested that some macroinvertebrates could benefit from the change in salinity, resulting in an overall shift in species composition.[57]

Many adult Australian freshwater fish appear to be salt-tolerant up to concentrations of around 10 g/L.[57,58] However, it is likely that other critical life stages, such as larvae, pre-hardened eggs, post-hardened eggs, and fry, may be considerably more sensitive.[57,58] As a component of a larger risk-assessment process, a cumulative distribution of conductivity toxicity values has previously been prepared for freshwater fish found in the Murray-Darling Basin.[57] It demonstrates the comparative sensitivity of the early life stages and shows that direct (acute) LD50 impacts are generally likely at somewhat lower salinities than slow (chronic) LD50 impacts.

The tolerance of Australian frogs to elevated salinity is not currently known, but overseas studies suggest considerable differences in sensitivity within and between species.[57] There is evidence that tadpoles are more sensitive to salinity than frogs, and that increased salinity results in a loss of suitable breeding sites.[57]

In addition to the direct impact of salinity on particular species, it is likely that changing salinity would disrupt broader ecosystem processes such as nutrient spiraling/recycling and energy flow through trophic webs.[57] Such processes underpin the health and integrity of entire ecosystems.

Terrestrial Environments

Membrane concentrates may be applied to terrestrial environments, either as an irrigation (reuse) process or simply for disposal by infiltration or evaporation. In either case, over time, salts present in the water accumulate in the soil profile as exchangeable ions. This can affect the physical and mechanical properties of the soil, such as soil structure, the degree of dispersion of soil particles, permeability, and stability of aggregates.

Osmotic effects caused by total dissolved salt concentration in soil water can have detrimental effects on plants.[60] Excellent drainage and maintaining a downward flux of dissolved salts through the root zone is the only practical way to manage this. Slight to moderate restrictions apply on irrigation use at TDS $>$ 450 mg/L and severe restrictions at TDS $>$ 2 g/L.[60]

In addition to osmotic effects, specific ion toxicity can also be a problem in soils. The most prevalent toxicity from the use of reclaimed water for irrigation is from chlorides and boron.[2] The source of boron in wastewater and reclaimed water is usually household detergents or discharges from industrial plants. Typically, the level of boron in reclaimed water is 0.2 to 0.5 mg/L greater than that in the drinking water from which it originated. Brackish water RO and NF membranes provide limited rejection of boron.[61] As a result, both the reclaimed water and the concentrate from the water reclamation plant may often be unsuitable for long-term irrigation of boron-sensitive crops. Naturally elevated concentration of boron in ocean water can also be an important consideration in the design of seawater desalination plants, especially when the desalinated seawater is used for irrigation of boron-sensitive food crops. Therefore, its effective removal is an important key consideration in the design configuration of many large plants.[61,62]

Irrigation water quality guidelines published by the Food and Agriculture Organization of the United Nations recommend maximum concentrations of trace elements in irrigation water.[60] Among these, selenium (0.02 mg/L) is likely to be a limiting element in some cases. Above this concentration, selenium is toxic to plants and possibly to livestock as well, if forage is grown in soils with relatively high levels of added selenium.[60]

High-sodium concentrations in soil can cause deterioration of the physical condition of the soil, such as by waterlogging, the formation of crusts, and reduced soil permeability.[63] In severe cases, the infiltration rate can be greatly reduced, preventing plants or crops from accessing enough water for good growth.[60] The sodium adsorption ratio (SAR), a simplified index of the relative sodium status of soil solutions, is used to indicate the degree of sodicity of the soil exchange complex.[63]:

$$SAR_p = \frac{Na_T}{(Ca_T + Mg_T)^{\frac{1}{2}}}$$

where the subscript "p" indicates "practical" SAR and subscript "T" represents the total concentrations of soluble ions in the saturated-paste extract, given in mol/m^3.

SAR has often been used to predict potential infiltration problems.[60] When the SAR is greater than 13, the soil condition is classified as sodic (sodium affected), implying the potential for clay dispersion and impaired soil permeability of fine-textured soils. Primarily because of the high levels of TDS, sodium, chlorides, and boron in the concentrate from seawater desalination plants, this concentrate is typically unsuitable for irrigating food crops. However, brackish water or surface water concentrates may be acceptable for irrigation of some halophytic plants.

Established Concentrate Management Practices

There are currently very limited options for concentrate reuse or treatment. Unlike sewage treatment, it generally isn't possible to reduce the chemical constituents of concentrate to simpler, less harmful compounds, as they are already predominantly simple inorganic species. As a result, the most common concentrate management practice is disposal.

Most disposal methods fall into one of the following categories: surface water discharge, discharge to sewers, subsurface injection, land application, or evaporation ponds.[26,64,65] As shown in Figure 2, these methods accounted for 98 percent of the methods used by plants with capacity greater than 95 KL/day in the United States in 2002.[64] These include NF and RO plants treating surface water, groundwater, municipal effluent, and seawater.[66]

In Australia, it is generally considered that concentrate discharge to a nearby water body (i.e., outfall to sea or surface water system) or injection into a saline aquifer are the cheapest and easiest options to implement.[67,68] In such situations, the only significant costs arise from construction of pipelines and/or bores, together with pumping and maintenance costs. In areas that are distant to the coastline, the most feasible options include evaporation, aquifer injection, or surface water body release.

The factors that influence the selection of concentrate management practices include the volume or quantity of the concentrate, geographical location of the concentrate (and specific attributes of the surrounding location), availability of a receiving site, regulatory permissibility of an option, acceptance

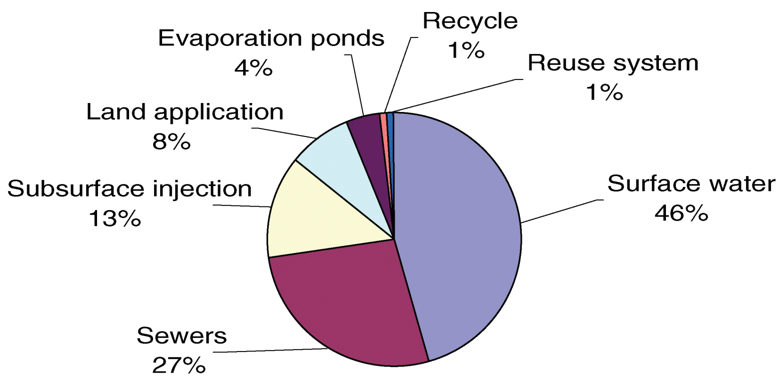

FIGURE 2. Methods of concentrate disposal in the USA 2002.[64]

by other stakeholders including the general public, capital and operating costs including pumping, and the potential for the facility to be expanded.[64] The various existing management (disposal) options for membrane concentrates are described in detail in the following sections.

Discharge to Surface Waters

Discharge to surface waters is by far the most widely used means of effluent disposal in Australia and internationally. It is used both for effluents generated from desalination as well as industrial and municipal wastewater discharge. In Australia, such discharges are closely regulated by the state-based environment protection agencies (EPAs).

The Australian and New Zealand Guidelines for Fresh and Marine Water Quality.[69] are the principal reference for considering the acceptability of proposed discharges. Importantly, these guidelines recognize and accept the concept of a mixing zone, described as "an explicitly defined area around an effluent discharge where certain environmental values are not protected" (p. 2-17).[69] The size, shape, and variability of mixing zones may be governed by the nature of the discharged brine as well as the design and operating conditions of the discharge infrastructure. A good management approach to minimize the effect of brine discharges on the receiving environment would be to minimize the size of the mixing zone.[70]

Nutrient control is particularly important for the discharge of concentrates generated from water reclamation plants to surface waters.[34] The use of mixing zones is not appropriate for managing the discharge of nutrients or bio-accumulatory or particulate substances.[71] For example, the impacts of the nutrients nitrogen and phosphorus may become evident a considerable distance from the discharge and are dependant upon the biological characteristics of the water body as a whole.

Australia's first planned indirect potable water reuse scheme is currently under construction in South East Queensland.[34] The RO concentrate generated from this scheme is to be discharged to the environmentally sensitive Moreton Bay, via the Brisbane River. The target concentrate loads of nutrients for this scheme are 4 mg/L as P phosphorous and 1 mg/L as N nitrate.[34] In order to minimize nutrient-related impacts, the RO concentrate will undergo phosphorous precipitation with ferric chloride and biological denitrification with methanol dosing. Denitrification has not frequently been used for such an application previously, and operation at elevated—and possibly fluctuating—salinity (4–6 g/L TDS) has been identified as a key challenge.[34]

Establishing that a proposed concentrate discharge is environmentally safe requires thorough engineering analysis, including hydrodynamic modeling of the discharge, whole effluent toxicity testing, salinity tolerance analysis of the aquatic species endemic to the area of discharge, and reliable intake water quality characterization that provides a basis for assessment of the concentrate's constituents and compliance with the numeric effluent quality standards applicable to the point of discharge.[72] Validated hydrodynamic modeling should incorporate water and sediment processes, air-water interface processes, salinity and temperature stratification, and overall accumulation if metals and nutrients are to be modeled for the far-field effects. Modeling should be further validated once plant operations commence.

Direct Discharge via a Dedicated Ocean Outfall

Direct ocean discharge of concentrates is widely practiced in many countries employing seawater desalination. Examples include plants in Saudi Arabia,[20,21] Malta,[20] Cyprus,[20] Oman,[44,73,74] Palestine,[75,76] Spain,[25,31] and Australia.[38] In fact, it has been reported that more than 90 percent of the large seawater desalination plants dispose their concentrate through a new ocean outfall specifically designed and built for that purpose.[72]

As a result of their high salinity, seawater concentrate plumes are denser than seawater and therefore have negative buoyancy and sink toward the seabed and move along the bathymetric contours.[70] This is in contrast to the more common wastewater plumes, which are buoyant and rise to the surface. Accordingly, understanding and modeling desalination plumes involves different challenges to those posed by wastewater discharge plumes.[70] The dense plume has fewer immediate and far field mixing processes than more buoyant plumes.[77]

A key challenge for dedicated ocean outfalls is to minimize the size of the zone in which the salinity is elevated before adequate mixing with ambient waters.[70] In some cases, this can be achieved by reliance on the mixing capacity of the tidal (surf) zone; however, this approach may lead to high salt concentrations along the shoreline.[78] In other cases, where the discharge occurs beyond the tidal zone and in low-energy environments, it is necessary to install diffusers to accelerate and facilitate mixing.[79] The salinity threshold mixing/transport capacity of the tidal zone and/or necessary diffuser configuration can be estimated with hydrodynamic modeling.[38] Two models used for salinity plume analysis are CORMIX and Visual Plumes.[72] Both allow the depiction of the concentrate plume dissipation under a number of outfall and diffuser designs and operational conditions. Other modeling techniques and criteria to enhance diffusion of discharged brine have also been described.[70,73,78] However, it should be noted that the science of predicting near field dilution achieved by dense fields has not been greatly studied.[77]

