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Perspective on desalination discharges and coastal environments of the Arabian Peninsula☆

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ABSTRACT

Two opposing views are held about the effects of desalination plants on coastal environments. One view is that brine discharged from desalination plants has minimal impact on the coastal environment. The other opinion claims that discharges from desalination plants pose a potential environmental hazard to coastal environments and particularly to those of the Arabian Gulf. The present study was carried out to determine whether negative environmental impacts could be detected in coastal waters of the Gulf and Red Sea near discharges from desalination plants in Saudi Arabia. Phytoplankton abundance, concentrations of chlorophyll *a*, nutrients, total suspended solids, trace metals, chlorination by-products, bacterial growth, and toxicity of effluents were assessed. Results indicate the brine discharges were not toxic to fish or brine shrimp. Mitigation of impacts from elevated temperature, salinity and chemicals in dual purpose plants is partly achieved by pre-dilution of brine reject stream with cooling water. Alternative pretreatment methods, chlorination and waste treatment are considered. There is accumulation of corrosion metals in sediments at the discharge site of a plant on the Gulf coast. However, their concentrations were within regulatory limits.

1. Introduction

The Arabian Peninsula, which is largely Saudi Arabia, with renewable water resources < 1000 m^3/capita/yr is a water scarce region as defined by the World Health Organization (WHO). Potable water demand in this region cannot be met from natural water resources. The Arabian Peninsula is a prime example of arid land where countries have opted for seawater desalination for fresh water supply, and it leads the world in production of freshwater through desalination (IDA Desalination Year Book, 2013; Dawoud and Al-Mulla, 2012). Desalination plants in the region are sourced either from coastal waters of the Red Sea or the Arabian Gulf (Gulf). These desalination plants source their water from open intake systems and discharge it directly into coastal waters. Desalination plants on the Gulf produce approximately 15 Mm^3 water/day (Dawoud and Al-Mulla, 2012). To satisfy this production 130 Mm^3/d must be withdrawn from the Gulf. Out of this, approximately 115 Mm^3/d are returned to the Gulf as brine discharge. Saudi Arabian desalination plants on the Red Sea remove approximately 17 Mm^3/d of which approximately 15 Mm^3 are discharged as brine. Desalination plants need clean water as feed; therefore, desalination authorities in the region have a great interest in keeping coastal waters free of pollution. The Red Sea is used less intensively for desalination than is the Gulf, and the Red Sea, being very deep and with more active water currents, is less prone to environmental perturbations compared to the Gulf. The physical configuration of the Gulf (e.g. its shallow depth and extremely low water exchange rate) poses distinct environmental challenges. These challenges are compounded by the intensive use of the Gulf as both a water source and an effluent recipient for other industries and anthropogenic activities.

In December 2010, the International Desalination Association (IDA) presented its first environmental symposium, "*Desalination and the Gulf: The Relationship between the Environment and Meeting the Region's Water Needs*" At Manama, Bahrain. This event was the culmination of a 12-month environmental assessment of the desalination industry by the IDA Environmental Task Force (ETF). The ETF produced a Blue Paper shaping a platform for action to safeguard the environmental well-being of the Gulf for future generations (International Desalination Association (IDA), 2011).

A comprehensive environmental database for coastal and open seawater opposite the Red Sea and Gulf desalination plants is lacking, but available data have lead to opposing views. One view suggests that brine discharged from desalination plants has minimal impact on the coastal environment (Viskovich et al., 2013; Vega and Artal, 2013; Saeed and Al-Nomazi, 2013). Therefore, popular reports about coastal

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water pollution from desalination plants seem overly cautious. The other opinion holds that discharges from desalination plants pose a potential hazard to coastal environments and particularly those of the Gulf (Dawoud and Al-Mulla, 2012; Van Gils, 2010; Lattemann, 2005).

