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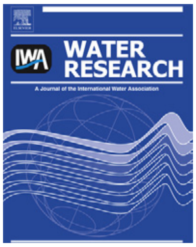

Review

Impacts of desalination plant discharges on the marine environment: A critical review of published studies

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ABSTRACT

Desalination of seawater is an increasingly common means by which nations satisfy demand for water. Desalination has a long history in the Middle East and Mediterranean, but expanding capacities can be found in the United States, Europe and Australia. There is therefore increasing global interest in understanding the environmental impacts of desalination plants and their discharges on the marine environment. Here we review environmental, ecological and toxicological research in this arena including monitoring and assessment of water quality and ecological attributes in receiving environments. The greatest environmental and ecological impacts have occurred around older multi-stage flash (MSF) plants discharging to water bodies with little flushing. These discharge scenarios can lead to substantial increases in salinity and temperature, and the accumulation of metals, hydrocarbons and toxic anti-fouling compounds in receiving waters. Experiments in the field and laboratory clearly demonstrate the potential for acute and chronic toxicity, and small-scale alterations to community structure following exposures to environmentally realistic concentrations of desalination brines. A clear consensus across many of the reviewed articles is that discharge site selection is the primary factor that determines the extent of ecological impacts of desalination plants. Ecological monitoring studies have found variable effects ranging from no significant impacts to benthic communities, through to widespread alterations to community structure in seagrass, coral reef and soft-sediment ecosystems when discharges are released to poorly flushed environments. In most other cases environmental effects appear to be limited to within 10 s of meters of outfalls. It must be noted that a large proportion of the published work is descriptive and provides little quantitative data that we could assess independently. Many of the monitoring studies lacked sufficient detail with respect to study design and statistical analyses, making conclusive interpretation of results difficult. It is clear that greater clarity and improved methodologies are required in the assessment of the ecological impacts of desalination plants. It is imperative to employ Before–After, Control-Impact monitoring designs with adequate replication, and multiple independent reference locations to assess potential impacts adequately.

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Contents

1. Introduction

Global population growth and increasing consumption continue to place ever-increasing pressure upon natural resources. One resource under particularly intense pressure and especially vulnerable to the effects of climate change is the supply of potable domestic water. As a result many nations are turning to the desalination of seawater to complement other sources of water supply.

Recent estimates suggest that up to 25 million m^3 of desalinated water is produced daily around the world (Lattemann and Höpner, 2008). Nations in the Middle East were the first to adopt and depend upon large-scale desalination (particularly the United Arab Emirates, Kuwait and Saudi Arabia) due to the limited sources of potable water in these arid areas and the availability of cheap energy. Presently, almost half of the world's desalinated water is produced in this region (Lattemann and Höpner, 2008). Many factors are contributing to the expansion of desalination capacities in new regions of the globe. Rapid population growth, anticipated changes to precipitation patterns brought by climate change, and technological improvements in energy requirements have meant that many nations with marginal water supplies are also turning to desalination as an additional source of potable water. Expanding desalination capacities can be found in the United States, Europe, China and Australia (Lattemann and Höpner, 2008; Tulharam and Ilahee, 2007). In California alone, it has been projected that up to 20 new desalination projects with a combined capacity of 2 million m^3/d of desalinated water will be constructed by 2030 (Lattemann and Höpner, 2008). Similarly, major desalination projects are underway in multiple Australian cities including Sydney, the Gold Coast region of Queensland, Melbourne, Adelaide and Perth (Cannesson et al., 2009; Christie and Bonnelye, 2009; Port et al., 2009; Trousdale and Henderson, 2009). Thus, it is clear that desalination has become a globally important method for delivering potable water to large cities and industry.

Desalination plants extract large volumes of seawater and discharge hypersaline brine back into the marine environment. The urgent need for water in many parts of the world has meant that historically, marine environmental issues associated with desalination have been considered secondary concerns (Safrai and Zask, 2008). Despite this, it is widely suggested that desalination plants have strong potential to detrimentally impact both physicochemical and ecological attributes of receiving marine environments (Winters et al., 1979; Miri and Chouikhi, 2005; Maugin and Corsin, 2005). Considering the widespread use of desalination it is essential to review and synthesize research that has examined the environmental and ecological effects of desalination plants on marine ecosystems. The focal point for concern has been the potential impact of hypersaline discharges (hereafter referred to as 'brine') upon the salinity of seawater, and resultant effects to marine communities around discharge outlets. However, concern also exists regarding the use and release of toxic antifoulants and anti-scalants to maintain plant infrastructure (Ketsetzi et al., 2008) and possible thermal stress associated with the release of heated effluent from some systems (Bath et al., 2004; Morton et al., 1996). Whilst studies have identified several potential mechanisms by which desalination plants may impact upon marine ecosystems (Lattemann and Höpner, 2008; Sadhwani et al., 2005; Tsiourtis, 2001a) many of the published review articles and case studies cite little or no peer-reviewed literature, and present little or no empirical data to support statements regarding the environmental effects of desalination (Areiqat and Mohamed, 2005; Baalousha, 2006; Mabrook, 1994). Hence, it is unclear whether the potential impacts of desalination plants are assumed or have been determined through rigorous ecological research.

We have conducted a systematic literature review of peer-reviewed publications to critically examine evidence of environmental effects from the discharge of effluents from desalination plants. We consider the effects of plant discharges upon the physicochemical and ecological attributes of recipient marine ecosystems. This review summarises information obtained from laboratory and field-based experiments, and ecological monitoring studies.