For the Perth Seawater Desalination Plant at Cockburn Sound, a series of models—including a one-dimensional box model and three-dimensional hydrodynamic models—and tests were used to ensure the plant would meet the required criteria at the edge of the mixing zone.[38] Increased certainty was achieved by running various scenarios and different models. Tank tests were also undertaken during the diffuser design, and an expert review of the design was undertaken prior to installation.[38]

Pilot field measurements indicated that during calm periods, near-bed dissolved oxygen levels naturally decrease in Cockburn Sound.[80] As a result and because of the semi-enclosed nature and topography of Cockburn Sound, a detailed study was undertaken to consider the extension (if any) of any natural stratification and associated dissolved oxygen issues that may result from brine discharge.[50] This study concluded that any additional effect on dissolved oxygen levels would be infrequent and minor. However, it recommended that because of the uncertainty of predictions for long calm periods, a monitoring program should be implemented as part of an adaptive management plan.[50]

The Perth desalination plant outlet is 1.2 m in diameter and has a 160 m-long, forty-port diffuser, where the ports are spaced at 5 m intervals with a 0.22 m nominal port diameter, located 470 m offshore, at a depth of 10 meters, adjacent to the plant in Cockburn Sound.[79] The diffuser is a bifurcated double-T-arrangement and incorporates a discharge angle of 60°. This design was adopted with the expectation that the plume would rise to a height of 8.5 m before beginning to sink due to its elevated density. It was designed to achieve a plume thickness at the edge of the mixing zone of 2.5 m and, in the absence of ambient cross-flow, 40 m laterally from the diffuser to the edge of the mixing zone.[81]

The operating license for the Perth desalination plant requires that certain dissolved oxygen levels are met in order for the plant to operate.[82] Furthermore, a minimum of 45 dilutions must be achieved at the edge of the mixing zone, defined in terms of a 50 m distance from the diffuser.[82] Extensive real-time monitoring is currently being undertaken in Cockburn Sound for the first year of operations to ensure the model predictions are correct and that the marine habitat and fauna are protected.[38] This includes monitoring of dissolved oxygen levels via sensors on the bed of the Sound. Visual confirmation of the plume dispersion was achieved by the use of 52 liters of Rhodamine dye added to the plant discharge.[83] The expulsion of the

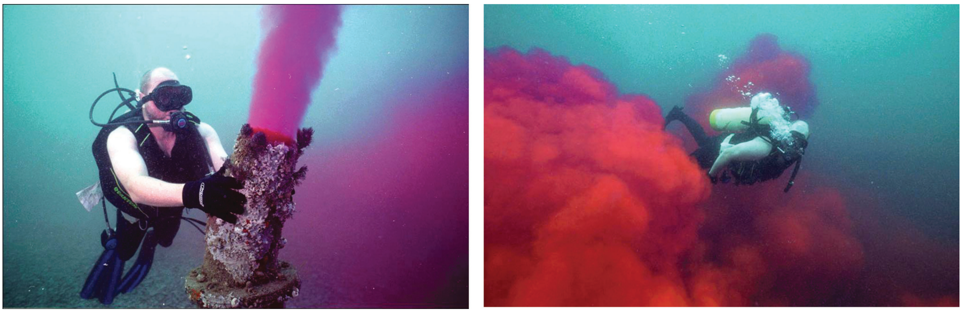

FIGURE 3. Rhodamine dye tests undertaken at the Perth Seawater Desalination Plant.[84]

Rhodamine dye from one of the plant diffusers is shown in Figure 3.[84] The dye was reported to have billowed to within about 3 meters of the water surface before falling to the seabed and spilling along a shallow sill of the Sound towards the ocean.[83] The experiment showed that the dye had dispersed beyond what could be visually detected within a distance of around 1.5 kilometers—well short of a protected deeper region of Cockburn Sound about 5 kilometers from the diffuser.[83] The environmentally benign dye experiment was first commission in December 2006 and repeated in April 2007 when conditions were calm.

Discharge via Existing Sewage Ocean Outfall

Concentrate may be discharged from an existing sewage ocean outfall, either by direct connection to the outfall (downstream of any sewage treatment plant [STP]) or by discharge to sewers and conveyance to an STP equipped with an outfall.[3] This approach has tended to be the default practice for concentrates generated from municipal wastewater reclamation plants in coastal Australian cities. However, some additional issues must be considered in the case of highly saline concentrates.

The most obvious advantage of discharging via an existing ocean outfall is the reduced requirement for new outfall infrastructure. A second advantage is the accelerated mixing that results from blending heavier-than-ocean-water desalination concentrate with the lighter sewage discharge. Co-discharge accelerates the dissipation of a saline plume by floating it upward and expanding the volume of the ocean water with which it mixes.[72] Where suitable relative volumes apply, the blending of non-saline sewage with highly saline concentrate may also be an effective means of discharging a combined solution of intermediate salinity.[72]

On the other hand, some concerns have been expressed regarding the combined discharge of high salinity brines with sewage.[8] One of the key concerns is that the high salinity may cause sewage contaminants and other particles to aggregate to assemblages of different sizes than they would otherwise. This would influence the rate of sedimentation, thus potentially disrupting benthic organisms or phytoplankton.

Co-discharge of desalination brine with municipal wastewater is the most common method of disposal in the Canary Islands (Spain).[25] Indirect co-discharge via sewers is also commonly practiced in regions with substantial numbers of small brackish water desalination plants, such as the Gaza Strip in Palestine.[75] Coastal wastewater treatment plants operating with ocean outfalls typically re-combine any recycled water RO concentrates with remaining effluents for outfall.

The addition of desalination concentrate to an existing sewage ocean outfall on the NSW Central Coast has been predicted to be of minimal environmental consequence.[85] This was based on expected near-field and far-field dilutions of treated effluent-concentrate mixtures developed from projected concentrate and effluent flows during the period 2001–2051. Far-field dilutions were estimated at a distance of up to 300 m from the release point. The modeling process was reported to demonstrate that the mixed discharge has a density similar to that of seawater such that the plume would come into contact with the seabed around 14 m from the release point rather than ascend to the surface. For the 2021 and 2051 scenarios, the plume would clear the bed and rise to the surface between 14–23 m and 20–26 m, respectively. It was reported that the salinity would be within 2 g/L of background levels of 34 g/L within 25 m from the release point.[85] It should be noted that the modeled outfall (Norah Head) is a particularly efficient outfall compared to many others in NSW.[86] and thus such effective mixing can not always be assumed at other locations.

An important consideration of combined discharge is that of the whole effluent toxicity (WET), which may result from ion imbalance from the blend of the two waste streams. Bioassay tests conducted at a short-lived Californian combined discharge scheme indicated that the blend could exhibit toxicity on fertilized sea urchin eggs and other marine species.[87]

Co-Location with Power Generation Plant

Co-location of a desalination facility with a power station on a large scale was first established by Poseidon Resources for the Tampa Bay Seawater Desalination Project,[88] and the concept has rapidly grown in popularity in the United States.[89] and worldwide.[6] In fact, the current largest seawater desalination plant in the world, at Ashkelon in Israel, has adopted this approach.[90] A key feature of many co-location schemes is the direct connection of the desalination plant intake and discharge facilities to the discharge outfall of an adjacently located coastal power generation plant. This provides for the use of the power plant cooling water both as a source of water for the seawater desalination plant and as blending water to reduce the salinity of the desalination concentrate prior to the discharge to the ocean.

As an example, a 50 ML (permeate) capacity seawater desalination plant operating at 50% recovery and treating seawater at 35 g/L TDS draws 100 ML/day feed flow from the power plant cooling loop and discharges a concentrate stream of 50 ML/day at 70 g/L TDS. If the cooling water intake is 1500 ML/day, after the 100 ML/day desalination plant withdrawal and subsequent blending of 50 ML/day of concentrate, the ultimate ocean discharge consists of 1450 ML/day of seawater at about 36.2 g/L TDS, a salinity of only 3.5% greater than ambient concentrations (as opposed to 100% greater without blending with cooling water discharge).[89]

There are numerous advantages of co-location of desalination and power plants.[72] These include the capital cost savings of not needing to construct a separate intake pipeline and structure, as well as a new discharge outfall. Required RO system feed pressures (and thus energy consumption) may be decreased as a result of using warmer water. Unit power costs may be further reduced by connecting directly to power plant generation facilities and avoiding power transmission charges. Accelerated approval processes may be accomplished as a result of avoiding construction of new intake and discharge outfalls in the ocean. Marine organism impingement and entrainment may be reduced because the desalination plant does not take additional seawater from the ocean. The impact on marine environment may be reduced as a result of faster dissipation of thermal plume and concentrate. Thermal discharge of the power plant to the ocean is decreased because a portion of this cooling water is converted to potable water. Finally, the use of already disturbed land at the power plant minimizes environmental impact.

Disadvantages of co-location have also been previously described.[72] The use of warmer water has a number of potential implications, including accelerated membrane biofouling and reduced rejection of some contaminants. Furthermore, warmer product water may promote the regrowth of microbial species. Source water must be cooled if its temperature is above 40°C in order to protect RO membrane integrity, and the product water would also normally be subject to certain temperature guidelines. RO membranes may also be exposed to iron, copper, or nickel fouling if the power plant condensers and piping are built of low-quality materials. Finally, operation of the desalination plant may be contingent on operational continuity at the power plant.

Plans for the Perth Seawater Desalination Plant were revised in 2004 to include a capacity expansion as well as securing the location of the plant, which potentially allowed for sharing of facilities with the Newgen Power Station (located on the Synergy Kwinana Power Station site).[81] However, although the desalination plant is sited adjacent to the power station, the two plants are discretely operated with no sharing of facilities.

The key reasons for this included the timing of the development of the two plants, guarantee of supply, and complexity of both operations. It was also considered that blending of discharges was not necessarily ideal because it was important to prevent the warmer cooling water (combined with the desalination concentrate) from becoming too dense and sinking to the seabed.

Beach, Beach Well, or Cliff-Face Discharge

A number of RO desalination plants in Oman and the United Arab Emirates (UAE) discharge brines directly to beach shorelines. While no in-depth analysis has been undertaken, no obvious adverse impact was reported in a survey involving visits to some of these facilities.[14]

At one stage, California's largest SWRO facility, in the city of Marina, retro-implemented an unusual discharge method.[91] This involved injecting the brine (TDS 43 g/L) into a shallow dune sand aquifer via a conventional well. There, it blended with native groundwater and ultimately diffused into the turbulent surf zone. A year of physical monitoring of the sea near the discharge point was unable to identify any impacts on benthic life.[91] However, discharge through the beach well was eventually discontinued due to severe scaling problems.[92]

A recent study from Spain suggests that actual dilution of the brine from a beach-discharge outfall may be lower than normally accepted.[41] In this case, elevated salinity was reported in deep localities several kilometers from the discharge point. Similarly, modeling from Oman suggests that continuously discharging brine wastes directly on the shoreline will result in increased salinity along the coastline.[74]

As somewhat of a combination of a discharge/beneficial reuse project, the City of Oxnard in California has proposed to convey desalination concentrate to a local tidal wetland and use it to supplement tidal flows and mitigate neglected areas of the wetland.[93]

Discharge to Short Coastal Creeks or Canals

In some cases, membrane concentrates are discharged to short creeks, rivers, or canals leading rapidly and directly to the sea. Examples of such practices have been described in the UAE[14] and Spain.[94]

One plant on the Mediterranean coast of Spain discharges brine to a canal called the Fontana Channel.[94] The reported benefits include the input of saline water to the canal to bring the density and temperature more in line with that of seawater before it reaches the sea. This effect has been enhanced by the incorporation of a novel brine dilution system.[94]

Disposal to Municipal Sewers

Discharge of concentrate via municipal sewers is one of the most widely practiced methods for disposal of concentrates from brackish water desalination plants in the United States.[95] It is also an important means of disposal for RO concentrates from a number of municipal water reclamation plants in Australia.