The opinion that desalination plant discharges are of minimal impact on the coastal environment is supported by two facts: 1) most constituents of desalination discharge are not harmful to the marine environment; 2) most plants are dual purpose facilities producing freshwater and generating electricity. Dual purpose operation is significant from an environmental perspective, because brine from desalination is diluted by huge quantities of cooling water. These two events offset the most common negative environmental impacts associated with brine discharges: increased salinity and water temperature in outfall areas.

Effluents from seawater reverse osmosis (SWRO) plants have higher salinities than do those from distillation plants because of higher recovery of desalinated water without need for cooling water. However, most SWRO plants in Saudi Arabia are co-located with distillation plants and share the same discharge structures. The cooling water of the distillation plants dilute the high salinity effluent from SWRO plants. Moreover, electrical generation facilities often located with desalination plants discharge additional cooling water that is mixed with the desalination effluent.

Another important reason for the minimal impact of brine discharge is the design of discharge structures that helps in negating possible environmental perturbations. Such discharge structures include *in vivo* pressured brine discharge nozzles and cascading open discharge channels (Viskovich et al., 2013; Al-Tisan and Saeed, 2014). The opposing opinion that brine discharge is a potential hazard to coastal environments stems from the fact that discharges from desalination plants contain various chemicals that could negatively impact aquatic life. There is also potential, negative impact from changes in the physical attributes of the receiving water such as increased temperature and salinity.

The aim of the present study is to assess impacts of desalination plants operated by the Saline Water Conversion Corporation (SWCC) of Saudi Arabia on coastal waters of the Gulf and Red Sea. Impacts of desalination discharges were assessed on biotic and abiotic components of the coastal water in the brine discharge sites and compared to both the intake sites and at Jubail to a control site 3 km north of the Intake bay representing uncontaminated conditions.

2. Materials and methods

Experiments were carried out to measure certain water column parameters in discharge sites and compare them to control site representing pristine seawater in four of the Saudi Arabian Saline water conversion Corporation's (SWCC) desalination/power plants (see Fig. 1). Parameters measured include: physico-chemical parameters (pH, temperature, and salinity), phytoplankton, chlorophyll *a*, nutrients, trace metals in water and fish tissues, toxicity, bacterial growth, and total suspended solids. Parameters measured at each desalination plant, dates of sampling and justifications for parameters analyzed are given in Table 1.

2.1. Locations

Environmental assessments were conducted at multi-stage flash (MSF) and SWRO desalination plants at Jubail, Saudi Arabia (Arabian Gulf coast) and at Jeddah, Saudi Arabia (mid-section of Red Sea). In addition, the study included a SWRO desalination plant at Haql located in the uppermost reaches of the Red Sea and a MSF desalination plant at Shuqaiq on the southern Red Sea coast (Fig. 1).

The Jubail desalination and power plants produce 1.2 Mm^3 of desalinated water per day of which 90,000 m^3 comes from a SWRO plant, commissioned in 1995. The MSF plant, commissioned in 1983, is a dual

Fig. 1. Sampling locations.

purpose plant generating 24,250 MWH of electricity per day. The plants are sourced from an excavated intake bay lagoon. The intake bay serves as a reservoir of source water for the plants. It is an excavated manmade lagoon set into the coast-line. The lagoon is protected and separated from the sea by cement breakwater walls with a 330-m wide opening onto the open sea. The mouth of the intake bay is 1.8 km from the shore. The lagoon extends ≈2.5 km along the shore and widens reaching a width of 700 m towards the middle. The water column depth is 4.2–5.4 m, depending on tide conditions (Fig. 2). Source water is withdrawn by five pumps creating a steady flow of water from the open sea. Brine is discharged into an open canal sitting well below the individual discharge lines of the desalination units. The canal is 2-km long with a depth of ≈2 m, and cascades towards the sea where there is a sudden outfall of brine into the coastal waters. The MSF plants and the SWRO plant share a common intake and discharge facilities. Brine is first collected from the MSF plants and discharged into the brine discharge channel and cascade towards the sea before being joined by discharge from the SWRO plant approximately 500 m from the discharge point. Just in front of the discharge point, there is a breaker wall that induces sufficient mixing and dilution before directing the flow of brine away from the intake area (Fig. 2). The depth of the receiving coastal water is 3–5 m depending on tide condition. Total seawater intake is 10–12.5 Mm^3/day, and the daily discharge is 9.0–11.2 Mm^3 made up of brine (≈10% of discharge) and cooling water (≈90% of discharge).