2. Methods

We took a systematic approach to the literature review using several search terms in all possible combinations to identify scientific literature related to environmental impacts of desalination plants. Search terms were: 'desal*', 'brine', 'enviro*', 'ecol*' and 'marine'. Three databases were searched: ScienceDirect® (1994 to present, some journals also have backfile indexing), Web of Science® (with some journals indexed from, 1900 to present) and Biological Abstracts® (1969–2004). Abstracts of all the search results were read and papers that were concerned with desalination plant impacts on any aspect of the marine environment were included in the review. The reference lists of selected articles were also searched to incorporate articles not indexed in the three databases or works published prior to the range indexed in the three databases. From each article, we recorded the journal title, aspect of marine environment studied (e.g. salinity, organism abundance, diversity) and research approach utilised (e.g. monitoring, laboratory experiment, field experiment). We also recorded the capacity of the plant (in terms of plant discharge per day), the salinity and temperature of the plants effluent and any observed ecological or toxicological effects when this information was presented.

3. Results and discussion

The literature searches identified 62 research articles that were published in peer-reviewed journals and were concerned with the environmental and/or ecological effects of desalination plant discharges in receiving marine waters. Monitoring studies were the most common type of empirical research, comprising approximately one third of all articles identified. Of the remaining articles, 16% presented the results of modelling studies that were almost universally concerned with modelling brine plumes in receiving waters. Laboratory-based experiments and toxicity tests were relatively rare, comprising 8% of all research articles. Only three papers were identified that included manipulative ecological field experiments. By far the largest category was review, discussion and opinion pieces that comprised 43.5% of reviewed articles. While these types of articles were relatively common, the majority included little quantitative data and tended to discuss potential effects qualitatively or inductively.

3.1. *Physicochemical impacts of desalination plant discharges*

The vast majority of environmental research into the impacts of desalination plants has focused upon the influence of brines upon physicochemical attributes of receiving environments. In particular, research has focused on the impact of desalination discharges on salinity and temperature around outfalls, and the introduction of contaminants.

3.1.1. *Salinity*

The focus of much desalination research has been on the intensity and extent of brine plumes in receiving waters. Published research reveals variable effects of desalination plants on the salinity of receiving waters (Table 1). Observed effects range widely from plumes with elevated salinities extending over tens of meters (Gacia et al., 2007; Raventos et al., 2006; Sadhwani et al., 2005; Talavera and Ruiz, 2001), hundreds of meters (Abdul-Wahab, 2007; Chesher, 1971; Einav et al., 2002; Malfeito et al., 2005; Ruso et al., 2007), or in extreme cases, several kilometres (Fernández-Torquemeda et al., 2005) from desalination plant outfalls. The variation of these findings is likely due to a combination of the differing capacity of the plants, the diffuser designs, the hydrology of the environment (Höpner and Windelberg, 1996; Einav et al., 2002) and the sampling effort within the studies themselves (i.e. their power to detect changes which is dependent on the amount of sampling and sampling design).

In the majority of cases, however, the intensity of the plume appears to diminish rapidly and is usually no greater than 2 parts per thousand (ppt) above the background salinity within 20 m of the outlet (Table 1). Plumes that extended over hundreds of meters tended to be only slightly greater than background levels; usually less than 0.5 ppt at most (Table 1). It should be noted that most of these studies relate to desalination plants that discharge into shallow low-energy environments in the Mediterranean Sea (Table 1). As brine discharges are often denser than seawater of natural salinities, plumes tend to extend further along the seafloor than at the surface (Chesher, 1971; Cintrón et al., 1970; Gacia et al., 2007; Purnama et al., 2005). This is of biological importance and potentially contributes to greater exposure of benthic organisms to brine discharges, than pelagic and planktonic organisms. For example, brine discharges to seagrass meadows may be more apparent when porewaters are analysed, rather than overlying waters (Gacia et al., 2007) and organisms inhabiting depressions in hard and soft substrata may be differentially exposed. Seagrass have been exposed to vertically stratified salinities (exposing either the entire plant, or only the basal leaves) under laboratory conditions to simulate this brine exposure scenario (Sánchez-Lizaso et al., 2008). Results showed significant effects to seagrass survival regardless of exposure method.

Mathematical models have been employed to predict the extent and intensity of brine discharge plumes in receiving waters and in the optimisation of outfall design. In areas of prevailing currents, models suggest that those currents tend to carry brine plumes further alongshore, than offshore (Shao and Law, 2009). The consequence is that the coastal fringe is likely to be the most susceptible to deleterious effects of desalination brines. Some models suggest that increases in salinity may vary around discharges over tidal cycles, with the greatest impacts seen on incoming tides, which act to concentrate brine around outfalls (Purnama and Al-Barwani, 2006). Thus, exposures to brines are likely to be both spatially and temporally variable in

Table 1 – Extent and intensity of brine plumes in receiving waters surrounding desalination plant discharge outlets.