The most significant advantage of disposal to sewers is that the process makes use of existing infrastructure, negating the need for new pipes and pumps. In some cases, the transportation of the brine over large distances may be facilitated by the flow of existing wastewater in the sewers. This would imply significant energy savings compared to alternate means of brine transportation.

A developing Australian 50 ML/day municipal water reclamation scheme is intended to discharge around 8 ML/day of RO concentrate to one of Sydney's major sewers, the Northern Suburbs Ocean Outfall Sewer.[96] The concentrate will be pumped around 20 km to the sewer, from where it will be transported more than 30 km further to Sydney's North Head Sewage Treatment Plant. This treatment plant discharges to the ocean after only primary treatment. The concentrate is expected to contain 3–4 g/L TDS, including high concentrations of sulfate (0.5–1 g/L), chloride (1–1.5 g/L), calcium (0.13–0.2 g/L), and alkalinity (0.48–0.85 g/L as $CaCO_3$), and has a pH of 7.5–8.0.[96] There is some concern that this composition may be prone to mineral deposition during transfer, which would eventually lead to blockages or reduced flow capacity. Accordingly, the concentrate quality will be monitored, and additional antiscalant added during the post-treatment phase if required. A 25 ML concentrate storage pond will also be constructed at the site of the RO plant, to be used during periods of extended wet weather when sufficient sewer capacity may not be available.[96]

However, in cases where biological treatment processes are in place at the end of the municipal sewer, disposal of brine to the sewer may often only be suitable for relatively small RO/NF plants discharging into large capacity sewage-treatment facilities. This is due to the detrimental effects of the concentrate's high TDS content on biological treatment processes, some of which may begin to be inhibited when plant influent TDS exceeds 3 g/L.[72]

Deep Well Injection

Brine disposal to unlined bores has been reported in a number of circumstances in Oman.[14,32] However, this practice was considered to have a high potential for rapid groundwater contamination.[14]

In Florida, concentrate disposal is largely accomplished through deep injection wells, which are permitted to safely dispose of the industrial wastewater discharged from desalination facilities.[97] In southwest Florida, challenges with naturally occurring radionuclides contributed to the requirement for deep injection wells.[95] In many cases, deep well injection is considered to be the only practical option due to the sensitive environments of many surface waters in that state. Because much of the population lives along the coastline and the optimum injection zone near the coast contains groundwater quality similar to seawater, the concentrate is considered to be a reasonable match. The level of treatment appropriate for the receiving zone and a thorough evaluation of the geology and hydrogeologic system at an injection site is paramount to the safe operation of these systems.[97]

Land Application

In most cases, concentrates cannot be disposed of on land due to the threat they pose to underlying ground waters and the direct impact on the terrestrial environment.[20] An early case-study from India indicated that seepage from brine discharged to an earthen canal resulted in contamination of the desalination source well leading to increased salinity and hardness.[98] Brine discharge to soils can also have serious detrimental effects on soil productivity.[15]

In some areas of the Gaza Strip where sewage systems are not available, it has been reported that brine is disposed of, along with sewage, via shallow drainage channels to poor land from which it either evaporates or infiltrates to groundwater aquifers.[75] Problems with illegal land-dumping of brine were also reported.

A large number of inland brackish water desalination plants were recently surveyed in the UAE.[15] Some of these are mobile and some are stationary; however, all of them discharge brine to land via unlined pits. Sampling at these sites has revealed that discharged brine is commonly contaminating local groundwater.

Evaporation Ponds

Evaporation ponds normally comprise simple, relatively shallow ponds for the evaporation of water from brine. They are particularly suited for the management of concentrate from inland plants in hot, dry areas.

Among the advantages of evaporation ponds are that they are comparatively simple to construct and, in some circumstances, require minimal maintenance or operator attention compared to mechanical systems. Typically, the only required mechanical equipment is a pump to deliver the brine to the pond. As a result, evaporation ponds can be relatively inexpensive to implement in areas with low land acquisition costs.

Limitations to the applicability of evaporation ponds include the need for large areas of land in regions where the evaporation rate is low compared to the concentrate production rate. Furthermore, poorly designed or constructed ponds may risk contamination of underlying aquifers by seepage. In most cases, impervious layers of clay or synthetic membranes are required to prevent loss by seepage. While maintenance needs can be relatively minor, the need for active erosion control, seepage control and wildlife management should be considered in all cases.

Australia has some experience with evaporation ponds from the management and interception of saline groundwaters in the Murray Darling Basin.[22,99] This has involved efforts to lower saline groundwater tables by extracting the water and pumping into evaporation ponds. The Murray-Darling Basin includes more than 180 evaporation ponds, or "basins,"[100] and knowledge gained from these facilities can be expected to be useful in planning for evaporation pond management of membrane concentrates.

The optimum sizing of evaporation ponds will depend on prevailing annual evaporation rates (including the effect of salinity on evaporation rate) and the anticipated brine volumes requiring disposal. The evaporation rate will determine the necessary surface area, while the optimum depth will be dependent on the required surge capacity, water storage, storage capacity for the salts, and necessary freeboard for rainfall and wave action. There are various methods available for the determination or estimation of these parameters.[22]

Impermeable liners are required in most circumstances, and these should be mechanically strong enough to withstand stress during salt cleaning.[22] In some cases, liners can be covered in sands to facilitate salt removal without damage. Alternatively, if no salt is removed from the pond for the first year or two of operation, a hardpan may be developed, helping to seal the base. A hardpan can only develop if the pond is allowed to completely dry out during the hottest periods of the year. In case of leakage, ponds may also be constructed with seepage-collection systems.

The use of hardpan seals may not always be optimum in all circumstances and requires careful management and monitoring. For example, experience with concentrate evaporation ponds at Dalby (QLD) has shown that the hardpan may crack while drying out. In this case, when the evaporation pond was re-filled, the brine leaked from the pond through cracks in the pan. Photographs from an environmental audit conducted by Dalby Town Council show evidence of such cracking (see Figure 4).[101]

One approach that has been promoted incorporates a number of smaller ponds constructed adjacent to one another by a pipeline placed no more than 30 cm above the bed of the ponds.[22] Smaller ponds are easier to manage and minimize wave action in windy conditions, which can damage the levees. The evaporation ponds are laid out as a series of shallow concentrating ponds followed by crystallization ponds.

FIGURE 4. Evaporation ponds at Dalby (QLD) showing evidence of cracking.[101]

A series of underlying principles for evaporative basin use within the Murray Darling Basin (intended for saline groundwater interception) have been proposed.[100] and may, in part, be suitable for adaptation for membrane concentrate management. Approaches for the minimization of costs for evaporative basins, specifically addressing siting, design, and construction factors, have also been previously considered in Australia.[102]

Evaporation ponds are used for brackish water desalination plants in Oman.[14] However, during site visits, many of these showed no evidence of salt build-up, suggesting that poor design or maintenance has lead to leakage from the ponds.

There is some evidence to suggest that industrial evaporation ponds may present a biological hazard to migratory waterfowl and other wildlife through the accumulation of selenium in the food-chain.[103]

ALTERNATIVE CONCENTRATE MANAGEMENT PRACTICES

Beneficial Concentrate Reuse

The identification of beneficial applications for concentrate reuse is highly attractive for a number of reasons. First, reuse applications may have less environmental impact than direct discharge of brines. Second, economically profitable reuse applications may help to offset the costs of water treatment processes. Third, some potential reuse applications may provide necessary input resources for membrane treatment processes such as thermal or electrical energy. Finally, the use of brines as alternative water sources for established practices may, in some cases, free-up more pure water for other uses.

There is no thorough review of the potential productive uses of membrane treatment brines in Australia, but productive uses of saline groundwaters have been given considerable attention. The most detailed of such reviews was produced by The National Dryland Salinity Program (NDSP) in 2001.[104] While the NDSP ceased in 2004, an online database, prepared by the program and called Options for the Productive Use of Salinity (OPUS), remains available.[105] The categories of saline industries identified within the OPUS database include agriculture, forestry and horticulture, fauna and algae, minerals, and energy. Many of the approaches and schemes identified may prove to be highly applicable to membrane treatment brines in Australia, particularly in inland areas.

It should be noted that most of the beneficial uses identified below do not actually eliminate the need to dispose of concentrate. They provide intermediate uses, which may provide opportunities to economically justify more expensive disposal options, but the need for ultimate disposal remains.

Aquaculture

The development of commercial inland saline aquaculture in Australia has been seriously considered and is of some interest to fisheries industry groups.[106,107] A few small-scale research and development or commercial inland saline aquaculture projects currently exist. These include a number of saltwater fish farms growing snapper, barramundi, silver perch, trout, and black bream. Other species include Artemia (brine shrimp), Dunaliella (micro-algae) and the tiger prawn *Penaeus monodon*.[106]

Brines from membrane-based water treatment operations haven't previously been considered as saline water sources for Australian aquaculture.[106,107] Sources of saline water previously considered include ground water interception schemes, natural saline lakes, saline and brackish waters from sedimentary basins and fractured rock aquifers, urban groundwater pumping to protect infrastructure and property from salinity, saline drainage from coal mines, and the proposed Esperance-Kalgoorlie seawater pipeline.

Thirteen criteria have been identified for the preliminary assessment of identified saline water resources for the establishment of hatchery or adult fish production aquaculture. Most, if not all, of these criteria will be applicable to potential schemes involving brines from membrane-based water treatments.[106] They include resource availability, resource salinity, ionic composition, other water quality, availability of freshwater, availability of land, nature of soil, environmental sensitivity, existing structures, availability of labor and commercial services, proximity of power supply, proximity to transport corridors, and opportunities for cost sharing.

A number of research and development areas have been proposed.[107] These include the growth of marine species using shallow aquifers, aquaculture from deep artesian water, winter culture of salmonids using shallow aquifers, artemia from existing facilities, high health prawn hatchery, environmental guidelines for inland saline aquiculture, and research and extension networking.

There are some significant limitations to the potential direct use of brine evaporation ponds for mainstream aquaculture species such as finfish and penaeid prawns.[107] Because evaporation ponds are designed to concentrate and precipitate out salt, the water becomes successively more concentrated as it moves through the ponds, thus requiring species that are able to tolerate considerable salinity variations. Furthermore, large surface areas and shallow depths are not ideal for commercial production or harvesting, and drainage or fallowing of the ponds may adversely affect their evaporative performance. Stocked fish would require the addition of supplementary nutrients, which may impact on water interchange, as well as on downstream activities such as salt production.