The Jeddah plants produce 500,000 m^3 of desalinated water per day (192,000 m^3 from MSF plant and 308,000 m^3 from SWRO plant) and generate11,600 MWH per day of electricity. The MSF plant was commissioned in 1981 and the SWRO plants comprised three phases: phase-1 with export design capacity of 49,000 m^3 was commissioned in 1989; phase-2 with export design capacity of 49,000 m^3 was commissioned in 1994; and phase-3 with export design capacity of 210,000 m^3 was commissioned in 2013. The plants are sourced from three adjacent intake points located about 40 m away from shore at a depth of 15 m. The MSF and SWRO plants share common intake and discharge structures. Their brine collects in a closed canal and discharges into an open coast area which is initially shallow (≤3 m) for about 50 m before sloping down sharply into deep coastal water of approximately 50 m depth. The discharge is ≈ 2.3 Mm^3 of water per day divided in a ratio of 1.0:2.8 (SWRO: MSF).

The Haql SWRO plant, commissioned in 1989, produces 4500 m^3 of desalinated water per day and discharges brine from a covered canal into the immediate coast water which is initially shallow before sloping down into deeper water of ≈20 m depth. The plant is sourced from the Gulf of Aqaba northern Red Sea. The water flows by gravity, through two pipes each 1-m diameter and extending from an intake chamber at

Table 1
Coastal environment parameters measured and dates of sampling.

Parameters	Plant	Date	Justification
Physico-chemical parameters	Jeddah (MSF/SWRO, Red Sea), Jubail (MSF/SWRO, Gulf)	2015–2016	Temperature and salinity are the most outstanding attributes of desalination/power plants discharge.
Phytoplankton and chlorophyll	Jeddah, Haql (SWRO, Red Sea), Jubail	2015–2016	Essential indicators for primary productivity.
Nutrients	Jeddah, Jubail	2015–2016	Trace any nutrient input from desalination plants and contrast with phytoplankton abundance.
Trace metals	Jeddah, Haql, Jubail	2015–2016	Accumulation of corrosion metals in water, fish and sediments.
Toxic effects	Jeddah, Haql, Jubail, Shuqaiq (MSF, Red Sea)	2016	Reveal toxic effects of brine to representative marine organism. Compare toxic effects of discharges from combined MSF/SWRO plants and individual SWRO and MSF plant.
Sediment Analysis	Jubail	2018	Indicate accumulation of trace metals and chlorination by-products in sediments in comparison to water column
Bacteria	Jeddah, Jubail	2015–2016	Bacterial generation time reflects on nutrient availability and biofouling on SWRO membranes.
Total Suspended Solids (TSS)	Jeddah, Haql, Jubail	2015–2016	TSS affect phytoplankton abundance and reflect on addition of suspended solids from pretreatment filters.

a depth of 5 m and 25 m from coast to a receiving shore tank. Water is pumped from the receiving tank to the plant. The Shuqaiq MSF plant, commissioned in 1989, produces 106,000 m^3 of desalinated water and generates 2137 MWH of electricity per day. The plant is sourced from an intake channel of 680 m length and a minimum depth of 4 m. The plant discharges brine from an open canal to coat water that is approximately 6 m deep.

2.2. Chemical additives

Chlorine is the common disinfectant used in all plants. In MSF plants (Jeddah, Jubail and Shuqaiq), chlorine is generated electrochemically from chlorine generators on shore and transported and dosed at the intake points. In Haql SWRO plant chlorine is produced from calcium hypochlorite and dosed at the intake chamber and at a receiving tank on shore. Sodium meta bisulfite (SBS) is dosed continuously after a dual media filter and is stopped for 1 h daily to allow chlorine to pass over the desalination membranes. Ferric chloride is used as coagulant and sulfuric acid is used as antiscalant.

In Jeddah, Jubail and Shuqaiq MSF plants, anitscalants used are polymers of polycarboxyllic acid containing no phosphorus and the antifoaming agents used are silicone-based chemicals containing mainly polydimethylsiloxane which is free from inorganic fillers.

2.3. Physico-chemical parameters

Temperature, salinity and pH were measured at Jeddah and Jubail. Temperature was measured using a mercury thermometer, pH a portable pH meter and salinity a temperature-compensated refractometer.

2.4. Phytoplankton

Phytoplankton in intake and discharge sites were captured with a standard, 55 μm mesh Nansen plankton net that was towed behind a boat at about 2 knots (3.7 km/h) for 10 min. On average, this procedure filtered 30 m^3 of water per tow. Plankton organisms removed from the plankton net were preserved in 5% buffered formalin. The abundance of phytoplankton was estimated by counting individuals in a 2.5 ml subsample placed in a Sedgwick Rafter counting chamber under a light microscope. Phytoplankton in discharge channels of desalination plants were enumerated in samples obtained by filtering 5000 ml effluent through the plankton net and transferring the captured plankton to 50 ml sterile seawater.

Chlorophyll *a* concentrations were measured in water samples collected from intake and discharge sites. Samples were filtered through 0.45 μm Millipore filters, extracted with acetone, and the extract was subjected to spectrometry (Parson et al., 1985).

2.5. Nutrients and total organic carbon

Inorganic nitrogen compounds (ammonia, nitrite and nitrate), phosphate, silicate and dissolved protein and sugar were measured in water samples from the Jeddah and Jubail sites following standard protocol presented in a manual of seawater analysis (Parson et al., 1985). Total organic carbon (TOC) was determined by using a non-dispersive, infrared detector after samples were acidified to purge off total inorganic carbon (American Public Health Association (APHA), 1998).

2.6. Trace metals in water and fish tissues

Concentrations of trace metals which are normally associated with

Fig. 2. General view of the intake and brine discharge system and coastal area of the Jubail desalination and power plants (left), and close view of the brine discharge channel (right).

corrosion were determined in source and discharge waters at Jubail, Jeddah, and Haql plants. One liter water samples were filtered (0.45 µm), and acidified by addition of nitric acid to obtain a sample pH of 2.0. Iron, nickel, copper and chromium concentrations were measured by atomic absorption technique (American Public Health Association (APHA), 1998).

Trace metal concentrations were also determined in tissues of fish held for 5 days in cages at the effluent outfall and in the intake water site at the Jeddah desalination plants. Rabbitfish *Siganus rivulatus* (approximately 50 g weight), obtained from a cage culture facility in coastal waters north of the plants, were suspended in fish cages at both locations. After 5 days, fish were dissected using a stainless steel dissecting kit, excised pieces of tissues were removed and freed from external moisture by blotting paper and weighed. Liver and muscle tissue from the dorsal mid-section of each of three fish from both sampling locations were analyzed for the trace metals iron, nickel, copper and chromium. These metals were also determined in fish captured from those congregating at the brine discharge site of the Jubail plants and in fish caught from the intake bay of the Jubail plants. Tissue samples also were obtained from moribund fish collected after the occurrence of sudden fish mortality in the Gulf coastal water near the Jubail desalination and power plants. Tissues were first digested in a solution of 0.25% hydrogen peroxide and 0.125 M nitric acid, and the mineralized contents were refluxed for several hours at relatively low temperatures until the solutions cleared (Al-Sulami et al., 2002). Solutions were made up to known volumes with deionized water and metals were measured by atomic absorption as mentioned above and expressed on wet matter basis.

2.7. Sediment and seawater analysis including control samples

Surface sediment samples were obtained at low tide from the discharge area of Jubail plants at a distance of 150 m from the discharge point and 10 m from shore in an area of approximately 0.75 m depth. