

CHAPTER 11

Impacts of Seawater Desalination on Coastal Environments

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11.1 INTRODUCTION

Arid and semiarid regions of the world are under constant water stress as they attempt to accommodate the growing need for food and potable water [1–3]. Current limitations in freshwater availability have stimulated the use of desalination technologies worldwide, with desalinated water coming online at a rate of $\sim 85 \text{ M m}^3 \text{ d}^{-1}$ [4,5]. Advances in membrane technology during the last decades have favored reverse osmosis, which currently accounts for $>80\%$ of the global desalination industry [6,7]. Large-scale desalination facilities that are based on seawater reverse osmosis (SWRO) use coastal water as feed and continuously discharge concentrated brine effluent back into the marine environment. The SWRO brine effluent contains high concentration of salts, as well as various chemicals such as antiscalants and coagulants if used in the facility and discharged with the brine effluent [8,9]. Brine effluent from large-scale desalination facilities is discharged back to the coastal environment via direct surface discharge on the coastline or via diffuser systems away from the shore (up to 2 km) [9–11]. To maximize dilution and increase the buoyancy of the SWRO brine effluent, it is often mixed with cooling water of adjacent power plants resulting in a warm (up to 25% over ambient) and saline (up to 10% over ambient) brine effluent plume. Nevertheless, the brine effluent can be denser than ambient seawater (depending on the volume of cooling water that is used for mixing) [12]. In such cases, the brine effluent tends to sink and flows as a concentrated stream on the seabed [12–14]. It has been previously pointed out that such dense saline plumes can extend further away from the discharge site along the seafloor (Table 11.1) and possibly accumulates within the sediment pore water. The brine effluent plume is dynamic and dispersed along with the

Table 11.1 Spatial dispersion of the brine-effluent plume at the seabed around desalination plants worldwide

Desalination plant	Brine discharge flux ($M m^3 y^{-1}$)	Discharge technology	2%–5% salinity above ambient (km^2)	5%–10% salinity above ambient (km^2)	References
Alicante (Spain) ^a	66	Beach discharge	~23	9.8	[13]
Maspalomas II (Spain)	22	Beach discharge	~0.2	~0.04	[15]
Ashkelon (Israel) ^b	120	Beach discharge	1.4	0.06	[16,17]
Hadera (Israel) ^b	145	Beach discharge	~2	~0.1	[16,17]
Sorek/Palmachim (Israel) ^c	90–150	Diffuser system	<2	<0.1	[18]
Perth (Australia)	0.14	Diffuser system	~0.11	<0.1	[19]
Monterey Bay regional water project (USA)	30	Diffuser system	~0.3	~0.12	[20]

^aBrine effluent was not diluted prior to discharge.

^bThe dispersion area is linked to the volume of cooling water from the adjacent power plant that was mixed with the brine effluent.

^cTwo separate discharge points that are close to each other.

(Table was modified after Frank H, Rahav E, Bar-Zeev E. Short-term effects of SWRO desalination brine on benthic heterotrophic microbial communities. *Desalination* 2017;417;52–59.)

cooling-water outflow from the adjacent power plant (in the case of surface discharge that is diluted) or from the outflow pipe in cases of direct dispersion by diffuser systems. The dispersion of the brine-effluent plume can also be affected by the bathymetry of the seabed at the outfall region. Although the overall footprint area of the brine-effluent plume can be estimated and modeled, the specific location of the brine effluent on the seafloor often vary due to changing currents [13,21]. These dynamic conditions can result in episodic short-term (hours or days) exposure of benthic organisms to the brine effluent at the perimeters of the plume as well as long-term chronic exposure (months or years) at the outfall or the plume center.

The possible impacts on coastal ecosystems related to SWRO desalination can be divided into three main categories [8,10,22–24]:

- (i) Impingement and entrainment of marine organisms associated with seawater that is drawn to the desalination facility (typically related to surface intake) [23,25–27]. Impingement refers to adult marine organisms such as fish, crabs, etc., which are large enough to be retained by the intake screens. Entrainment is associated with smaller (often planktonic) organisms including larva and juveniles of different marine species that pass through the intake screens and are transported with feedwater into the desalination facility. The survival rates of entrained organisms are often considered to be nearly zero. Yet, the actual survival rates and significance of impingement and entrainment of organisms are different from site to site and are often not clear.
- (ii) Constant release of brine effluent that is a byproduct of the desalination process. The disposal of brine effluent may result in osmotic stress due to elevated salinities compared to those in the receiving environment. Thermal stresses are also associated with the desalination brine effluent if it is mixed with coolant water of adjacent power plants.
- (iii) Discharge of different chemicals that are often used in the desalination process into the coastal environment along with the brine effluent. These chemicals include different types of antiscalants and coagulants. Antiscalants may induce local eutrophication of oligotrophic coastal environments by adding organic phosphorus (e.g., polyphosphates), while coagulants can enhance water turbidity and water coloration.

In the past decade a comprehensive, long-term monitoring of large-scale SWRO desalination facilities along the Israeli coastline has reported that antiscalants, coagulants, and heavy metals were not detected at the outfall area [18,29–31]. In addition, it was determined that antiscalants and

coagulants did not accumulate around the outfall area of these specific desalination facilities. However, previous studies and surveys around other operational desalination facilities worldwide have shown that exposure to the brine effluent (mainly to elevated salinities) could impact marine organisms, including vertebrates, invertebrates, seagrass, and polychaeta as well as plankton and fish larva, in a diameter of up to a several 100 m from the outfall [8,16–18,25,30,32–35]. Moreover, it has been suggested that these impacts may be more significant in enclosed basins, nature reserves, rocky shores and/or around other sensitive marine environments where water circulation is limited [36–38]. Nevertheless, to date, the effects of brine–effluent discharge on coastal marine ecosystems are poorly understood, thereby merit further research via controlled bioassay experiments and more importantly long-term monitoring campaigns around the outfall of operational desalination facilities.