However, one particularly promising potential saline aquaculture species appear to be Artemia (brine shrimp).[107] Artemia are euryhaline, but thrive in hypersaline environments. They are generally hardy and easy to grow, with the availability of sufficient appropriate nutrient at appropriate cost likely to be the key limit to production.

Artemia are widely used as a fish-feed, and thus could be harvested for live feeding to adjacent finfish. Alternatively, they can be harvested either as cysts or as live biomass, and processed as appropriate (e.g., dried flakes) for marketing locally and overseas. NSW Fisheries report that there are immediate markets for cysts, Artemia biomass and derived products for the aquarium trade, and other aquaculture.[107] These markets have been expanded by global shortages in Artemia, rapidly expanding demand, and prices that have rapidly increased over recent years.[107] It has been reported that live adult Artemia can reach prices of up to $100/kg.[108] Large fertilized ponds at optimum growing temperatures (19–25°C) provide microalgal populations for Artemia to graze on, reaching adult size within two weeks.[108] The potential Australian and overseas demand for this product has been estimated at 260 tonne/year.[67,68] Countries with existing commercial Artemia enterprises include the United States (California), the Philippines, and Vietnam.[107]

Artemia are effective for cleaning up residual organic waste, and hence may complement adjacent production of conventional species. Other forms of local agriculture may also provide some of the essential nutrients needed for their cultivation.

While Artemia are now found in some Australian salt lakes, they are not naturally endemic to Australia. In contrast, Australia's saline lakes do harbor numerous the native brine shrimp *Parartemia,* which have been ignored until recently.[109] An Australian company, Para Tech International Pty Ltd, located at Jurien Bay in Western Australia, claims to have developed promising technology to deliver a reliable commercial supply of Parartemia. The company is currently raising capital to support the construction of a first full-scale production unit for larger scale grow-out and international sales.

A small-scale experimental groundwater interception scheme has been operational in South Australia since 1997.[108,110] This scheme was designed to develop an aquaculture-based salt interception scheme with pumping costs recovered by revenue generated through the sale of cultured products. Studies have demonstrated that the saline groundwater is suitable for the culture of snapper, black bream, and King George whiting.[110] In addition, prolific growth of Artemia was reported, and the microalga *Dunaliella salina* was cultured producing commercially valuable β-carotene.

Since its upgrade in 2002–2003, the scheme has been known as the "Cooke Plains Inland Saline Aquaculture Research Centre" (CPISARC).[108,111] The aim of the CPISARC was to produce 1.5 tons of fish per annum while sequentially flowing the fish effluent water through Artemia, oyster, and seaweed ponds for sediment and nutrient removal. The bio-mechanically filtered water would then be either reused in the fish ponds or diverted to evaporation pits to produce raw salt. However, the project has been plagued by problems, and the anticipated five-year funding ceased after eighteen months.[108] Many of these problems were managerial (delays in construction of the facility); however, numerous technical problems were also encountered, including insufficient aeration, restricted water flows, blocking of outlet screens, and water quality issues. These technical problems led to very poor seaweed and Artemia production. The results from this project indicate that operating such a scheme is complex and requires further research.

In 2002, NSW Fisheries opened the Inland Saline Aquaculture Research Centre (ISARC) approximately 30 km from Wakool, NSW.[112,113] The ISARC includes five 500 m^2 plastic-lined earthen ponds and a 600 m^2 plastic-lined reservoir pond. A major purpose of the facility is to determine whether a number of marine or salt-tolerant freshwater species can be cultured economically in inland areas. Furthermore, there are several other experimental saline aquaculture projects around Australia, and R&D activities are coordinated by the National Aquaculture Council project funded by the Fisheries Research and Development Corporation. A useful source of further information is the online Australian Aquaculture Portal.[112]

Solar Ponds for Thermal Energy and Electricity Production

Saline ponds can be used to store large amounts of thermal energy from the sun, which may then be used directly for a range of applications or converted to electrical energy. Ponds used in this manner are known as "salinity gradient solar ponds" or, simply "solar ponds."

Solar ponds typically rely on salinity-stabilized stratification. High salt concentrations at the lower levels of the pond impart a higher density than the middle and upper levels of lower salinity. In a well-managed pond, the salinity gradient will be large enough that vertical convection is minimized even when more heat is absorbed in the lower zones.

Water is transparent to visible light but less so to infrared radiation. As a result, energy in the form of sunlight that reaches the lower zones of the pond is absorbed there and can escape only by conduction. Water is a moderately low conductor of thermal energy, so, provided a substantial gradient zone is maintained, heat is effectively trapped in the lower zone.

Studies of a solar pond in El Paso, Texas, show a specific gravity maintained above 1.20 in the bottom 150 cm, gradually decreasing to slightly above 1.00 at a height of 250 cm, from which point it remains stable to the pond surface (height approx 330 cm).[114] This specific gravity gradient maintains a temperature gradient with temperatures above 85°C up to 150 cm and gradually decreasing to around 25°C above 250 cm.

The thermal heat from solar ponds can be used directly for a range of applications such as process heating, space heating and thermal desalination.[114] Alternatively, an organic Rankine cycle engine can be employed to convert the thermal energy to electricity. In this process, the hot water is used to evaporate a low boiling solvent to a high-pressure vaporr, which is subsequently used to drive a turbine.

It has been estimated that solar ponds can produce heat (60–80°C) for a wide range of applications in Australia at an average cost of AU$10 per gigajoule, or two-thirds of the cost of liquid petroleum gas or fuel oil in rural areas.[115]

Solar-pond powered desalination was studied at the El Paso Solar Pond Project, El Paso, Texas from 1987 until funding ceased in 2003.[3,114] Most of the research had focused on the technical feasibility of such a combined system, with a later shift of emphasis to long-term reliability, thermodynamic efficiency improvements, and favorable economics. As a component of this project, a membrane distillation unit and a brine concentration and recovery system have been trialed.

A further significant solar ponds research project has been funded by the Australian Greenhouse Office under the Renewable Energy Commercialisation Program.[115] Project partners include RMIT University, Geo-Eng Australia Pty Ltd., and Pyramid Salt Pty Ltd. For this research, a 3000 square meter solar pond was constructed in northern Victoria. Pyramid Salt intend to use the ponds' heat for commercial salt production as well as for aquaculture producing brine shrimps for stock feed. Electricity production from the stored thermal energy is a planned subsequent stage of research.[115]

The use of solar ponds to power desalination processes on the Virgin Islands (USA) has recently been considered.[116] In this case, wind was determined to be the preferred energy source for the plant with solar ponds considered theoretically viable, but requiring too great an amount of land for the specific intended location.

Irrigation of Salt-Tolerant Plants

Halophytic (salt-loving) and salt-tolerant pasture species have become important productive means of utilizing saline-impacted agricultural lands in Australia.[104] A number of trials have been conducted to study and promote various species, but no single pasture species, or group of species, appears to be ideally suited to all situations. A range of promising crops and a couple of case studies were reviewed by the National Dryland Salinity Program in 2001.[104] However, the aim of the work was primarily to identify means of making productive use of lands already impacted by salinity.

Soil and groundwater salinity are major environmental problems in Australia. It is highly unlikely that proposals that threaten to exacerbate these problems would be approved in any circumstances. Accordingly, any proposals to use desalination brines for irrigation in Australia would certainly require efficient drainage systems to capture the runoff. The drainage water would then require further processing prior to ultimate disposal.

A potential benefit of using brackish water desalination brines for irrigation of salt-tolerant plants is that it may free up higher quality water for other uses. The production of marketable crops may also assist in offsetting desalination treatment costs to some degree.

A property outside Quorn in South Australia has received some recognition for its successful irrigation use of highly saline (4.5 g/L TDS) bore water.[117] Conventionally, salinity limits for viable horticulture are around 1.5 g/L. However, this property produces a variety of crops, including olives, pistachios, grapefruits, quandongs, and Shiraz grapes. It has been suggested that the key to the successful use of such saline water is simply the use of drip irrigation onto a large and thick area of mulch at the base of the plant.[117] Some trees, such as olives, almonds, and pistachios, appear to be doing very well after more than two decades.

Australian researchers have begun examining options for using reclaimed wastewater concentrate (which contains nutrients and essential divalent metals) in combined irrigation/fertilization schemes.[118]

It has been reported that olive and date trees are cultivated with desalination brine irrigation in some areas of Palestine.[75] However, the impact on the soil, groundwater, and trees has not been assessed.

Secondary Oil and Gas Recovery

During the initial stages of recovery of oil and natural gas from reservoirs, the natural pressure of the reservoir, sometimes combined with mechanical pumps, is used to bring the hydrocarbons to the surface. However, only about 10 percent of a reservoir's oil can typically be extracted during this 'primary recovery'. 'Secondary recovery' techniques are used to extend the productive life of hydrocarbon reservoirs, often increasing ultimate recovery to 20 to 40 percent. Secondary recovery involves the injection of an external fluid such as water or gas into the reservoir through injection wells located in rock that has fluid communication with production wells. The purpose of secondary recovery is to maintain reservoir pressure and to displace hydrocarbons toward the wellbore.

Secondary recovery of oil by water injection is used in Australia. For example, at the Windalia reservoir, Barrow Island (Western Australia), water is injected into 268 wells to displace oil toward producing wells.[119]

It has been suggested that membrane concentrate could be used as an injection fluid for secondary hydrocarbon recovery.[3] However, at least in the United States, regulatory hurdles involving the classification of wells have so far prevented the adoption of this application.[3] Issues of compatibility of concentrates and the nature of the hydrocarbon reservoir would also need to be addressed.

Dust Suppression, Roadbed Stabilization, and De-icing

The use of concentrate for applications such as dust suppression, roadbed stabilization, and de-icing has been previously reported.[3] It was suggested that environmental testing of such products may be required, and that blanket or general approval should not be given for brines, which are very often site-specific. Alternatively, each plant's concentrate would require testing and approval.

Transportation of water is energy-intensive and expensive. Therefore, local uses would need to be identified on a case-by-case basis. Furthermore, the applications would need to be long-term to match the life of the water treatment plant and not subject to significant seasonal variations.

It is not considered that these applications would be viable for large volumes of concentrate in the United States,[3] and for similar reasons are unlikely to be of significance in Australia.

Solar Cooling of Greenhouses

A recently proposed application of desalination brine is as a desiccant solution for a greenhouse cooling system.[120] The solar-driven refrigeration system relies on the presence of suitably hygroscopic salts such as magnesium and calcium chloride. In this concept, air would be passed through a desiccant pad, where its humidity is decreased through contact with the desiccant solution, then passed over an evaporator pad, where it is subsequently wetted and cooled. The cooled air would then enter the greenhouse interior. Such a scheme would appear to be capable of using only a very small volume of brine, diluting it somewhat in the process.