Reference	Capacity (ML/d)	Discharge (ML/d)	Salinity of brine (ppt)	Location	Habitat	Plume extension and intensity
Abdul-Wahab, 2007	92.4	NR	37.3	Muscat, Oman	Soft sediments	Returned to background levels within approximately 100 m of outlet
Abdul-Wahab, 2007	191	NR	40.11	Muscat, Oman	Soft sediments	Appeared to return to background levels 980 m from outlet
Altayaran and Madany, 1992	106	288	51	Sitra Island, Bahrain	Soft sediments	Salinity of receiving water reach 51 ppt, relative to reference areas of 45 ppt, plume extended at least 160 m from discharge. Temperature also affected, discharged at 10–15° C above ambient, receiving water up to 7° C above ambient
Chesher, 1971	9.1	22	40–55	Florida, USA	Artificial hard substrata and soft sediments	0.5 ppt above background levels within 10–20 m of outlet. Nevertheless, slight elevation was maintained for 600 m within the harbour basin
Talavera and Ruiz, 2001	25	17	75.2	Canary Islands, Spain	Sub-tidal rocky reef	2 ppt above background on the seabed and 1 ppt on the surface within the 20 m of the outlet; similar to background levels at 100 m.
Einav et al., 2002	NR	NR	NR	Dhkelia, Cyprus	NR	Above background 100–200 m from outlet, occasionally as high as 60 ppt.
Fernández-Torquemeda et al., 2005	50	75	68	Alicante, Spain	Seagrass and soft sediments	0.5 ppt above ambient for up to 4 km from outlet along the seafloor
Malfeito et al., 2005	28	NR	44	Javea, Spain	Seagrass and soft sediments	Slightly above background up to 300 m from the outlet
Raventos et al., 2006	60	33	60[a]	Blanes, Spain	Seagrass and soft sediments	At background levels within 10 m of outlet. No apparent measurement or analysis of salinity
Ruso et al., 2007	50	65	68	Alicante, Spain	Soft sediments	2.6 ppt above ambient within 300 m[b] of outlet; 1 ppt within 600 m[b]; similar to background at 1300 m[b]
Safrai and Zask, 2008	274	600	42	Ashkelon, Israel	NR	Approximately 2 ppt above ambient within 400 m of outlet, <1 ppt above ambient within 4000 m of the outlet
Sadhwani et al., 2005	25	NR	75	Canary Islands, Spain	Soft sediments	75 ppt effluent diluted to 38 ppt within 20 m of outlet, no details given as to background salinity
Gacia et al., 2007	NR	2	60	Formentera, Balearic Islands, Spain	Seagrass and soft sediments	5.5 ppt above background 10 m from outlet; 2.5 ppt at 20 m; 1 ppt at 30 m; not measured any further than this

NR = not reported. [a] - g/L, [b] Inferred from figure, estimate only.

recipient systems with intensity of exposure varying over spatial scales of 10–100 s of meters, and a minimum temporal scale of hours.

3.1.2. *Temperature*

The desalination process of some plants also elevates temperature of the brine relative to background levels in receiving waters, although far fewer papers in the current review deal with the effects of desalination plants on temperature relative to salinity. Several authors have suggested that elevated temperatures in receiving waters may have played a significant role in the observed ecological effects of desalination plants (Mabrook, 1994; Miri and Chouikhi, 2005). Multi-stage flash (MSF) and other forms of thermal distillation tend to have the greatest impact on intake water temperature, and can release brines 10–15 °C warmer than oceanic intake waters (Hoepner, 1999; Lattemann and Höpner, 2008). Reverse osmosis processes are increasingly common and these tend to result in ambient temperature plumes (Dweiri and Badran, 2002).

As with studies into the effect of brines on salinity in receiving waters, findings have been variable with respect to thermal effects. For example, modelling and monitoring studies in Western Australia found a multi-purpose power and desalination plant discharge could increase the temperature of receiving waters within a 7 square kilometre area surrounding outfalls by 0.1–0.5 °C (Bath et al., 2004). Other studies have found minimal thermal impacts in the vicinity of outfalls despite the desalination process increasing the temperature of intake waters by up to 15 °C (Altayaran and Madany, 1992; Elhassadi, 2008). Typically, thermal impacts appear to be associated with MSF plants and generally dissipate quickly with temperatures diminishing in receiving waters to background levels within tens of meters of outfalls (Elhassadi, 2008; Winters et al., 1979). Again, the distribution and extent of thermal impacts is influenced by the location of the plant discharge, with brine discharges to enclosed water bodies more likely to result in measurable thermal effects than discharges to well-flushed environments.

3.1.3. *Contaminants*

The role of desalination plants as sources of potentially toxic contaminants is well established. In the Arabian Gulf, (an historical 'hotspot' of global desalination activities) it is estimated that between 11 and 20 million m^3 of desalinated water and brine effluent is produced every day (Hashim and Hajjaj, 2005; Lattemann and Höpner, 2008). In a synthesis of chemical discharge information from 21 plants in the Red Sea, it was estimated that 2708 kg chlorine, 36 kg copper and 9478 kg anti-scalants are released every day into the Red Sea alone through desalination activities (Hoepner and Lattemann, 2002). Similarly, monitoring of water quality surrounding a single Florida desalination plant during the late 1960s and early 1970s found up to 45 kg of copper to be discharged for each day of operation (Chesher, 1971). Copper concentrations in receiving waters were 5–10 times higher than ambient concentrations and were often present at levels exceeding toxicity thresholds for native species (Chesher, 1971).

Not surprisingly therefore, several studies describe substantial contamination of marine habitats around desalination outfalls. Waters and sediments around plant outlets may contain elevated concentrations of metals (Crockett, 1997), hydrocarbons (Saeed et al., 1999) and anti-foulants and anti-scalants used to clean reverse osmosis membranes and reduce fouling of the piping (Chesher, 1971; Miri and Chouikhi, 2005). In a review of desalination plant effluents from 28 different plants, as much as 60% exceeded the United States Environmental Protection Agency (USEPA) acute copper water quality criteria (Paquin et al., 2000). Much of the concern centres on the use of copper alloy condensers in plants, however, the authors noted that the lack of clean sampling techniques in earlier studies, and overly protective criteria, possibly led to an overestimation of water quality issues. Further support is provided by other authors who suggest that under optimal operational conditions, the likelihood of metals exceeding water quality criteria in effluents from plants using copper–nickel alloys is very low (Oldfield and Todd, 1996). Furthermore, while some contaminants such as anti-scalants and metals from plant infrastructure may be introduced to brines during the desalination process, brine components such as copper are also extracted from intake waters and concentrated in brines. Thus, at least a portion of metal load around desalination outfalls is due to extraction and concentration of naturally occurring metals in the intake waters. Regardless of source, the discharge of brines with high metal contents has the potential to impair biological communities and biomonitoring studies have found accumulation of metals in macroalgae, mussels (Romeril, 1977) and benthic sediments (Sadiq, 2002) around desalination plant outfalls.