In this book chapter, we review the latest reports and studies focusing on the impact of SWRO desalination brine–effluent discharge on marine ecosystems, namely, coastal flora and fauna. It should be noted that throughout the chapter we do not report on lifecycle assessments nor define impact as “positive” or “negative” implications but rather specify “impacts” as any deviation from the natural environmental conditions at the site prior to discharge. Finally, we describe the needs for dynamic site-specific monitoring approaches and suggest possible means to minimize the effects of SWRO desalination on coastal marine organisms and ecosystems.

11.2 THE IMPACT OF DESALINATION BRINE EFFLUENT ON ZOOPLANKTON

Plankton are free-floating organisms that depend on ocean currents for movement and consists of diverse groups including bacterioplankton, phytoplankton, and zooplankton. Planktonic organisms range in size from picoplankton (0.2–2 μm) to large zooplankton (up to few mm long). In this chapter, we will focus on zooplankton while phytoplankton and bacterioplankton are covered in greater detail in another chapter (see Chapter by Nurit Kress et al.) of this book.

Zooplankton consists of a large and complex group of animals including crustacean, copepods, marine larvae, and various worms. The life cycle of many zooplankton organisms can be complex and include egg, larvae, and adult stages. The potential impacts of desalination brine effluent may be vary for these different life stages making assessment of the impacts on specific

species harder to quantify [39]. Zooplankton can inhabit both the pelagic and the benthic zones of the ocean. In this chapter, we will focus on pelagic zooplankton those that live in the water column. Zooplankton grazes on microplankton, primarily phytoplankton and bacterioplankton, which are in turn dependent on seasonal changes such as temperature [40,41] that affect the growth rates, metabolism, and respiration rates [42,43].

To date, there have only been a handful of studies investigating the effects of desalination brine effluent on pelagic zooplankton. These studies have found that the adult stages of zooplankton have a higher tolerance for salinity changes than larvae stage [44]. For adult zooplankton, mortality is generally not observed until salinity is increased by about 40% over ambient salinity, whereas reproduction and survival of eggs and juvenile can be affected by a salinity increase of about 20% above ambient [44–49]. However, the response varies among species, for example, an incubation experiment exposing rotifers to desalination brine effluent where the salinity was 40% above ambient conditions reported no significant mortality [50]. A summary of reported mortality rates for different zooplankton species at elevated salinities is detailed in Table 11.2.

Table 11.2 A summary of mortality of various zooplankton species in increased salinities

Species	Location	Salinity increase from ambient seawater (%)	Salinity measured	Mortality (%)	References
Rotifer	South Korea	30–40	40	7	[50]
Mysid shrimp	Texas, USA	60	45	40	[49]
Copepod juvenile	Tungkang, Taiwan	25	25	30	[44]
Copepod adult	Tungkang, Taiwan	25	25	0	[44]
Copepod juvenile	Florida, USA	30	45	40	[48]
Copepod adult	Florida, USA	30	45	15	[48]
Copepod juvenile	Wukan Bay, Japan	20	35	70	[47]

It should be noted that the salinity increase over the ambient coastal environment following the brine-effluent discharge of SWRO is often lower than 10%.

Increases in temperature (within an organism's tolerance range) typically enhance growth rates of larvae and increase respiration in adult copepods [39,51]. Increases in sea-surface temperature on a global scale have been connected with decreases in zooplankton abundance and shifts in zooplankton communities [43,52]. Accordingly, local temperature increases within the discharge plume of SWRO plants, at facilities in which the brine effluent is diluted with power-plant cooling water, are expected to show a similar pattern on zooplankton communities.

Chemical additive used in some SWRO desalination facilities such as antiscalants or coagulants may also impact zooplankton if discharged with the brine effluent. To the best of our knowledge, there are currently no studies published on the effects of antiscalants or coagulants on zooplankton. However, a study in the fresh water Lake Tahoe (California, USA) pointed to a significant decrease in reproduction among copepods cultivated with the addition of aluminum-based coagulants [53].

The overall impacts of desalination brine-effluent discharge on zooplankton are vague and not well understood. Moreover, the possible effects of SWRO brine on the zooplankton food web (related to phytoplankton and bacterioplankton) were not studied and are currently unknown. It is possible that SWRO effluent will impact zooplankton species around the outfall, but at this point, there are not sufficient data to arrive at a satisfying conclusion.

11.3 BENTHIC BACTERIA AROUND THE OUTFALL OF DESALINATION FACILITIES

Marine sediments are biodiverse ecosystems playing a key role in different biogeochemical cycles such as nutrient recycling and organic matter decomposition [54,55]. Heterotrophic bacteria have a central role within the benthic fauna community as they regulate various biochemical processes such as decomposition of organic matter and nutrients remineralization in the sediment [56,57]. Organic matter and nutrients can then be released to the water column and/or assimilated by benthic bacteria. This bacterial biomass can then be consumed by bacterivores and utilized by higher trophic levels [57–61]. The growth efficiency and community structure of benthic bacteria is often affected by environmental parameters such as temperature, salinity, oxygen concentrations, organic matter quantity and quality, as well as nutrients availability. These parameters impact the metabolic patterns of bacteria, for example, by changing the rates of anabolic reactions (carbon assimilation) or catabolic processes (respiration) [62,63]. It should be noted that cyanobacteria (photosynthetic prokaryotes) also constitute an

important component of the benthic microbial assemblage and they play an important role as primary producers [64].