Concentrate Volume Reduction (to Zero Liquid Discharge)

Concentrate volume reduction would not be expected to help with discharge methods where the concentrate is eventually mixed with receiving water. In such cases, it would tend to make the concentrate less compatible with the receiving water. On the other hand, volume reduction may be useful prior to some disposal options, such as evaporation ponds or deep well injection, which may benefit from smaller volumes. Accordingly, it is considered that in the absence of options for evaporation ponds or deep well injection, there is usually little gained by minimizing the volume of concentrate unless this is done as part of a zero liquid discharge (ZLD) processing scheme.[3,64]

ZLD means that no liquid wastes leave the boundary of the water treatment plant. ZLD will transfer the challenges of disposal from those for a concentrated liquid solution to those of a solid. The difficulties associated with the disposal (including costs) of mixed solids can also be expected to be significant in most cases and should be carefully considered for all proposals.

Some of the most commonly used commercially available ZLD technologies include thermal brine concentrators, spray dryers, high recovery RO, evaporation ponds, crystallizers, and enhanced evaporation systems.[121] Among the enhanced evaporation systems, there are three main techniques for minimizing energy consumption. These are the so-called *multiple effect arrangement*, *thermal vapor recompression* (TVR), and *mechanical vapor recompression* (MVR). These three techniques may be applied individually or in combination.

The multiple effect arrangement employs numerous heating stages, where the vapor produced in each stage is used as the heating medium of subsequent stages (as opposed to being *lost* to the condenser). A TVR system relies on vapor from a boiling chamber being recompressed to the higher pressure of a heating chamber, so that further energy is added to the vapor. The elevated pressure causes the saturated steam temperature to be raised proportionally, enabling the vapor to be reused for further heating. Steam jet vapor recompressors, which have no moving parts, are used for this purpose. An MVR system is similar in principle to a TVR system, except the vapor is recompressed to a higher pressure by means of a mechanically driven compressor. Advantages of MVRs include reduced energy consumption, rapid evaporation (high throughput), and the availability of relatively simple systems. An MVR evaporator can produce final effluents up to 280 g/L depending on the initial water quality.[121] The limiting factor is typically the onset of sodium sulfate or sodium chloride crystallization.

ZLD has been used at coal-fired power plants in the United States since the mid-1970s.[122] One example is the Texas Independent Energy Guadalupe Power Plant in Marion, Texas. This plant incorporates an MVR evaporator for brine concentration and then a crystallizer. There, 99 percent of the wastewater is recovered as high-quality distillate of 5–10 mg/L TDS.[122] The blowdown from the brine concentrator is then further treated by a steam-driven calandria crystallizer, which, when coupled with a dewatering pressure filter, reduces the waste stream to solids suitable for offsite disposal.

A similar operation is in place for the ZLD treatment of coal mine drainage at Debiensko, Poland.[123] In this scheme, all of the drainage from two mines is treated by two evaporators and a crystallizer, preventing the discharge of 310 tons per day of salt to local surface waters.[123]

Another common mechanism for recovery of saline wastewaters is a falling-film evaporative brine concentrator.[124] These installations are very effective but require large amounts of energy, making them vulnerable to rising energy costs as well as maintenance costs associated with exotic metallurgies. They are also capital-intensive, require a fairly large footprint, and are said to be complex and difficult to operate in a variable plant environment.[124]

An Australian company, Aqua Dyne, Inc., has developed an MVR system called *JetWater*.[125] This system relies on efficient heat exchange between incoming and outgoing water streams. The feedwater is preheated by the condensate leaving the system before being vaporized and mechanically compressed. Steam is then condensed in a falling film heat exchanger at the higher pressure, allowing further use of the latent heat of vaporization to vaporize incoming feedwater. Small volumes of concentrated brine are periodically drawn off for disposal.

In Australia, ZLD would most likely be achieved by RO concentration to close to the technical limit of the process (~70 g/L salinity) followed by some means of evaporation. Evaporation purely by the application of thermal energy is constrained by high costs and evaporation ponds by the need for large amounts of suitable space. Some alternative approaches are described below.

One approach under investigation is wind-aided intensified evaporation. A recently described wind-aided process is based on vertically mounted, continuously wetted evaporation surfaces.[126] On a footprint-to-footprint comparison, trials indicated a 13-fold improvement in evaporation compared to an open evaporation pan. A range of alternative adsorbents for such a process have recently been subjected to initial testing for suitability.[127] Other potential approaches to enhanced evaporation include the use of evaporative basins incorporating optimized design characteristics and the use of waste heat, where available, to accelerate processes.

Product water recovery in an RO system is limited by precipitation of sparingly soluble salts on the feed side of the membrane. Deposition of these inorganic precipitates on the membrane surface results in a loss of membrane performance, and this type of membrane fouling is referred to as scaling. The key troublesome scalants are commonly salts of barium, calcium, and silica. A promising approach to further concentrating RO brines is to remove these scalants by lime softening, followed by a secondary RO treatment of the softened brine.[29,124,128] This approach has been proposed for what is expected to be the world's largest inland desalination plant, in El Paso, Texas. Pilot testing has demonstrated that an initial RO recovery of 85–90 percent can be achieved using a silica polymerization inhibitor and antiscalant, and a further 70 percent of the water can be recovered from the brine following softening.[29] The silica-rich lime sludge produced in this process was found by a local cement manufacturer to be of possible interest as a road-base and embankment material additive.

A cost comparison for a range of brine disposal options for a hypothetical situation in Phoenix, Arizona, has been reported.[121] This assessment indicated that ZLD has the potential to be cost-competitive in some situations, especially when the recovery of otherwise wasted water is considered. The inclusion of high recovery RO was found to dramatically reduce the size of the required subsequent thermal brine concentrator, thus significantly reducing energy costs. Unfortunately, these decreased energy costs were largely replaced by increased costs of chemicals and sludge disposal.

Selective Salt Recovery

Seawater usually contains sixty elements from the periodic table, some of which are very scarce on land and/or are very expensive.[129] In some circumstances, it can be economically viable to target and extract specific salts for extraction. Various products are potentially available from seawater, brackish groundwaters, and reclaimed waters.

The commercial extraction of mineral salts from brines is normally undertaken by solar evaporation and subsequent crystallization. For example, this is an important means of sodium chloride production from the Dead Sea.[130] Furthermore, potassium minerals, iodides, bromides, nitrates, and sulfates can be recovered in some circumstances.[131] Computer-based visualization methods are available to simulate brine evaporation and thus predict or optimize the recovery of specific salts.[132] For salt extraction to be viable on a large scale using solar energy, however, the climatic conditions need to be suitable, and suitable land area is required for evaporation ponds.

The Pyramid Salt Company in northern Victoria employs evaporation ponds to harvest salt from saline groundwater. The products are then sold for a variety of purposes, including stock feed and medical and chemical uses. It was reported that for this scheme, each one-hectare pond cost in the order of $20,000 to construct.[67,68] The ongoing operational costs include labor and equipment for salt harvesting, cleaning, and packaging. Good quality salt can be sold in Australia for between $25 and $250/ton, depending on the purity and composition.[67,68]

An Australian company, Geo-Processors Pty Limited, promoted a process technology termed ROSP, which is the linked operation of reverse osmosis and an integrated process call SAL-PROC™ for selective salt extraction.[133] The SAL-PROC™ process involves multiple evaporation and cooling steps, supplemented by mineral and chemical processing. It has been reported that some insights and details of the ROSP and SAL-PROC™ processes are available in the patents taken out by Geo-Processors.[121] The exact treatment sequence and conditions are not provided, but it is apparent that the key is an intricate understanding of the many potential crystallization processes and how they are affected by parameters such as temperature, pressure, pH, and ionic composition.

Sodium chloride and a range of other chemical products are recoverable by the SAL-PROC™ process, which may be applied to diverse industrial, agricultural and environmental applications.[133]

A desktop analysis has suggested that the products listed in Table 2 could potentially be recovered from brines produced from a number of commercial desalination plants in Oman by SAL-PROC™.[32]

There is scope for these sequential salt precipitation processes to be optimized by geochemical modeling, such as those employed by software applications including Visual Minteq.[134] However, the necessary thermodynamic constants (such as solubility products) are generally unknown for high temperatures. Additionally, corrections must be applied to the thermodynamic constants as a result of ionic strength effects, but most commonly applied ionic strength correction models (such as the Debye-Huckel equation or the simpler Davies equation) are inadequate at the high ionic strengths of interest. Approaches such as the use of Pitzer equations may be required but also involve considerable uncertainty.[135]

Salt recovery is successfully employed at the seawater RO plant in Eilat, Israel.[136] The brine from this 10 ML/day plant is fed to a series of evaporation ponds and thereafter to a slat processing factory for commercial production. It has been reported that in addition to costs saved from discharge facilities, this approach can be a lucrative opportunity under suitable prevailing conditions.[136] These included strong solar radiation, very low precipitation, low-cost desert land, short and easy transport to ports, and relatively good accessibility to Asian nations, which are large consumers of salt.

TABLE 2. Potential products from SAL-PROC™ treatment of brines from some Oman desalination plants.[32]

Product name	Chemical composition	Physical form	Indicative price (AU$ in 2003)	Potential applications/markets
Gypsum–magnesium hydroxide	$CaSO_4{\cdot}2H_2O$ + Mg(OH)2	Fine grain slurry	150/t	• Sodic soil remediation • Fertilizer additive • Drip feed application
Magnesium hydroxide	$Mg(OH)_2$	Fine grain slurry	400/t	• Wastewater treatment • Agriculture • Cattle feedstock additive • Refractories
Sodium chloride	NaCl	Crystalline salt	70/t	• Food processing • Agriculture • Chlor-alkali
Precipitated calcium carbonate	$CaCO_3$	Fine grain, crystalline	300–900/t	• High value paper coating pigment • Filler in plastics paint, ink, and sealant production
Sodium sulfate	Na_2SO_4	Crystalline	170–200/t	• Pulp and paper industries
Calcium chloride	$CaCl_2$	Concentrated solution (35–38%)	220/t	• Road base stabilization • Sodic soil remediation • Dust suppression • Drip feed application

A short list of elements of particular interest for possible extraction was recently published and is reproduced in Table 3.[129] The list was prepared by consideration of current prices, estimated evolution of markets, production costs, occurrence on land, speciation of the element in seawater, concentration in seawater, reactivity, and potential extractability from seawater. The figures in the list relate specifically to a hypothetical SWRO desalination plant at La Skhira (Tunisia). The plant is assumed to produce around 168 ML/day potable water, with a recovery ratio of 40 percent and an availability factor of 91 percent.