3.2. *Ecological impacts of desalination plant discharges*

Our review found that a variety of approaches have been taken to determine the ecological impacts of desalination plant discharges in marine ecosystems. These include field-based monitoring, and laboratory and field experiments. The following discussion has also been summarised in Tables 2 and 3.

3.2.1. *Field-based monitoring*

Exposure to desalination discharges has been shown to lead to detectable ecological impacts in seagrass habitats, and to phytoplankton, invertebrate and fish communities in areas surrounding outlets. Fernández-Torquemeda et al., (2005) claim a reduction in echinoderm densities in seagrass meadows adjacent to brine discharge was attributable to desalination discharge, however details of the analytical model are not presented. Gacia et al. (2007) also found significant increases in leaf necrosis and decreased carbohydrate storage in leaf tissues in *Posidonia oceanica* meadows, which they attributed to both brine exposure and increases in nutrient availability. These impacts to seagrasses can occur following increases of only 1–2 ppt in salinity highlighting the potential sensitivity of these species to desalination brines (Sánchez-Lizaso et al., 2008). Brine discharges over soft bottom habitats may alter the structure and diversity of infaunal communities (Ruso et al., 2007, 2008). Research has found increased dominance of nematodes adjacent to brine discharges (Ruso et al., 2007), and reduced diversity and abundance of polychaetes up to 400 m from a discharge (Ruso et al., 2008). Benthic diatom communities may also be reduced in richness and abundance, as well as lower containing chlorophyll-*a* concentrations than in un-impacted areas (Crockett, 1997).

Massive losses of coral, plankton and fish in the Hurghada region of the Red Sea have been attributed to desalination discharges, although the data supporting this claim were not presented by the authors and the impacts must be considered anecdotal (Mabrook, 1994). Some research suggests that certain coral species may be relatively resilient to both sudden and prolonged increases in salinity, in the order of 10 ppt, or a 33% increase above ambient (Muthiga and Szmant, 1987). Impacts to planktonic communities may be minimised in areas of strong flow and tidal mixing. In habitats of this nature, ecological effects of brine discharges to plankton communities are generally limited to the point of discharge only (Azis et al., 2003). When discharges are released into embayments, they may have long residence times, leading to plankton die-off as a result of various factors including salinity stress, reduced dissolved oxygen levels, the production of hydrogen sulfide, or reductions in pH (Cintrón et al., 1970; Winters et al., 1979). Prolonged exposure to such conditions would presumably impair the colonisation and survival of benthic communities (Cintrón et al., 1970).

Extensive biological monitoring around a Florida desalination plant found a range of significant biological effects in receiving waters. Amongst a summary of findings, reductions in the abundance of plankton, sessile invertebrates (included serpulids, barnacles, bryozoans, sabellids, ascidians and oysters) and echinoderms were all attributed to the discharge

Table 2 – Summary of contaminants from desalination brines in marine ecosystems.

Reference	Location/ region	Matrix/species/ community	Summary of findings
Contaminant monitoring			
Hoepner and Lattemann, 2002	Red Sea (21 plants)	Discharge	Estimate that up to 2708 kg Cl, 36 kg Cu, 9478 kg anti-foulants released from desalination plants into the Red Sea each day
Crockett, 1997	McMurdo, Antarctica	Sediments	Found higher concentrations of copper, lead and zinc in sediments near a combined waste water-desalination plant outfall relative to control areas
Saeed et al., 1999	Kuwait	Seawater samples	Compared concentrations of hydrocarbons in waters around plant outlets and inlets. Found higher concentrations of many analytes around plant outlets
Chesher, 1971	Key West, Florida	Seawater samples	Copper concentrations in waters surrounding plants were five to ten times higher than background levels, and occasionally present at concentrations exceeding toxic thresholds to native organisms. Estimate that up to 45 kg of copper was discharged from the plant for each day of normal operation
Paquin et al., 2000	USA (28 plants)	Discharge	In a review of chemical data from 28 plants, up to 60% of samples exceeded water quality criteria for Cu at the time of collection. However, the authors state that a lack of clean techniques in earlier studies may have biased results, and that less conservative revised Cu criteria were not exceeded
Romeril, 1977	Jersey, England	Epibiota	Found greater accumulation of copper in algae and limpets around desalination plant compared to a reference location approximately 3 miles from the discharge
Sadiq, 2002	Ras Tanajib, Saudi Arabia	Sediments	Concentrations of Cd, Cu, Hg, Ni, P and Zn elevated in sediments within 100–250 m of outfall, concentrations decreased away from outfall out to 3 km

of desalination brines (Chesher, 1971). Many of the effects appeared to be related to the discharge of brines with excessive copper concentrations.

Some studies have not detected any effects of desalination plant discharges on seagrasses (Talavera and Ruiz, 2001) and macrobenthic organisms such as fish, crabs, echinoderms, molluscs and polychaete worms (Raventos et al., 2006). For example, Raventos et al. (2006) found no response of macrobenthic organisms to desalination discharge, in a region where the brine dissipated within 10 m of the outfall. In some cases, studies conclude that desalination plants have either substantial impacts (Mabrook, 1994), or negligible impacts (Tsiourtis, 2001b) upon the ecology of the receiving system but present no details of monitoring designs or supporting data.