Currently, studies or technical reports regarding the impact of SWRO brine-effluent discharge on benthic bacteria are highly scarce. To the best of our knowledge, there are also no published data on the effects of desalination brine effluent on benthonic cyanobacteria. In the following section, we will focus on benthic heterotrophic bacteria and review the possible effects of osmotic stress due to SWRO brine-effluent discharge.

11.4 SHORT- AND LONG-TERM IMPACT OF SWRO BRINE-EFFLUENT DISCHARGE ON BENTHIC BACTERIA

Exposure of benthic bacteria to SWRO brine effluent may impose short-term (days) to chronic (years) effects. It was recently shown in controlled microcosm experiments that short-term (2 days) exposure to elevated salinity (>5% above the ambient) resulted in a significant reduction (60%) in bacteria abundance [21]. In addition, the metabolic activity per bacterial cell was found to increase following these short-term (days) exposures to SWRO brine effluent. It has been proposed that under these higher salinity conditions osmotic shock has prompt production of osmoprotectants [21], namely, carbon-rich molecules that are used to adjust the osmotic pressure of the bacterial cell to allow survival [65–67].

Chronic effects of SWRO brine effluent on benthic bacteria are of great importance due to long-term operation of desalination facilities. Environmental measurements were recently conducted near a large-scale operating desalination facility with a surface discharge system (producing $\sim 150 \text{ Mm}^3 \text{ Y}^{-1}$ of desalinated water) along the Israeli coastline. Sediments were sampled by the *RV Mediterranean Explorer*. Three locations were selected for each desalination facility: at the brine-effluent outfall, within the brine-effluent plume, and at reference stations that were not affected by the brine effluent. The outfall station was chronically exposed to salinity of up to 9% above ambient, while the “plume” station was exposed to variable conditions between 2% and 5% above ambient salinity. The chronic exposure to brine effluent at the outfall resulted in higher bacterial abundance and production (52% and 60%, respectively) compared to the reference station (Fig. 11.1). Diversity analysis indicated that community structure at the outfall and reference stations were significantly different. The main families at the outfall station comprised primarily *Stramenopiles*, *Pirellulaceae*, *Piscirickettsiaceae*, while the reference station was colonized by *Bacteriodaceae*, *Prevotellaceae*, and *Enterobacteriaceae* families (Frank et al., unpublished data).

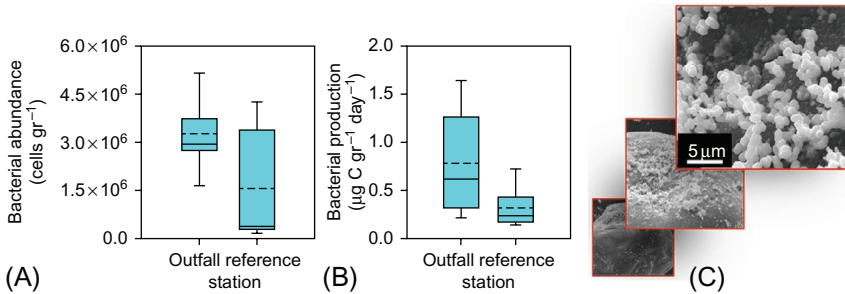


Fig. 11.1 (A) Benthic bacterial abundance and (B) production near a large-scale SWRO desalination facility within the outfall and reference stations (Frank et al., unpublished data). The figures represent the pooled data from four annual cruises. (C) Representative micrograph of benthic heterotrophic bacteria attached to a sand grain.

We stress that additional environmental campaigns from these sites as well as different coastal ecosystems are needed to establish a clear conclusion regarding the chronic effects of SWRO brine effluent on benthic bacteria.

Changes in the community structure and metabolic traits of benthic bacteria can potentially affect ecosystem functionalities on long time scales [68]. The effect of brine effluent on benthic bacteria needs to be further assessed in regards to the size of the outfall area and habitat properties such as sediment type and bathymetry. It should be highlighted that the impact of water temperature and chemical discharge (such as antiscalants) on benthic microbial communities has been overlooked so far and therefore warrants further investigation.

11.5 IMPACT OF OSMOTIC STRESS ON BENTHIC MEIOFAUNA

Soft bottom meiofauna include various microscopic organisms that range from tens of micrometers to one mm. These organisms consist of invertebrates from different phyla such as Crustacea, Echinodermata, Mollusca, Annelida, Nematoda, and Foramenifera [69,70]. Meiofauna could impact microbenthic abundances and shape the macrobenthic populations by grazing on their larvae [71]. In coastal environments, the number of meiofaunal species dwelling within the sediment is high and often exceeds the number of species living on the seabed due to the turbulence conditions [70].

Previous reports have highlighted that benthic Meiofauna (specifically metazoans) are highly sensitive to different anthropogenic effects [33,69]. Therefore, metazoans are often used as bioindicators to assess impacts on

the meiofaunal community in coastal environments. Nematodes are the most abundant and diverse phylum within the meiofauna group [71–73]. As permanent dwellers of the interstitial coastal environment, they are constantly exposed to anthropogenic pollutants [72,74], and possibly also to osmotic stress due to brine effluent from desalination discharge. Although Nematodes are used as bioindicators for different pollutants, [71,74] to date no dedicated studies were conducted to assess the impact of desalination on the activity and biodiversity of nematodes.