A number of approaches were trialed for the effective extraction of the elements presented in Table 3.[129] The most promising of these comprises the initial extraction of phosphorous by precipitation of phosphates using alum. This is followed by an innovative liquid-liquid extraction of caesium using calixarenes. Indium is then recovered by a second liquid-liquid extraction employing organic acids. Finally, the remaining brine is evaporated using

TABLE 3. Valuable elements considered to be potentially extractable from brine produced by a SWRO plant at la Skhira (Tunisia).[129]

Element	Seawater content (mg/L)	Available quantity (t/y)	Major use	Selling price (US$/kg)	Value (M US$/year)
Na	1.05×10^4	1.5×10^6	Fertilizers	0.13	180
Mg	1.35×10^3	1.9×10^5	Alloys	2.8	525
K	3.8×10^2	5.3×10^4	Fertilizers	0.15	8
Rb	1.2×10^{-1}	17	Laser	79,700	1,300
P	7.0×10^{-2}	10	Fertilizers	0.02	0
In	2.0×10^{-2}	3	Metallic protection	300	0.9
Cs	5.0×10^{-4}	0.07	Aeronautics	63,000	4
Ge	7.0×10^{-5}	0.01	Electronics	1,700	0.02

solar ponds, and germanium and magnesium are extracted from the residual crystals. An approach was also postulated for incorporating rubidium extraction into the process. Experimental verification and economic evaluation of the concept is underway.[129]

A promising approach for the beneficial recovery of phosphate from municipal effluent RO concentrates was recently reported.[137] In this process, phosphate is removed using a polymeric ligand exchange resin and recovered through struvite ($MgNH_4PO_4{\cdot}6H_2O$) precipitation, which is directly usable as a slow release fertilizer. In addition to potential economic advantages of phosphorous recovery, the consequential reduction in eutrophication capacity of the remaining concentrate presents an obvious environmental advantage.

Factors That Influence Costs

Factors that influence the costs associated with various approaches to concentrate management are very site-dependent. Furthermore, it is likely that in many cases they will prove also to be time-dependent, as land usage, environmental regulations, technological developments, and energy costs vary over time. Accordingly, it is not possible to provide definitive costs for competing concentrate management or disposal options. Nonetheless, the major factors generally contributing to overall costs for various approaches can be identified.

A comprehensive analysis for major inland disposal practices in the United States has been provided by Mickley & Associates and published by the U.S Department of the Interior, Bureau of Reclamation.[66] The major factors influencing deep well injection costs were identified as the depth of the well and, to a lesser extent, the diameter of the well tubing and casing strings. The minimal cost of a well (of any size) was reasoned to be sufficiently high that such wells are normally only feasible with large concentrate flow rates.

Assuming that irrigation need to be in place and land need not be purchased, the major cost elements for spray irrigation of concentrate include the distribution system material costs, installation costs, and the cost of a sufficiently sized storage tank. Evaporation ponds are land-intensive, and the land usually does need to be purchased for their construction. In general, evaporation ponds were determined to require more land than spray irrigation for a given volume flow. The major capital cost element is commonly the liner material. Zero liquid discharge was reported to not typically be an economical disposal option. The capital costs of the necessary brine concentrator and crystallizer can be significant; however, on an annualized cost basis, the operational energy cost is, by far, the major element leading to excessively high costs.

CONCLUSIONS

The sound management of waste streams from high-pressure membrane-based water treatment is of growing importance in Australia and internationally. Existing approaches are characterized by efforts to dispose of both the water and the dissolved components of concentrates in a manner that is ideally rapid, inexpensive, and protective of the impacted environment. However, the simultaneous achievement of these goals can be difficult, and, in some circumstances, alternative solutions are required.

Seawater desalination concentrates are commonly discharged back into the marine environment, usually via a dedicated ocean outfall and in some cases via a diffuser. The environmental impacts of this process are highly variable depending on the location and the specific design of the outfall. Long-term experience with management and disposal of concentrate from seawater and brackish water desalination plants worldwide over the last 15 years indicates that the impact of these plant discharges on the environment is site-specific and may vary from benign to significant, depending on the size of the plant; the type, salinity tolerance, and abundance of the environmental flora and fauna; and the hydrodynamic conditions of the ocean in the area of discharge. Experience with the implementation of large-scale seawater desalination plants in Australia supports the general observation that when properly engineered and constructed, concentrate discharge to the ocean is environmentally safe. For large seawater desalination projects, the development and use of site-specific models and near-field dispersion monitoring are warranted for improved pre-construction assessment. Furthermore, little is known about salinity variation tolerance of benthic marine organisms in many locations, including Australia. Thus, further site-specific research in this area is required in order to be able to properly assess risks to marine ecosystems.

For brackish groundwater desalination and groundwater softening plants, the key environmental impacts associated with concentrate disposal tend to be related to elevated salinity as well as ion imbalance-related toxicity.

For surface water and wastewater reclamation plants, the elevated content of nutrients and anthropogenic pollutants are further important concerns. There has been limited characterization of waste-streams generated from high-pressure membrane treatment of municipal effluents (water reclamation), and the impact of these concentrates on the environment is not well documented or understood. Therefore, further research associated with the characterization of the waste streams from water reclamation plants is required. Specific research is required for improved understanding of the potential of these waste streams to cause ion imbalance-triggered toxicity to aquatic flora and fauna, as well as toxicity due to elevated concentrations of anthropogenic contaminants.

Many inland schemes do not have feasible access to large saline water bodies for disposal. In such circumstances, the use of evaporation ponds is usually the preferred solution. However, these typically require large areas of land and, in some cases, present risks to underlying aquifers by seepage. Improvements in pond construction or management to achieve an effective seal and avoid cracking would be a welcome advance.

Emerging approaches to concentrate management include their beneficial reuse, which in some circumstances may provide newly recognized value and thus facilitate more expensive ultimate disposal means. Potential beneficial uses include applications in aquaculture, solar ponds for thermal energy and electricity production, irrigation of salt-tolerant plants, secondary oil and gas recovery, dust suppression, roadbed stabilization, deicing, and solar cooling of greenhouses. However many of these applications require highly site-specific requirements to be met, and most are expected to be suitable for only very limited volumes of concentrate. All of these approaches require technical refinement before they can be considered to be readily implementable in a manner that is cost-effective and environmentally sustainable.

In the long term, the only truly sustainable solution may be recovery of most or all of the water and recovery and use of all the salts. Technologies to enable cost-efficient zero liquid discharge are currently being pursued by a number of research and technology-development projects. The most pressing challenge to be overcome is the minimization of energy consumption. Costs associated with zero liquid discharge may be partially offset by the recovery and sale of mineral salts. Innovative treatment and crystallization processes that lead to the selective recovery of a range of relatively pure salts would be significant advances.

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REFERENCES

[1] U.S. Bureau of Reclamation and Sandia National Laboratories. (2003). *Desalination and water purification technology roadmap—a report of the executive committee*. Desalination & Water Purification Research & Development Program Report #95.

[2] Metcalf & Eddy, Inc. (2003). *Wastewater engineering, treatment and reuse*. New York: McGraw-Hill.

[3] Jordahl, J. (2006). *Beneficial and nontraditional uses of concentrate*. Alexandria, Va.: WateReuse Foundation.

[4] Radcliffe, J.C. (2004). *Water recycling in Australia*. Parkville, Victoria, Australia: Australian Academy of Technological Sciences and Engineering, 233 pp.

[5] Falconer, I., McMichael, A., Mikhailovich, K., and Law, I. (2007). *Public health and safety in relation to water purification for drinking water supplies: Advice to the Chief Minister of the ACT and the ACT Government on the health and public safety of the Water2WATER proposal*. Canberra, Australia: Expert Panel on Health appointed by ACT Government.

[6] Ludwig, H. (2004). Hybrid systems in seawater desalination—practical design aspects, present status, and development perspectives. *Desalination,* 164, 1.

[7] Millero, F.J. (2005). *Chemical oceanography*. *Marine Science Series*. Boca Raton, Fla.: CRC.

[8] Hashim, A., and Hajjaj, M. (2005). Impact of desalination plants fluid effluents on the integrity of seawater, with the Arabian Gulf in perspective. *Desalination,* 182, 373.

[9] Nunes, R.A., and Lennon, G.W. (1986). Physical property distributions and seasonal trends in Spencer Gulf, South Australia: an inverse estuary. *Australian Journal of Marine and Freshwater Research,* 37, 39, 1986.

[10] Hu, C., Montgomery, E.T., Schmitt, R.W., and Muller-Karger, F.E. (2004). The dispersal of the Amazon and Orinoco River water in the tropical Atlantic and Caribbean Sea: Observation from space and S-PALACE floats. *Deep Sea Research Part II: Topical Studies in Oceanography,* 51, 1151.

[11] Gaid, A., Bablon, G., Turner, G., Franchet, J., and Christophe Protais, J. (1998). Performance of three years' operation of nanofiltration plants. *Desalination,* 117, 149.

[12] Bergman, R.A. (1996). Cost of membrane softening in Florida. *Journal American Water Works Association,* 88, 32.

[13] Cohen, D., and Conrad, H.M. (1998). 65,000 GPD fluoride removal membrane system in Lakeland, California, USA. *Desalination,* 117, 19.

[14] Ahmed, M., Shayya, W.H., Hoey, D., and Al-Handaly, J. (2001). Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates. *Desalination,* 133, 135.

[15] Mohamed, A.M.O., Maraqa, M., and Al Handhaly, J. (2005). Impact of land disposal of reject brine from desalination plants on soil and groundwater. *Desalination,* 182, 411.

[16] Zularisam, A.W., Ismail, A.F., and Salim, R. (2006). Behaviours of natural organic matter in membrane filtration for surface water treatment—a review. *Desalination,* 194, 211.

[17] Ventresque, C., Gisclon, V., Bablon, G., and Chagneau, G. (2000). An outstanding feat of modern technology: The Mery-sur-Oise nanofiltration treatment plant (340,000 m^3/d). *Desalination,* 131, 1.

[18] Verliefde, A., Cornelissen, E., Amy, G., Van der Bruggen, B., and van Dijk, H. (2007). Priority organic micropollutants in water sources in Flanders and the Netherlands and assessment of removal possibilities with nanofiltration. *Environmental Pollution,* 146, 281.

[19] Yoon, Y., Westerhoff, P., Snyder, S.A., and Wert, E.C. (2006). Nanofiltration and ultrafiltration of endocrine disrupting compounds, pharmaceuticals and personal care products. *Journal of Membrane Science,* 270, 88.

[20] Einav, R., Harussi, K., and Perry, D. (2002). The footprint of the desalination processes on the environment. *Desalination,* 152, 141.

[21] Hoepner, T., and Lattemann, S. (2003). Chemical impacts from seawater desalination plants—a case study of the northern Red Sea. *Desalination,* 152, 133.

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

[23] Crisp, G. (2006). Australia's first big plant thinks "green." *The International Desalination and Water Reuse Quarterly,* 16, 19.

[24] Waddell, D. (2005). *Environmental assessment for the concept plan for Sydney's Desalination Project*. Sydney, Australia: GHD.

[25] Sadhwani, J.J., Veza, J.M., and Santana, C. (2005). Case studies on environmental impact of seawater desalination. *Desalination,* 185, 1.

[26] Van der Bruggen, B., Lejon, L., and Vandecasteele, C. (2003). Reuse, treatment, and discharge of the concentrate of pressure-driven membrane processes. *Environmental Science and Technology,* 37, 3733.

[27] Mauguin, G., and Corsin, P. (2005). Concentrate and other waste disposals from SWRO plants: Characterization and reduction of their environmental impact. *Desalination,* 182, 355.