As for salinity, the variation in the ecological effects observed in these studies is probably a combination of the differing intensities and frequencies of exposure to the saline plumes, the temperature of the released water, the environment in which it is being released (e.g. hydrology, temperature), the organisms inhabiting the environment and the studies themselves (i.e. the amount of sampling, appropriate sampling designs, etc.). In addition, environmental issues associated with older desalination plants have often been linked to excessive copper content of desalination brines (Chesher, 1971), an issue that is now largely avoidable with proper plant maintenance and operation (Oldfield and Todd, 1996). Few of the published studies have attempted to assess the spatial extent of the reported ecological effects through the use of nested monitoring programs, and many are vague with respect to sampling and statistical techniques applied, making conclusions difficult. For this reason, our summary of field monitoring results in Table 3 is limited to studies that have incorporated multiple reference locations into their study design. It is widely accepted that individual reference locations are insufficient as natural spatial variation may confound comparisons with the impact location (Underwood, 1994).

3.2.2. *Toxicological and laboratory-based evidence*

In addition to field-based monitoring studies, laboratory-based toxicity testing has been used to predict the effects of brines and brine constituents on aquatic organisms. These studies may take the form of single species tests (Dupavillon and Gillanders, 2009; Mandelli, 1975), multi-species screens (Iso et al., 1994), and tests on both lethal and sub-lethal endpoints (Iso et al., 1994; Mandelli, 1975).

Much of the experimental research has focused upon the effects of brine upon seagrass (*P. oceanica*) and associated fauna. Laboratory experiments have observed reduced growth, greater occurrence of necrotic lesions and premature senescence in seagrasses at salinities of approximately 39 ppt, which represents only a minor increase above ambient salinity in the study region (Sánchez-Lizaso et al., 2008). Salinities of 40–45 ppt appear to cause significant increases in the mortality of exposed plants, epifaunal mysids and echinoderms (Sánchez-Lizaso et al., 2008). Chesher (1971) exposed echinoderms, seagrass (*Thalassia testudinum*), and ascidians (*Ascidia nigra*) to diluted brines in laboratory experiments for 24–96 h. Ascidians were the most sensitive with 50% mortality following 96-h exposures to 5.8% brine dilutions. Echinoids showed similar levels of mortality across 96 h in 8.5% brine dilutions. Seagrass photosynthesis was reduced by 50% following 24-h exposures to 12% brine dilutions (Chesher, 1971). The results of these studies contrast somewhat with experiments conducted on seagrasses from naturally hypersaline environments. Growth and leaf production of seagrasses collected from Shark Bay, Western Australia (some sections of which may have salinities as high as 70 ppt), were greatest at salinities of 42.5 ppt (Walker and McComb, 1990). Senescence and mortality occurred at salinities between 50 and 65 ppt (Walker and McComb, 1990). Thus, it is not possible to provide a global salinity value that is protective of seagrass communities. However, laboratory research suggests that in the Mediterranean desalination brines influence salinity

Table 3 – The ecological and toxicological effects of desalination brines in marine ecosystems

Reference	Location/ region	Matrix/species/community	Summary of findings
Biological monitoring[a]			
Fernández-Torquemeda et al., 2005	Alicante, Spain	Seagrass (*Posidonia oceanica*) and epifauna	Echinoderms disappeared from the impact location following commissioning of plant, and one of the controls also exposed to a lesser extent. Salinity adjacent to the outfall corresponded to that which was toxic to *Posidonia oceanica* in Sánchez-Lizaso et al., 2008, shoot division appeared lower at the exposed site
Chesher, 1971	Key West, Florida	Plankton, echinoids, ascidians and seagrass	Found reduced abundance of plankton in water surrounding discharge, as well as reduced abundances of hard substrate epifauna (serpulids, barnacles, bryozoans, sabellids, ascidians, and oysters) and echinoderms in exposed areas. The majority of effects were attributed to the copper content of the brine
Gacia et al., 2007	Formentera, Spain	Seagrass (*Posidonia oceanica*)	Found increased leaf necrosis, greater epiphyte cover and decreased carbohydrate storage in seagrass tissues in meadows exposed to brines for more than 6 years, relative to control locations
Crockett, 1997	McMurdo, Antarctica	Sea ice chlorophyll	Sea ice samples taken from vicinity of a mixed brine/waste water outfall contained lower chlorophyll-*a* concentrations than sea ice samples from control locations
Ruso et al., 2007	Alicante, Spain	Sediment infauna	Infaunal communities close to a desalination plant outfall were dominated by nematodes (up to 98%). Polychaetes, molluscs and crustaceans became more abundant in infaunal communities with increasing distance from the discharge
Ruso et al. 2008	Alicante, Spain	Sediment infauna	Monitoring of transects adjacent to a discharge and 400 m north and south of the discharge found reduced abundance and diversity of polychaete assemblages directly adjacent to outfall. Polychaete families showed variable sensitivities with Ampharetidae being the most sensitive, and Paraonidae the least sensitive
Raventos et al., 2006	Blanes, Spain	Sediment infauna	Monitoring found no effects of brine discharge on community structure or on the abundance of fish and invertebrates in sediment habitats
Sánchez-Lizaso et al., 2008	Alicante, Spain	Seagrass (*Posidonia oceanica*)	Seagrass meadows adjacent to plant discharge experience 1–2 ppt increases in ambient salinity, as well as increased nutrients. Exposed meadows had increased necrotic marks and lower epifaunal abundances (see also laboratory and field experiments)
Laboratory experiments			
Dupavillon and Gillanders, 2009	Spencer Gulf, SA	Cuttlefish (*Sepia apama*)	Exposed cuttlefish embryos until hatch date to a range of salinities, and a control of 39 ppt. Size and weight of hatchlings was reduced at salinities above 42 ppt. Fewer survived to term at 45 ppt, and survivors showed reduced ink production and mobility. No individuals survived to term at salinities greater than 50 ppt
Chesher, 1971	Key West, Florida	Echinoids, ascidians and seagrass	Organisms were exposed to dilutions of brines for 24–96 h. Ascidians were the most sensitive, with 50% mortality on exposure to 5.8% effluent. Echinoids showed reduced survival on exposure to 8.5% dilutions. Seagrass photosynthesis was inhibited following exposure to 12% brines for 24 h
Mandelli, 1975	Texas, US	Oyster (*Crassostrea virginica*)	Conducted 60-d exposures of juvenile and adult oysters to brines with salinities of 45–55 ppt. Survival and reproduction were affected, with toxic effects attributed primarily to the copper content of brine. Pathogenic fungus infection also increased on exposure to brines
Iso et al., 1994	NA	Fish (*Pagrus major*, *Pleuronectes yokohamae*) and clam (*Tapes philippinarum*)	Laboratory exposures to a range of salinities found no effects at salinities below 50 ppt. Juvenile *Pagrus major* exposed to salinities of 70 ppt died within 1 h, with some mortality at 50 ppt. Larval *Pleuronectes yokohamae* died at salinities of 55 ppt after approximately 6-d of exposure. Egg hatching was delayed at 60 ppt and completely inhibited at 70 ppt. Mortality of clams was noted at 60 ppt following 48-h exposures. Fish appeared to avoid all waters tested above control salinities
Latorre, 2005	Spain	Seagrass (*Posidonia oceanica*)	Growth of seagrass in the laboratory was significantly lower on exposure to salinities of 43 ppt (50% lower) and 40 ppt (14% lower) compared to control salinities of 38 ppt
Sánchez-Lizaso et al., 2008	Alicante, Spain	Seagrass (*Posidonia oceanica*)	Fifteen-day laboratory exposures to a range of salinities showed significant sub-lethal effects of salinities 1–2 ppt above ambient upon seagrass growth and survival (see also monitoring and field experimental results)