Crustaceans were also shown to be highly sensitive to many different anthropogenic pollutants [75,76] as well as to salinity increase due to SWRO brine-effluent discharge. For example, amphipods assemblages studied near the San Pedro desalination facility in SE Spain where they were exposed to high salinity levels of up to 53 near the brine-effluent outfall [77] show reduced abundance and diversity (Fig. 11.2, Shannon-Wiener index). Moreover, salinity changed the biological traits and functionality of the community selecting for detritivorous and domicolous species, at the expense of carnivorous, omnivorous, and fossorial species. It should be noted that once a diffuser system was deployed at the end of the discharge pipeline (4 years after operation initiation), amphipods abundance rapidly recovered.

Near the same desalination facility, an investigation of brine-effluent effects on Polychaeta assemblages was also conducted [78]. Community parameters including family richness, diversity, and abundance were measured. Polychaeta assemblage was mainly disturbed close (0–300 m) to the discharge

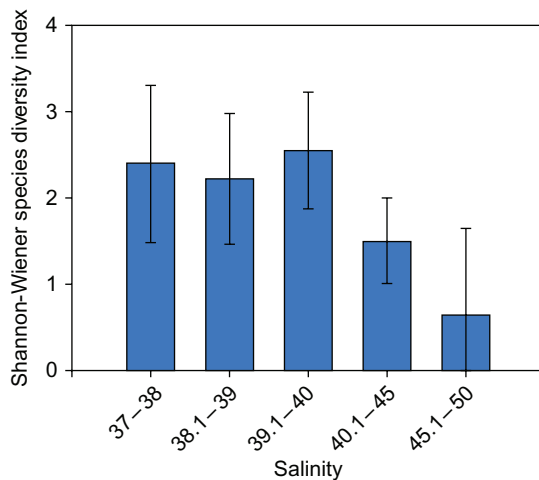


Fig. 11.2 Meiofaunal diversity in different salinities measured along a brine-effluent plume from four operating desalination facilities [77–80].

point, where abundance, richness and diversity were reduced. Following the deployment of the diffuser, nearly full recovery of the Polychaeta diversity and richness was achieved. Similar findings were reported in a study that was conducted in Chabahar bay (Oman Sea, Iran), indicating a decrease in abundance, richness, and diversity closest to the brine-effluent outfall [79]. Polychaeta were also investigated near the outfall of a large desalination facility in Alicante (NE Spain) discharging $\sim 65,000 \text{ m}^3 \text{ d}^{-1}$ of brine effluent at a salinity of 68 (note, brine was not mixed prior to discharge). Polychaeta assemblages were different at the outfall, and composed of a homogeneous group of several families. Measurements at the two stations closest to the brine-effluent outfall (distance of $\sim 660 \text{ m}$ between them) showed a decrease in richness, diversity, and abundance at all sampling dates (compared to un-impacted locations). It should be noted that a previous study has indicated that few Polychaeta families (Syllidae and Capitellidae) displayed short-term resistance or tolerance (Paraonidae) to osmotic stress, while the abundance of other families (Mpharetidae, Nephtyidae, and Spionidae) sharply decreased [80].

Echinoderms such as starfish, sea urchins, and sea cucumbers are also ecologically important benthic macro fauna. These organisms function as filter feeders and predators of benthic algae, benthic bacterial consortiums (termed also as biofilms), as well as other meiofauna such as bivalves and snails. It has been shown that this group of organisms can comprise $>90\%$ of the benthic biomass [81]. Echinoderms were reported to be strict marine phyla and therefore are expected to be highly sensitive to changes in salinity [46]. A study conducted near the Alicante desalination plant pointed out a significant decrease in Echinoderms abundance (100%) after the desalination plant started operating (2003) [82]. A significant recovery of Echinoderms abundance was noted after initiating mixing of the brine effluent with seawater prior to discharge. A recent study [77] noted that the use of Echinoderms abundance and the benthic opportunistic polychaeta and amphipods (BOPA) indices were an effective and convenient measure for the determination of environmental degradation as a result of brine-effluent discharge. The BOPA (Eq. 11.1) indices measure the proportion of opportunistic Polychaeta families (Capitellidae, Eunicidae, Magelonidae, Nephtyidae, and Paraonidae) [78] in relation to the proportion of amphipods, which are considered to be sensitive to environmental changes. It is calculated according to the equation:

$$\text{BOPA} = \log \left[\frac{f_{P_{op}}}{f_a + 1} + 1 \right] \quad (11.1)$$

where f_{op} is the opportunistic Polychaeta proportion of all fauna (0–1) and f_a is the amphipod proportion of all fauna (0–1) [83]. The maximum value of the index is 0.3013, and it indicates a highly disturbed area with only opportunistic Polychaeta families, while 0 indicates no opportunistic Polychaeta, or higher proportion of Amphipods in the benthic metazoan community.

During the last decade, a series of comprehensive monitoring surveys for benthic meiofauna (abundance and community structure) were conducted adjacent to large-scale SWRO desalination facilities located on the Israeli coastline [16,18,29–31]. These facilities apply two disposal approaches: surface discharge of brine, which is diluted with cooling water of an adjacent power plant (used at Hadera and Ashkelon desalination plants) or a diffuser system discharging the brine away from the shore (used at Sorek\Palmachim desalination plants). Significant changes to the community structure of benthic meiofauna near the brine\cooling-water outfall of Hadera and Ashkelon desalination facilities were reported [17,28]. In some cases, there was also a reduction in the abundance of benthic meiofauna next to the outfall brine\cooling water. It should be stressed that these effects were only observed within a few hundred of meters of the discharge point and could not be linked directly to osmotic/temperature stresses related to brine-effluent discharge [17,28]. Instead, it was suggested that these changes in benthic meiofauna resulted from physical disturbance of the sediment due to the strong water currents of the discharged brine/cooling water [17,28]. Monitoring reports from the Sorek\Palmachim desalination outfall list no significant impacts of brine effluent on benthic meiofauna [18,30,31]. However, a report from 2014 noted that some local effects on the community structure of benthic meiofauna may be linked to the brine-effluent discharge [30]. These reports concluded that additional monitoring campaigns were recommended to determine the significance of these effects.