[28] Bellona, C., Drewes, J.E., Xu, P., and Amy, G. (2004). Factors affecting the rejection of organic solutes during NF/RO treatment—a literature review. *Water Research,* 38, 2795.

[29] Ning, R.Y., Tarquin, A., Trzcinski, M.C., and Patwardhan, G. (2006). Recovery optimization of RO concentrate from desert wells. *Desalination,* 201, 315.

[30] Tanninen, J., Kamppinen, L., and Nystrom, M. (2005). Pretreatment and hybrid processes. In Schaefer, A.I., Fane, A.G., and Waite, T.D., eds. *Nanofiltration principles and applications.* Oxford, UK: Elsivier Ltd., 241.

[31] Perez Talavera, J., and Quesada Ruiz, J. (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.
[32] Ahmed, M., Arakel, A., Hoey, D., Thumarukudy, M.R., Goosen, M.F.A., Al-Haddabi, M., and Al-Belushi, A. (2003). Feasibility of salt production from inland RO desalination plant reject brine: A case study. *Desalination,* 158, 109.
[33] Kleinschmidt, A.C. (2005). *Laboratory services test report*, 170805-2304-1.
[34] Walker, T., Roux, A., and Owens, E. (2007). Western Corridor Recycled Water Project—the largest recycled water scheme in the southern hemisphere. In Khan, S.J., Stuetz, R.M., and Anderson, J.M., eds. *Water reuse and recycling.* Sydney, Australia: UNSW Publishing, 498.
[35] Khan, S.J., Wintgens, T., Sherman, P., Zaricky, J., and Schäfer, A.I. (2004). Removal of hormones and pharmaceuticals in the Advanced Water Recycling Demonstration Plant in Queensland, Australia. *Water Science and Technology,* 50, 15.
[36] Drewes, J.E., Bellona, C., Oedekoven, M., Xu, P., Kim, T.U., and Amy, G. (2005). Rejection of wastewater-derived micropollutants in high-pressure membrane applications leading to indirect potable reuse. *Environmental Progress,* 24, 400.
[37] Hoepner, T. (1999). A procedure for environmental impact assessments (EIA) for seawater desalination plants. *Desalination,* 124, 1.
[38] Rhodes, M. (2006). Marine management is high priority. *The International Desalination and Water Reuse Quarterly,* 16, 30.
[39] Höpner, T., and Windelberg, J. (1996). Elements of environmental impact studies on coastal desalination plants. *Desalination,* 108, 11.
[40] von Medeazza, G.L.M. (2005). “Direct” and socially-induced environmental impacts of desalination. *Desalination,* 185, 57.
[41] Fernandez-Torquemada, Y., Sanchez-Lizaso, J.L., and Gonzalez-Correa, J.M. (2005). Preliminary results of the monitoring of the brine discharge produced by the SWRO desalination plant of Alicante (SE Spain). *Desalination,* 182, 395.
[42] Latorre, M. (2005). Environmental impact of brine disposal on Posidonia seagrasses. *Desalination,* 182, 517.
[43] Raventos, N., Macpherson, E., and Garcia-Rubies, A. (2006). Effect of brine discharge from a desalination plant on macrobenthic communities in the NW Mediterranean. *Marine Environmental Research,* 62, 1.
[44] Abdul-Wahab, S.A. (2007). Characterization of water discharges from two thermal power/desalination plants in Oman. *Environmental Engineering Science,* 24, 321.
[45] Whitfield, A.K., Taylor, R.H., Fox, C., and Cyrus, D.P. (2006). Fishes and salinities in the St Lucia estuarine system—a review. *Reviews in Fish Biology and Fisheries,* 16, 1.
[46] Walker, D.I. (1985). Correlations between salinity and growth of the seagrass *Amphibolis antarctica* (Labill.) Sonder ex Aschers. in Shark Bay, Western Australia, using a new method of measuring production rate. *Aquatic Botany,* 23, 13.
[47] Walker, D.I., Kendrick, G.A., and McComb, A.J. (1988). The distribution of seagrasses in Shark Bay, Western Australia, with notes on their ecology. *Aquatic Botany,* 30, 305.

[48] Walker, D.I., and McComb, A.J. (1990). Salinity response of the seagrass *Amphibolis antarctica* (Labill.) Sonder ex Aschers.: An experimental validation of field results. *Aquatic Botany,* 36, 359.
[49] D. A. Lord & Associates Pty Ltd. (2005). *Ecological assessment of the effects of discharge of seawater concentrate from the Perth seawater desalination plant on Cockburn Sound*. Report No. 05/028/1.
[50] van Senden, D., and Miller, B.M. (2005). *Stratification and dissolved oxygen issues in Cockburn Sound pertaining to discharge of brine from desalination*. Technical Report 2005/03. Manly Vale, NSW: The University of New South Wales, Water Research Laboratory.
[51] Rose, A.L., Salmon, T.P., Lukondeh, T., Neilan, B.A., and Waite, T.D. (2005). Use of superoxide as an electron shuttle for iron acquisition by the marine cyanobacterium *Lyngbya majuscula*. *Environmental Science and Technology,* 39, 3708.
[52] The Ecology Lab. (2005). *Planning for desalination: Marine ecological assessment*. 340405 F, Sydney, Australia.
[53] Oceanica Consulting. (2007). *Perth metropolitan desalination plant—Cockburn sound benthic macrofauna community and sediment habitat: Comprehensive baseline survey. Report to Water Corporation, Oceanica*. Report 500.
[54] Hammond, M., Blake, N., Hallock-Muller, P., Luther, M., Tomasko, D., and Vargo, G. (1998). *Effects of disposal of seawater desalination discharges on Near Shore Benthic Communities*. Report of Southwest Florida Water Management District and University of South Florida.
[55] Voutchkov, N. (2007). Assessing salinity tolerance of aquatic life to desalination plant discharges. *Asian Water,* 23, 13.
[56] Davis, J.R., and Koop, K. (2006). Eutrophication in Australian rivers, reservoirs and estuaries—a southern hemisphere perspective on the science and its implications. *Hydrobiologia,* 559, 23.
[57] Clunie, P., Ryan, T., James, K., and Cant, B. (2002). *Implications for rivers from salinity hazards: Scoping study*. Report produced for Murray-Darling Basin Commission, Strategic Investigations and Riverine Program, Project R2003. Victoria, Australia: State Government of Victoria, Department of Natural Resources and Environment.
[58] Hart, B.T., Bailey, P., Edwards, R.H., K., James, K., McMahon, A., Meredith, C. and Swadling, K. (1991). A review of salt sensitivity of the Australian freshwater biota. *Hydrobiologia,* 210, 105.
[59] Bailey, P.C., and James, K.R. (2000). *Riverine and wetland salinity impacts—assessment of R&D needs*. Occassional paper 25/99. Land and Water Resources Research and Development Corporation. Braddon, ACT, Australia.
[60] Ayers, R.S., and Westcot, D.W. *Water quality for agriculture*. (1985). FAO Irrigation and Drainage Paper 29, Rev. 1. Rome, Italy Food and Agriculture Organization of the United Nations.
[61] Gorenflo, A., Brusilovsky, M., Faigon, M., and Liberman, B. (2007). High pH operation in seawater reverse osmosis permeate: First results from the world's largest SWRO plant in Ashkelon. *Desalination,* 203, 82.

[62] Redondo, J., Busch, M., and De Witte, J.-P. (2003). Boron removal from seawater using FILMTEC™ high rejection SWRO membranes. *Desalination,* 156, 229.
[63] Sposito, G. (1989). *The chemistry of soils*. New York: Oxford University Press.
[64] Mickley, M.C. (2004). Review of concentrate management options. In Arroyo, J.A., ed. *The future of desalination in Texas, volume 2: Biennial Report on Seawater Desalination*. Austin, Tex.: Texas Water Development Board, 173.
[65] U.S. Department of the Interior. Bureau of Reclamation BUREC Database Download Page. Available at: http://www.usbr.gov/pmts/water/media/burec.html (accessed May 22, 2007).
[66] Mickley, M.C. (2006). *Membrane concentrate disposal: Practices and regulation.* 2nd ed. Desalination and Water Purification Research and Development Program Report No. 123.
[67] Agriculture Fisheries & Forestry, Australia. (2002). *Economic and technical assessment of desalination technologies in Australia, with particular reference to National Action Plan Priority regions*. Canberra, ACT, Australia.
[68] Agriculture Fisheries & Forestry, Australia. (2002). *Introduction to desalination technologies in Australia*. Canberra, ACT, Australia.
[69] National Water Quality Management Strategy. (2000). Australian and New Zealand guidelines for fresh and marine water quality. Paper number 4.
[70] Roberts, P.J.W., Ferrier, A., and Daviero, G. (1997). Mixing in inclined dense jets. *Journal of Hydraulic Engineering,* 123, 693.
[71] National Water Quality Management Strategy. (2000). *Australian and New Zealand guidelines for fresh and marine water quality, volume 2: Aquatic ecosystems—rationale and background information*. Appendix 1: Mixing zones adjacent to effluent outfalls. Commonwealth of Australia, Canberra, ACT, Australia.
[72] Voutchkov, N. (2005). Alternatives for ocean discharge of seawater desalination plant concentrate. *20th Annual WateReuse Symposium: Water Reuse & Desalination: Mile High Opportunities*. WateReuse Association, September 18–21, Denver, Colorado.
[73] Purnama, A., and Al-Barwani, H.H. (2004). Some criteria to minimize the impact of brine discharge into the sea. *Desalination,* 171, 167.
[74] Purnama, A., Al-Barwani, H.H., and Al-Lawatia, M. (2003). Modeling dispersion of brine waste discharges from a coastal desalination plant. *Desalination,* 155, 41.
[75] Al-Agha, M.R., and Mortaja, R.S. (2005). Desalination in the Gaza Strip: Drinking water supply and environmental impact. *Desalination,* 173, 157.
[76] Baalousha, H. (2006). Desalination status in the Gaza Strip and its environmental impact. *Desalination,* 196, 1.
[77] Miller, B.M. *Desalination Planning Study: Ocean modelling report*. (2005). Sydney, Australia: The University of New South Wales, Water Research Laboratory.
[78] Purnama, A., and Al-Barwani, H.H. (2006). Spreading of brine waste discharges into the Gulf of Oman. *Desalination,* 195, 26.
[79] Crisp, G. (2007). Desalination—the focus of Australia's current membrane interest. *AWA Membranes Specialty Conference II*. Melbourne, Victoria: Australian Water Association.

[80] Pattiaratchi, C. (2005). A pilot field measurement program to define dissolved oxygen dynamics in Cockburn Sound. WP 2096 CP. Nedlands, WA: Centre for Water Research, University of Western Australia.

[81] Strategen. (2004). *Metropolitan Desalination Proposal—Section 46 Review*. Prepared for Water Corporation.

[82] Government of Western Australia, Department of Environment and Conservation. Licence for Prescribed Premises—Perth Seawater Desalination Plant. Licence Number 8108/1, Perth, Western Australia.