(*continued on next page*)

Table 3 (*continued*)

Reference	Location/ region	Matrix/species/community	Summary of findings
Walker and McComb, 1990	Shark Bay, WA	Seagrass (*Posidonia australis*)	Collected seagrass from a naturally hypersaline environment (Shark Bay, Western Australia) where salinity may reach 70 ppt. In laboratory exposures, seagrass had the greatest growth and production at 42.5 ppt, with increasing mortality and senescence at salinities of 50–65 ppt
Field experiments			
Chesher, 1971	Key West, Florida	Hard substrate epifauna	Echinoderms, ascidians, gorgonian corals, and stone crabs were transplanted to sites receiving effluents. Echinoderms were the most sensitive, dying within 2–3 d exposure to low concentrations of brines. Survival improved when copper emissions were reduced following plant maintenance
Latorre, 2005	Spain	Seagrass (*Posidonia oceanica*)	Small-scale simulations of brine discharge were conducted in the microcosms and in experimental field plots. Details of the methodology are not presented, by salinities of 50 ppt resulted in complete mortality of seagrass in 15-d. Salinities of 45 ppt lead to approximately 50% mortality
Sánchez-Lizaso et al., 2008	Alicante, Spain	Seagrass (*Posidonia oceanica*)	Seagrass were exposed to brines in the field for a period of three months. Exposures raised natural salinities of 37.7 ppt to 38.4–39.2 ppt in experimental plots. Exposed seagrass experienced poorer survivorship, and surviving plants had reduced shoot and leaf abundance

a Biological monitoring studies are limited to studies incorporating multiple reference locations.

sufficiently to impact upon the health and survival of seagrasses and associated invertebrate communities (Sánchez-Lizaso et al., 2008).

Salinities of 55, 60 and 70 ppt have been found to be acutely toxic to juvenile sea bream, clams and larval flounder, respectively (Iso et al., 1994). Behavioural avoidance was noted at salinities of 45 ppt (Iso et al., 1994). In 60-d exposures, desalination brines reduced the survival and impaired reproduction in the oyster *Crassostrea virginica* (Mandelli, 1975). These toxicological effects were primarily attributed to dissolved copper present in the desalination effluent. In addition to direct toxicological effects, the altered physicochemical characteristics of the brine appeared to enhance pathogenic fungus infection rates in the exposed oysters (Mandelli, 1975).

Recent experiments have shown desalination brines to be acutely toxic to developing cuttlefish embryos, attributable to both increased salinities, and trace metal concentrations in brines (Dupavillon and Gillanders, 2009). In laboratory exposures, fewer eggs of the giant Australian cuttlefish *Sepia apama* developed to term when exposed to brine effluent with salinities greater than 45 ppt. Surviving individuals at these concentrations displayed behavioural effects such as slow response to stimulation and reduced ink-jet defence responses (Dupavillon and Gillanders, 2009). In brines exceeding 45 ppt, mortality of exposed eggs was absolute (Dupavillon and Gillanders, 2009).

3.2.3. *Field-based experimentation*

Manipulative ecological experiments in the field are important complements to ecological studies. Manipulative experiments assist in establishing a causal relationship between the discharge of brines and observed ecological effects. However, only three studies utilised manipulative field experiments in the current review. In novel experiments, brine from a pilot desalination plant was pumped to experimental seagrass plots in the field for a period of three months (Latorre, 2005; Sánchez-Lizaso et al., 2008). During these exposures, salinities were elevated from control salinities of approximately 37.7 ppt, to 38.4–39.2 ppt. These slight but long-term (3 months) increases in salinity resulted in reduced survivorship of seagrass, and exposed patches showed poorer vitality as measured by shoot abundance, length and biomass, and presence of necrotic lesions. Monitoring of meadows adjacent to plant outfalls also found reduced shoot density, greater abundance of epiphytes and reduced abundance of epifauna (Latorre, 2005; Sánchez-Lizaso et al., 2008).

Additionally, Chesher (1971) describes the results of *in situ* bioassays whereby echinoderms ascidians, gorgonian corals and stone crabs were transplanted to sites and caged in areas receiving brine inputs. Echinoderms showed the greatest sensitivity and died within days of exposure to as little as 3% brines in seawater, but survival increased rapidly when corroded copper–nickel trays were replaced in the desalination plant (Chesher, 1971). For this reason, impaired survival was attributed to the copper content of the desalination brine.