11.6 THE EFFECTS OF DESALINATION BRINE EFFLUENT ON SEAGRASS

Seagrass meadows are highly productive habitats and form key ecosystems in coastal environments worldwide [84,85]. Seagrass meadows export on average 24% [86] of their net production and serve as important trophic links to nearby ecosystems [84]. The contribution of seagrass meadows includes sediment stabilization and improvement of water clarity, source of food to the coastal and adjacent ecosystems, provision of oxygen to the water and

sediment as well as a habitat for various organisms [84,85]. Accordingly, seagrass meadows are estimated as one of the most valuable habitats in terms of ecosystem functionality [87]. SWRO desalination facilities have shown to impact the physiology and growth of seagrass meadows due to osmotic stress around the brine-effluent discharge point (Fig. 11.3) [88–91].

Posidonia oceanica is an endemic specie to the Mediterranean Sea [92]. In a series of mesocosm experiments, the susceptibility of *P. oceanica* to elevated salinities was tested by evaluating the mortality of leaves and their recovery after returning to ambient salinities [91]. It was found that the growth of the leaves was inhibited in salinities above 39 and overall mortality occurred at salinities above 53. A later study examined the effects of elevated salinities [37–43] on photosynthesis by *P. oceanica*. The results indicate that net and gross photosynthetic rates of *P. oceanica* were significantly reduced by 25%–33% and 13%–20%, respectively, following exposure to higher salinities than

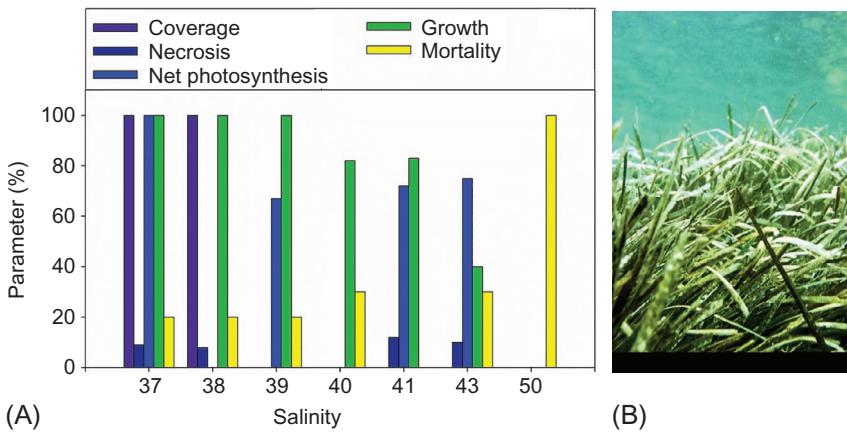


Fig. 11.3 (A) Ecological and physiological parameters of Seagrass that were altered due to elevated salinities. Measurements were taken from mesocosm experiments and different environmental samplings. All data represent percent change from the control in the specific study or experiment the data were taken from. (B) An example of *Posidonia oceanica* meadow, Photo credit (personal permission): Sagi Maayan. (The data for the figure were adapted from Gacia E, Invers O, Manzanera M, Ballesteros E, Romero J. Impact of the brine from a desalination plant on a shallow seagrass (*Posidonia oceanica*) meadow. *Estuar Coast Shelf Sci* 2007;72(4):579–590. Fernández-Torquemada Y, Sánchez-Lizaso J.L. Effects of salinity on leaf growth and survival of the Mediterranean seagrass *Posidonia oceanica*. *J Exp Mar Bio Ecol* 2005;320(1):57–63. Marin-Guirao L, Sandoval-Gil J.M, Ruz J.M., Sánchez-Lizaso J.L. Corrigendum to photosynthesis, growth and survival of the Mediterranean seagrass *Posidonia oceanica* in response to simulated salinity increases in a laboratory mesocosm system. [*Estuar Coast Shelf Sci* 2011;92:286–296]. *Estuar Coast Shelf Sci* 2011;93(1):86.)

the control. In addition, dark respiration of *P. oceanica* increased significantly (by 98%) when exposed to high salinities [41,43]. It was suggested that the respiratory demand for osmoregulation reduces the photosynthetic rates and therefore inhibits growth [89]. An in situ study that was performed close to an operating desalination facility at the Balearic Islands of Spain found that chronic exposure to the brine effluent resulted in *P. oceanica* leaf necrosis [90]. Finally, it has been reported that no *P. oceanica* were observed up to 25 m from the discharge point [90].

Cymodocea nodosa also showed sensitivity to exposure to SWRO brine effluent [93]. *C. nodosa* is a relatively small, fast-growing seagrass that can tolerate a broad range of environmental conditions. Nevertheless, exposure to brine effluent for 1 month (near the Alicante desalination plant, NW Spain) caused reduction in growth rates and higher mortality of shoots closer to the brine-effluent discharge [93]. It has been suggested that the constant salinity increase following brine-effluent discharge resulted in higher energetic costs, due to a need for maintenance of a proper turgor pressure. It has also been speculated that *C. nodosa* plants were losing their inner cellular water content and were accumulating ions from the environment to achieve the proper pressure to cope with the elevated salinities. Changes in water salinities and osmoregulation were possibly the reason for shoots deterioration following the chronic exposure to SWRO brine-effluent.