[83] Okely, P.N., Antenucci, J.P., and Imberger, J. (2007). *Field investigation of the impact of the Perth Seawater Desalination Plant discharge on Cockburn Sound during summer*. Perth, Australia: Centre for Water Research, University of Western Australia.

[84] Water Corporation. (2006). Photographs taken by the West Australian Newspaper. Provided courtesy of Water Corporation, Perth, WA.

[85] Sinclair Knight Merz. (2005, July). *Gosford Wyong Water Supply Desalination Scheme—Statement of Environmental Effects*. St. Leonards, NSW, Australia.

[86] Ingleton, T.C., and Large, D.G.B. (2004). NSW ocean outfalls: Using near field models to investigate hydrodynamic performance. *Australian Journal of Water Resources,* 8, 45.

[87] Bay, S., and Greenstein, D. (1994). Southern California Coastal Water Research Project. Annual Report 1992–93: Toxic effects of elevated salinity and desalination waste brine. Westminster, Calif.: SCCWRP, 149.

[88] Callahan, N.V., and Herd, K.R. (2005). Tampa Bay Seawater Desalination Project. *20th Annual WateReuse Symposium, 'Water Reuse & Desalination: Mile High Opportunities'*. WateReuse Association, September 18–21, Denver, Colorado.

[89] Alspach, B. (2005). Factors driving the increasingly favorable economics of seawater desalination in America. *20th Annual WateReuse Symposium, 'Water Reuse & Desalination: Mile High Opportunities'*. WateReuse Association, September 18–21, Denver, Colorado.

[90] Einav, R., and Lokiec, F. (2003). Enviromnental aspects of a desalination plant in Ashkelon. *Desalination,* 156, 79.

[91] Campbell, R.L., and Jones, A.T. (2005). Appropriate disposal of effluent from coastal desalination facilities. *Desalination,* 182, 365.

[92] Voutchkov, N. (2006). Plans for seawater desalination in California. *Water,* 33, 66.

[93] Jordan, B.L., Veerapaneni, V., and Wang, S. (2005). Surf's up dude! Learning from the new wave of desalination plants on the West Coast. *20th Annual WateReuse Symposium, 'Water Reuse & Desalination: Mile High Opportunities'*. WateReuse Association, September 18–21, Denver, Colorado.

[94] Malfeito, J.J., Diaz-Caneja, J., Farinas, M., Fernandez-Torrequemada, Y., Gonzalez-Correa, J.M., Carratala-Gimenez, A., and Sanchez-Lizaso, J.L. (2005). Brine discharge from the Javea desalination plant. *Desalination,* 185, 87.

[95] Mickley, M.C. (2001). Membrane concentrate disposal: Practices and Regulation—Final Report. Desalination and Water Purification Research and Development Program Report No. 69. US Department of the Interior, Bureau of Reclamation, Technical Services Center. Water Treatment Engineering and Research Group. Prepared by Mickley & Associates, Boulder, Colorado.

[96] Sydney Water Corporation. (2007). *Western Sydney Recycled Water Initiative Replacement Flows Project Environmental Assessment*. Sydney, Australia: Sydney Water Corporation.
[97] McNeal, M.B., and Elarde, J.R. (2005). Converting domestic wastewater injection wells to concentrate disposal wells while increasing beneficial use of reclaimed water through ASR. *20th Annual WateReuse Symposium, 'Water Reuse & Desalination: Mile High Opportunities'*. WateReuse Association, September 18–21, Denver, Colorado.
[98] Rao, N.S., Rao, T.N.V.V., Rao, G.B., and Gopala Rao, K.V. (1990). Impact of reject water from the desalination plant on ground water quality. *Desalination,* 78, 429.
[99] Walker, G., Christen, E., Jolly, I., and Leaney, F. (2000). On-farm and community scale salt disposal basins on the Riverine plain. Managing disposal basins for salt storage within irrigation areas: Final report—project 17034. Technical report 00/18. CSIRO Land and Water, Black Mountain, ACT, Australia.
[100] Christen, E., Jolly, I., Leaney, F., Narayan, K., and Walker, G. (2000). On-farm and community scale salt disposal basins on the Riverine plain: Underlying principles for basin use. Technical report 26/99. CSIRO Land and Water, Black Mountain, ACT, Australia.
[101] Dalby town council. (2005). Environmental audit, 19 July 2005.
[102] Singh, J., and Christen, E.W. (1999). Minimising the cost of evaporation basins: Siting, design and construction factors. Technical report 12/99. CSIRO Land and Water, Black Mountain, ACT, Australia.
[103] Tanner, R., Glenn, E.P., and Moore, D. (1999). Food chain organisms in hypersaline, industrial evaporation ponds. *Water Environment Research,* 71, 494.
[104] National Dryland Salinity Program. (2001). Options for the productive use of salinity (OPUS), 27L067A-01-0915-00.
[105] National Dryland Salinity Program. Options for the Productive Use of Salinity (OPUS). Available at: http://www.ndsp.gov.au/opus/menu.htm (accessed May 22, 2007).
[106] Allan, G.L., Banens, B., and Fielder, S. (2001). *Developing commercial inland saline aquaculture in Australia, part 2: Resource inventory and assessment.* Fisheries Research & Development Corporation, Deakin, ACT, Australia.
[107] Allan, G.L., Dignam, A., and Fielder, S. (2001). *Developing commercial inland saline aquaculture in Australia, part 1: R&D Plan*. Fisheries Research & Development Corporation, Deakin, ACT, Australia.
[108] Flowers, T.J., and Hutchinson, W.G. (2004). Productive uses for saline groundwater using semi-intensive integrated aquaculture. Centre for Natural Resources Management project no. 2002/016 final report.
[109] Geddes, M.C. (1981). The brine shrimps Artemia and Parartemia—comparative physiology and distribution in Australia. *Hydrobiologia,* 81–2, 169.
[110] Flowers, T., and Hutchinson, W. (2002). Bedford groundwater interception scheme. 8th National Conference and Workshop on the Productive Use and Rehabilitation of Saline Lands (PUR$L), Freemantle, Western Australia.
[111] Flowers, T.J., and Hutchinson, W.G. (2004). Preliminary studies towards the development of an aquaculture system to exploit saline groundwater from salt

interception schemes in the Murray Darling Basin. Centre for Natural Resource Management Project No. 2002/015 final report. West Beach, South Australia, Australia.
[112] Australian Aquaculture Portal. (2006). The aquacultre industry—inland saline. Available at: http://www.australian-aquacultureportal.com/saline/facilities.html (accessed 23 January 2006).
[113] Davidson, S. (2005). A fish farming salinity solution. *Ecos*, 25, 33.
[114] Lu, H., Walton, J.C., and Swift, A.H.P. (2001). Desalination coupled with salinity-gradient solar ponds. *Desalination,* 136, 13.
[115] Australian Greenhouse Office. (2003). Renewable energy commercialisation in Australia. Canberra, ACT, Australia.
[116] Miilu, M. (2003). *Desalination and its potential for harnessing brine and solar energy in the U.S. Virgin Islands*. Cambridge, Mass.: Massachusetts Institute of Technology.
[117] Landline—Australian Broadcasting Corporation Salt Gardner. Available at: http://www.abc.net.au/landline/ll030598.htm (accessed 3 May, 1998).
[118] Leslie, G., Stevens, D., and Wilson, S. (2005). Designer reclaimed water. *Water,* 32, 75.
[119] Government of Western Australia—Department of Industry and Resources. (2005). *Western Australian Oil and Gas Review 2005*, Perth, Western Australia.
[120] Davies, P.A., and Knowles, P.R. (2006). Seawater bitterns as a source of liquid desiccant for use in solar-cooled greenhouses. *Desalination,* 196, 266.
[121] Mickley, M.C. (2005). *Membrane concentrate management—state of the science paper*. Joint Water Reuse and Desalination Task Force. Boulder, Colorado, USA.
[122] Ciszewski, D. (2004). Integrated approach to water/wastewater treatment at zero liquid discharge. Combined cycle power plants. TP-505 E-US 1204. Watertown, Mass.: Ionics Incorporated.
[123] Sikora, J., and Szyndler, K. (2004). Desalination plant at Debiensko, Poland: Mine drainage treatment for zero liquid discharge. TP-517 EUS 1204. Watertown, Mass.: Ionics Incorporated.
[124] Madole, J., and Peterson, J. (2005). Concentrate management using lime softening and vibratory microfiltration. *20th Annual WateReuse Symposium, 'Water Reuse & Desalination: Mile High Opportunities'*. WateReuse Association, September 18–21, Denver, Colorado.
[125] Aqua Dyne—Water Purification Specialists. Web site. Available at: http://www.aquadyne.com.au (accessed May 22, 2007).
[126] Gilron, J., Folkman, Y., Savliev, R., Waisman, M., and Kedem, O. (2003). WAIV—Wind aided intensified evaporation for reduction of desalination brine volume. *Desalination,* 158, 205.
[127] Arnal, J.M., Sancho, M., Iborra, I., Gozalvez, J.M., Santafe, A., and Lora, J. (2005). Concentration of brines from RO desalination plants by natural evaporation. *Desalination,* 182, 435.
[128] Bond, R., Veerapaneni, V., Edwards-Brandt, J., and Burns, N. In *Update on AWWARF/CEC Research Project: Zero liquid discharge for inland desalination*, 20th Annual WateReuse Symposium 'Water Reuse & Desalination: Mile High Opportunities', Denver, Colorado, Sep 18-21, 2005; WateReuse Association: Denver, Colorado, 2005.

[129] Le Dirach, J., Nisan, S. and Poletiko, C. (2005). Extraction of strategic materials from the concentrated brine rejected by integrated nuclear desalination systems. *Desalination,* 182, 449.

[130] Abu-Khader, M.M. (2006). Viable engineering options to enhance the NaCl quality from the Dead Sea in Jordan. *Journal of Cleaner Production,* 14, 80.

[131] KilIc, O. and KilIc, A.M. (2005). Recovery of salt co-products during the salt production from brine. *Desalination,* 186, 11.

[132] Hammi, H., Musso, J., M'Nif, A., and Rokbani, R. (2004). Crystallization path of natural brine evaporation using the DPAO method. *Desalination,* 166, 205.

[133] Geo-Processors Pty Ltd. Web site. Available at: http://www.geo-processors.com.au (accessed May 22, 2007).

[134] KTH Department of Land and Water. Resources Engineering Visual MINTEQ, version 2.40. Available at: http://www.lwr.kth.se/English/OurSoftware/vminteq (accessed May 22, 2007).

[135] Pitzer, K.S. (1984). A consideration of Pitzer equations for activity and osmotic coefficients in mixed electrolytes. *Journal of the Chemical Society—Faraday Transactions I,* 80, 3451.

[136] Ravizky, A., and Nadav, N. (2007). Salt production by the evaporation of SWRO brine in Eilat: A success story. *Desalination,* 205, 374.

[137] Kumar, M., Badruzzaman, M., Adham, S., and Oppenheimer, J. (2007). Beneficial phosphate recovery from reverse osmosis (RO) concentrate of an integrated membrane system using polymeric ligand exchanger (PLE). *Water Research,* 41, 2211.