3.3. *Impact minimisation*

Desalination technologies have evolved rapidly in recent decades. In a 1991 review, it was found that over 65% of desalination plants relied upon thermal distillation processes referred to as multi-stage flash (MSF), a process which yields high temperature brines, and greater atmospheric pollution (Al-Mutaz, 1991; Morton et al., 1996). Historically, MSF plants have been popular in the Middle East where rich fossil fuel deposits have meant cheap energy is available (Tulharam and Ilahee, 2007). In nations such as the United States and Australia, these methods are rapidly being replaced by membrane based methods of desalination such as reverse osmosis (RO) plants, which tend to have lesser thermal impacts, but produce saltier brines (Dweiri and Badran, 2002; Tulharam and Ilahee, 2007). Developing pressure exchange technologies may assist in reducing the salt content of RO brines (Campbell and Jones, 2005). By reducing recovery rates (i.e. reducing the amount of freshwater extracted from a given volume of seawater), RO plants may improve energy efficiency, produce less salty brines, and reduce the need for pretreatment of intake waters with chemicals (Campbell and Jones, 2005).

One mechanism to reduce potential environmental effects of brine is to dilute brine with power plant cooling waters (Einav and Lokiec, 2003). In many cases these plants are co-located and modelling suggests this would greatly limit the extent and magnitude of brine plumes in receiving waters (Einav and Lokiec, 2003). Similarly, brines may be diluted with natural seawater or municipal waste waters to reduce salinity prior to discharge (Baalousha, 2006; Malfeito et al., 2005). In addition, there is a current focus of research on the development of effective anti-scalants with no biological effects (Ketsetzi et al., 2008; Mavredaki et al., 2007). This may assist in the production of less toxic brines in the future. It has also been suggested that desalination of groundwater is a more environmentally friendly alternative to seawater desalination, although the availability of appropriate groundwater resources will likely be a limiting factor in many areas (Muñoz and Fernández-Alba, 2008). Energy costs are reduced and discharge brines are less salty than those produced following seawater desalination (Muñoz and Fernández-Alba, 2008), however, desalination of groundwater with low levels of salinity may result in brines with lower salinity than marine waters, thereby trading an issue of hypersaline brines for one of hyposaline brines if marine environments are to be the recipient of discharges.

Jetties have been constructed adjacent to desalination plant discharges, to minimise the spread of brine plumes and encourage more rapid mixing by creating offshore currents (Altayaran and Madany, 1992). This has been done not only to limit the intrusion of brines into seawater intake areas, but also to minimise areas of ecological impacts, however these structures appear to have limited success in either of these applications (Altayaran and Madany, 1992).

A clear consensus amongst many articles is that discharge site selection is perhaps the primary factor that determines the extent of ecological impacts of desalination plants (Lattemann and Höpner, 2008; Maugin and Corsin, 2005; Tsiourtis, 2008). Major marine habitat types have been ranked in order of predicted sensitivity to desalination brines (Höpner and Windelberg, 1996). Turbulent coastal environments with continuous flushing are predicted to be less susceptible to detrimental impacts of desalination brines than lower-energy systems, and habitats with strong tidal influence (Höpner and Windelberg, 1996). These predictions do not appear to have been drawn from empirical research, but rather observations and assumptions pertaining to physical characteristics of each of these types of environments. Whilst it does seem logical that well-flushed environments may experience reduced intensity and duration of exposure to effluents of any type, there is a strong possibility that the ecological impacts of desalination plants will resist prediction along such simplistic lines. Furthermore, areas known to support important biological resources should be avoided. The presence of rare, valuable or unique habitat and biological resources within the vicinity of desalination plant discharges should be a primary consideration in discharge site selection as a means of minimizing potential impacts to marine ecosystems (Dupavillon and Gillanders, 2009; Lattemann and Höpner, 2008).

Modelling approaches have also been used to improve the design of discharges such that impacts on salinity are minimised. Models suggest that the worst discharge design, from the perspective of dilution of brines, is an intertidal, or surface discharge as plumes tend to extend further and dilute less rapidly (Alameddine and El-Fadel, 2007; Bleninger and Jirka, 2008). Similarly, semi-enclosed seas, such as the Arabian Gulf, or Red Sea are more susceptible to significant increases in salinity around outfalls due to the limited flushing these environments experience (Cintrón et al., 1970; Purnama et al., 2005). The spatial extent of brine plumes and coastal erosion due to outfalls can be minimised by building discharges further offshore (Al-Barwani and Purnama, 2007, 2008; Purnama et al., 2003; Shao and Law, 2009). It has historically been recommended that sub-surface discharges release a 'jet' of brine at an angle of approximately 60° to the seafloor, and this has become the design standard for brine discharges (Roberts et al., 1997). However, more recent models suggest a shallower discharge angle of 30–45° may enhance mixing and offshore transport of desalination brines in coastal waters with moderate-to-steep bottom slopes (Bleninger and Jirka, 2008; Jirka, 2008; Maugin and Corsin, 2005). Thus there is broad agreement amongst modelling studies that sub-tidal, offshore discharge in an area of persistent turbulent flow is the optimal design to minimise the spatial extent and intensity of brine plumes.