Hence, it has been previously suggested that seagrass species inhabiting soft bottom habitats may serve as bioindicators for habitat degradation in response to brine-effluent discharge [92,94]. Criteria for seagrass species to be used as a bioindicator for the impact of brine effluent on the coastal environment were established by carrying controlled, laboratory experiments. The Seagrass *Posidonia australis* was incubated for 6 weeks at elevated salinities [37–54] and the following physiological parameters were monitored: survival, growth, photosynthesis, metabolism parameters, carbohydrate, and amino acid concentration [95]. Additional mesocosm experiments were conducted in order to evaluate the growth and survival of other seagrass species including *C. nodosa* and *Zostera noltii hornemann*. These seagrass species were grown with salinities of up to 72 [91]. It should be noted that these salinities levels are not found next to the outfall of operating desalination facilities. Nonetheless, in these studies, survival and growth of shoots were significantly decreased compared to the control treatments. Additional physiological parameters of *P. australis* were found to be affected by the high salinity concentrations after 6 weeks of incubation [95]. Specifically, it was found that amino acids composition in rhizome and leaf tissues increased, and compatible solutes concentration in leaf tissue raised [95].

It has recently been reported that for large seagrass species necrosis had the shortest response time to hypersalinity, while in small species photosynthetic rate, necrosis, leaf growth, and mortality all had a similarly short response time. In both cases, response time ranged from immediate to 10 weeks [94]. We conclude that it is essential to test what are the proper physiological parameters (e.g., photosynthetic rate, leaf necrosis, and meadow density) to be used in order to evaluate the extent of habitat deterioration. It should be highlighted that the seagrass species and the relevant brine-exposure time should also be considered before using seagrass as brine-effluent bioindicators.

11.7 DESALINATION BRINE-EFFLUENT IMPACTS ON FISH LARVAE

Fish eggs and larvae are small (1 mm to >10 mm, species dependent) plankton that drift in the upper photic zone of the water column. Fish eggs are completely dependent on ocean currents, buoyancy, and water density for their position in the water column, while the larval stage have some limited swimming ability [96–98]. The larvae are hatched with yolk sac still attached to their body, which is consumed within the first few days after hatching (Fig. 11.4). As larvae grow, they start developing swim bladders, which are used by adult fish to maintain buoyancy [98,107]. Temperature increase (within the species' tolerance range) tends to accelerate embryo and larvae

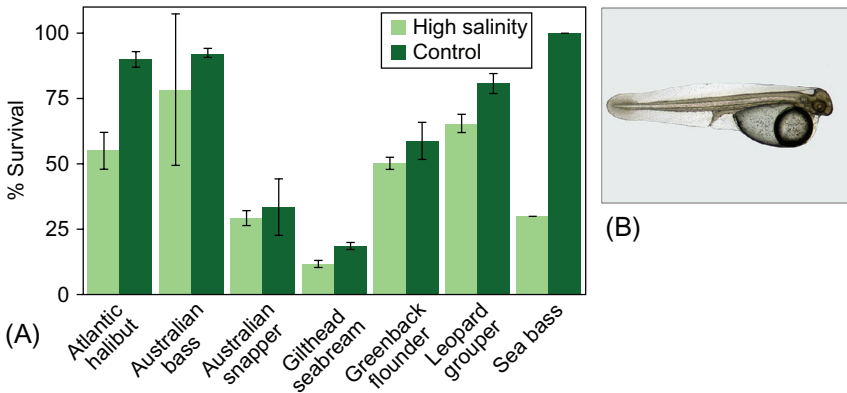


Fig. 11.4 (A) The percent survival of the larvae of seven species of fish. Larvae were hatched in either “optimum salinity” (Control) or in salinity treatments ranging from 5% to 15% over optimum [99–105]. (B) A newly hatched Sea Bass larvae, photocredit (personal permission); David J Ostrach, pH.D [106].

development, which can increase the risk of larvae mortality since the development time is shortened [107,108]. At the early developmental stage, fish larvae undergo significant morphological changes. Therefore, the larvae are more susceptible to environmental changes [108,109]. The development of the egg and larvae can vary from days to weeks depending on the species; therefore, larvae can be affected by changes in their environment even if the exposure is on time scale of hours [98,107,110,111].

Larvae and eggs of different fish species appear to have great resilience to small changes in salinity. However, at salinity increases of ~50% or higher than ambient (which are rarely or ever encountered in modern desalination facilities), larvae and eggs show significant and acute mortality (after 24–48 h of exposure) [112–114]. Increasing salinity to 5%–15% above ambient (which could be encountered sometimes close to the outfall) lowers the larvae's survival rate, but the impact is rarely found to be significant. Fig. 11.4 compares the survival of larvae of 7 species of fish when salinity is increased by 5%–10% over ambient conditions [99–105]. In addition to increased mortality, it has been shown that fish larvae decrease in size and have higher degree of defective and/or inefficient inflation of swim bladders when cultivated in salinity of 10%–15% higher than ambient [99,100,104,105,113].

In laboratory experiments, higher temperatures (~5°C over ambient) lowered the survival of fish eggs and larvae [102,103,109]. Higher temperatures can also shorten the hatching time of eggs resulting in undeveloped larvae or a quicker absorption of the yolk sac of developed larvae [115]. Certain species have shown swim bladder defects at higher temperatures, and one species (Australian Snapper, *Pagrus auratus*) had a 100% mortality rate with a 30% temperature increase above maximum environmental temperatures for 9 days [100,102,116,117].

Larvae of different species of fish respond differently to various stressors. For some species, the combined effect of increasing salinity and temperature increased mortality and swim bladder deficiency [103,116], but for other species this synergy was not found and only temperature changes were found to have a significant impact on the larvae [100,102].

At present, no studies have investigated the effects of chemicals used (antiscalants and coagulants) in SWRO desalination facilities on fish larvae or fish. However, studies on coagulants (aluminum based) in a fresh water setting have shown a negative impact on fish embryo development and fish larvae survival at high concentrations [53,118]. To the best of our knowledge, there are currently also no published studies reporting on experiments with actual brine effluent from desalination plants; hence, the direct effects

of SWRO brine-effluent discharge on fish eggs or larva remain unknown. We stress that dedicated research as well as monitoring programs are highly needed to evaluate the impacts of desalination brine-effluent discharge on prominent species of fish eggs and larvae around the outfall of these facilities.

11.8 THE EFFECTS OF DESALINATION BRINE EFFLUENT ON CORALS PHYSIOLOGY

Coral reefs comprise some of the richest habitats in the ocean, supporting great biodiversity, biomass, and productivity [119]. In addition, coral reefs are important for local economies, fisheries, and tourism [119–121]. Corals are marine invertebrates (phylum: Cnidaria; class: Anthozoa) and the hermatypic coral species (reef building) can consist of large colonies that span many kilometers. These corals have a mutualistic relationship with dinoflagellates of the genus *Symbiodinium* (referred to as Zooxanthellae) that are integrated within the tissue of the coral where they provide organic matter to the coral via photosynthesis in return of nutrients [122,123]. Corals are osmoconformers and adjust their osmotic balance with intercellular osmolytes. The osmotic balance can be affected by many environmental stressors (temperature, nutrient levels, and salinity changes) and an imbalance of osmolytes often leads to coral bleaching [124]. Coral reefs are often found around tropical, subtropical, and even cold-water regions resulting in specific adaptations (e.g., to temperature, salinity, etc.) of species even within the same genus [125,126]. In the last decade, coral reefs have experienced an increase in the extent and frequency of bleaching events due to different environmental stressors such as rising ocean temperatures, seawater acidification as well as anthropogenic impacts such as coastal eutrophication [120,121,127–130]. In line with these, the construction of new desalination facilities around coastal zones with coral reef ecosystems raises concerns over the possible impact on coral physiology and survivability [131,132].

Coral habitats can experience changes in salinity on diurnal and seasonal time scales as tides and rainfall/evaporation can impact local salinity [133]. Short-term exposure studies (5–7 days) with elevated salinities (~15% above ambient) have shown a similar response in different coral species (*Porites furcata*, *Siderastrea radians*, and *S. siderea*): (i) decrease in primary production within the first 6–12 h following exposure, (ii) retraction of coral polyps, and (iii) discoloring of the tissue [134–136]. In these studies, corals were able to recover to normal primary productivity rates (postincubation) within 36 h to 1 week, and made a full recovery of polyps and tissue within 1 week to a month.

Previous reports have indicated that exposure of *Stylophora pistillata* for 3 weeks to increase salinity of ~10% above ambient resulted in 70% mortality [137]. However, in a recent study with *Stylophora pistillata* in 10% above ambient salinity, mortality was not detected, but a significant drop in protein content and zooxanthellae abundance was measured (Fig. 11.5). A similar response was observed for *Acropora tenuis* and *Pocillopora verrucosa* both in salinity of 10% over ambient and in 10% increased salinity with addition of phosphanate (<2 mg/L).

The dramatic decrease in zooxanthellae and protein contents (Fig. 11.5) and the mortality reported by Ferrier-Pagès [137] stresses the need for monitoring of coral reefs in the vicinity of desalination plants. A recent in situ study (the only one to date) in the Red Sea has positioned the coral *Fungia granulosa* at the discharge channel of an operating SWRO plant and followed different parameters [132]. The corals showed no change in primary production and none of the specimens were significantly affected. Furthermore, pure cultures of the symbiotic zooxanthellae (*S. microadriaticum*) were incubated in salinities between 25 and 55. Cell growth of *S. microadriaticum* was found to decrease only in salinities of 55 (which is not likely to occur around the outfall of SWRO desalination facilities), indicating a high salinity tolerance of the zooxanthellae.

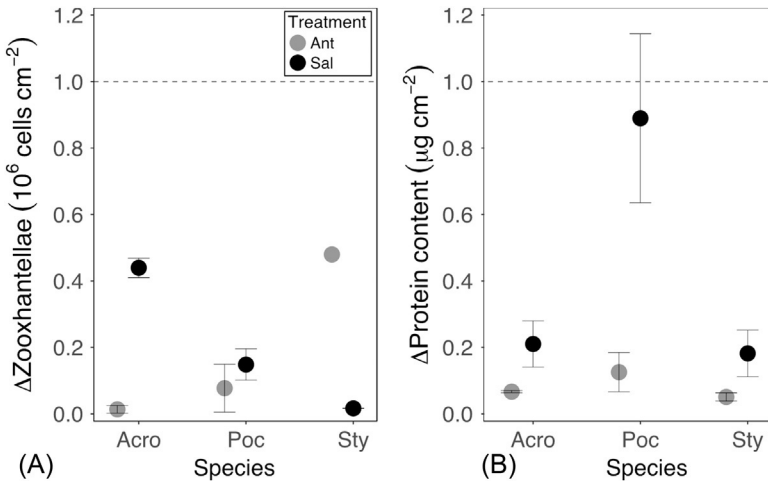


Fig. 11.5 Data from 4-week-long coral incubation with 10% salinity increase over ambient (*solid black*) and 10% salinity increase with 6 μL L⁻¹ phosphanate addition (*solid gray*). (A) The relative change between treatment and control zooxanthellae abundance for *Acropora* (Acro), *Pocillopora* (Poc) and *Stylophora* (Sty). (B) Relative change in protein content between treatment and control.

In general, antiscalants (phosphonate based) are not harmful in the doses used in desalination plants (~ 2 mg/L) [138]; however, recent observations pointed that these concentrations may impact the physiology of *S. pistillata*, *A. tenuis*, and *P. verrucosa* (Petersen et al., unpublished data). To the best of our knowledge, no published studies have reported on the effects of coagulants on corals.

Rising ocean temperatures is one of the main stressors causing coral bleaching [128,139]. The water temperature of desalination brine effluent can be elevated compared to background ambient temperatures (by up to 25% over the ambient), and this results in local plumes of warm seawater around the discharge area ([8,10,140], Frank et al., unpublished data). Exposure to temperature of as little as 3°C above mean maximum levels for several weeks has shown to cause bleaching in *Pocillopora* sp., *Montastrea* sp., *Acropora* sp., and other species spanning reefs in Hawaii, Caribbean, and Australia [125,126,140–142]. Thermal stress was also positively correlated with coral disease outbreaks [125,139]. However, the response varies based on location as *S. pistillata*, *P. damicornis*, and *A. eurystoma* that were collected in the Gulf of Aqaba (Red Sea) did not show any significant change after 4 weeks of incubation in temperatures of 10% above ambient. Only at a 40% temperature increase (from $\sim 25^\circ\text{C}$ to 34°C), the abundance of zooxanthellae was significantly reduced [143].

Corals exposed to multiple environmental stressors tend to have a higher risk of bleaching and a higher mortality rate [128,134,139]. This is because the efficiency in which the corals sustain energy-demanding processes becomes compromised under multiple stressors. This effect was shown by Lirman et al. [134] who exposed corals to salinity of 25% above ambient and found that they were unable to clear their tissue of sediment [134]. The response to different stress factors, such as increased salinity and temperature, is variable between species of coral even in the same geographic location. This underlines the difficulty of providing globally relevant guidelines for desalination management around coral reefs to minimize possible impacts, and emphasizes the need for local environmental studies prior to the construction of large-scale desalination facilities. At this point, published data on the direct effect of desalination brine-effluent discharge on coral reefs are extremely scarce and virtually nonexistent. Therefore, we stress that coral mesocosm studies (short term) as well as dedicated monitoring schemes (long term), should be carried out to determine the local impact of brine-effluent discharge on coral reefs.

11.9 LOOKING FORWARD: NEXUS OF SWRO DESALINATION AND COASTAL ENVIRONMENTS

SWRO desalination industry is booming with a tight, bidirectional (intake and discharge) interface to the coastal environment. Extensive information has been accumulating during the past decade with respect to the possible impacts imposed by the desalination industry on the marine environment [8,11,17,18,22,24,25,32,36–38,79,138]. These effects were suggested to impact different marine organisms; however, they were more pronounced in sessile organisms such as seagrass or benthic fauna. It should be stressed that the reported impacts of most SWRO desalination were highly local and restricted only to the vicinity of the intake port or the outfall area. Yet, we surmise that due to growing water scarcity, future concerns related to desalination expansion and possible impacts to coastal environments (specifically to enclosed and sensitive ecosystems) should be further evaluated. These impacts may include: (i) Construction of new SWRO desalination facilities at high densities; (ii) Designing increasingly larger SWRO desalination plants with greater production capacities ($>300 \text{ Mm}^3 \text{ y}^{-1}$) and (iii) Drawing large volumes of feed-water from the ocean, while discharging large amounts of brine effluent to coastal environments with limited water circulation.

We suggest that mitigating the impacts of the SWRO desalination on the coastal environments in years to come could be optimized (together with standard provisions such as near- and far-field modeling) by the following measures:

- (i) Carrying dedicated precursory environmental-impacts-assessments that are site specific. Namely, to determine the chemical concentrations at which adverse biological effects are apparent for endemic organisms prior to the contraction of any large-scale desalination facility. These values should be used as a reference point and set the criteria for future, long-term monitoring surveys.
- (ii) Conducting long-term monitoring programs that are tailored to each desalination site (e.g., based on the biology and hydrography of the location) or region (such as the oligotrophic environment or semien-closed lagoons). Parameters that will be monitored should be pre-determined according to ranges of sensitivity of key organisms that are relevant to the coastal environment, similar to Long et al. [144]. We stress that these monitoring programs should be dynamic and evaluated yearly to minimize oversampling and reduce redundancy

in terms of the sampled parameters. Providing such data could contribute to better and more realistic regulation for the interface of the desalination industry and coastal environments.

- (iii) Applying best-available technology to reduce any possible effects on the coastal environment that may result from SWRO desalination brine effluent. We propose that using diffuser systems as a favorable discharge approach will reduce the impact of brine on the coastal ecosystems. The advantages of the diffuser systems over surface discharge include minimizing the dependency on power-plant cooling water for dilution and setting the buoyancy of the brine-effluent plume prior to discharge. In addition, using diffuser system will enable to discharge the brine far from the shoreline and/or away from any ecologically sensitive areas. Brine effluent can be allocated via the diffuser system into predetermined locations, thereby maximizing dispersion by coastal currents. Finally, we urge that additional impetus should be allocated toward development of new approaches to minimize the use of chemicals in the desalination process [145] and eventually toward zero liquid discharge solutions.

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