4. Conclusion

4.1. *Monitoring ecological impacts of desalination plants – state of the art*

From a review of the literature it is clear that there is a widespread belief and recognition that desalination plants pose a potentially serious threat to marine ecosystems. The evidence for salinity, thermal, and contaminant impacts of desalination brines upon receiving water quality is relatively clear, however, when brines are released to well-flushed environments impacts tend to be on a small-scale (10 s of meters). Laboratory-based experiments, toxicological investigations and manipulative field experiments clearly demonstrate the potential for brines and their constituents to illicit adverse impacts on aquatic organisms when present at sufficient concentrations. In some cases substantial toxicological effects of desalination brines have been detected on marine vertebrates and invertebrates, at dilutions likely to be encountered in the vicinity of desalination outfalls. Thus, our review of the literature does show that desalination plants may adversely impact the ecology of marine ecosystems. However, while some earlier studies found broad-scale impacts upon the ecology of receiving environments, recent research stresses that appropriate discharge site selection, modelling of ocean currents, and proper plant maintenance and operation will minimise the spatial extent of the ecological effects of desalination plant discharges.

The one area where evidence is clearly lacking is in field-based ecological monitoring. Unfortunately, many of the published ecological monitoring programs do not appear to be scientifically defensible assessments of impacts. Thus, there is a general lack of empirical evidence supporting conclusions regarding the effects of desalination brines in receiving systems, a fact that is recognised in almost all regions that operate large plants (Baalousha, 2006). The only possible exception to this is in seagrass habitats, where biological monitoring studies have been combined with laboratory and field experiments to assess the effects of brines on seagrass ecosystems (Sánchez-Lizaso et al., 2008). Furthermore, professional experience suggests much of the research into ecological and environmental effects of desalination plants may be present in the grey literature (i.e. unpublished technical reports produced by consultants and government bodies). This literature is notoriously difficult to access for the purpose of literature review. It is essential that scientists involved in such research be supported and encouraged to publish their results in peer-reviewed journals to further advance knowledge in this area. Well-designed monitoring programs can assess the spatial extent of impacts resulting from desalination discharges, and are required to further feed into future decisions regarding site selection criteria for discharges.

It is worth highlighting that many published manuscripts purport to describe or review ecological impacts of desalination plants, but cite little or no peer-reviewed literature (Areiqat and Mohamed, 2005; Baalousha, 2006; Elhassadi, 2008; Miri and Chouikhi, 2005), provide little or no details of methodologies and statistical analyses (Azis et al., 2003; Elhassadi, 2008; Latorre, 2005; Mabrook, 1994), and, occasionally, present purely qualitative evidence (Mabrook, 1994). Environmental research must move from qualitative to quantitative approaches, following robust experimental designs as used to assess ecological impacts in other areas of marine research (Underwood, 1994). With expanding desalination capacities occurring in many regions around the world there is a clear need to monitor their impacts upon marine ecosystems using sound and defensible scientific approaches.

In conclusion, we can recommend the following key areas where future research would be valuable.

1. *Use of manipulative field experimentation to examine the effects of desalination brines under field conditions*. As discussed, only three studies were identified in this review that conducted manipulative experiments under field conditions. However, each of these studies was able to provide observations of impacts to multiple species simultaneously, demonstrate that small shifts in salinity (1–2 ppt) could have substantial consequences for exposed communities, and provide insights into the constituents of brines that were responsible for observed effects (Chesher, 1971; Latorre, 2005; Sánchez-Lizaso et al., 2008). Field experiments of this nature may be challenging to conduct, but clearly the information provided is extremely valuable. These studies could simulate effluent release in a range of flow conditions to examine impacts at a range of exposure intensities.
2. *Before–After Control-Impact (BACI) monitoring programs utilizing multiple reference locations and repeated sampling before and after plant operation*. Ecological monitoring programs that examine human effects in marine ecosystems should include multiple reference locations and replicated sampling before and after the activity of concern takes place (Underwood, 1994). In addition to those studies reviewed here, BACI monitoring studies that incorporate multiple reference locations have been implemented to detect the potential ecological effects of desalination plants in Australia, although data are yet to be published in peer-reviewed journals (Cannesson et al., 2009; Port et al., 2009). Without the use of appropriate reference locations and baseline estimates of ecological condition it is extremely difficult to demonstrate that an effect has or has not taken place, which is problematic for both operators and regulators. Generally, these designs will require sampling of at least five reference locations on at least three times prior to and during the operation of the plant (annually where possible to avoid confounding by seasonal changes). Post-operation studies (i.e. those with no before-operation data, also referred to as After, Control-Impact studies) can be performed, but they inherently have lower confidence attached to them as any differences between reference and potentially impacted locations may have existed prior to the operation of the plant (Glasby, 1997). Nevertheless, in situations where pre-construction data is not available, a study including multiple sampling times and numerous independent reference locations should provide a reasonable assessment of the effects of an existing plant. A range of statistical models and philosophical approaches to the analysis of these types of studies have been suggested, and these should be reviewed as part of the design process of any new ecological monitoring program (Downes et al., 2008; Glasby, 1997; Stewart-Oaten and Bence, 2002; Underwood, 1994).
3. *Whole of effluent testing and ecological monitoring to examine interactions, synergistic and additive effects of a range of climatic conditions and desalination brines*. Different climatic conditions may have additive or synergistic effects upon the responses of marine communities to desalination brines. Toxicity testing could be conducted under a range of environmental conditions (e.g. temperatures) using local organisms relevant to the development location to address these interactions. Ecological monitoring studies could also be designed to assess the potential for different responses of marine communities to desalination brines between summer and winter seasons.
4. *Specific tests of commonly used anti-scalants used in desalination plants*. There is a dearth of basic toxicological information in the published literature pertaining to commonly used anti-scalants that are currently included in brine effluent. Studies that optimise the use of such anti-scalants in order to minimise their inclusion in brine are required.
5. *Publishing studies in the scientific literature*. Experience suggests much of the research associated with the effects of desalination plants has been published only in the grey literature. It is important that these studies be published in peer-reviewed journals to further shape the design, location, and management of desalination plants to minimise or eliminate any potential impacts.

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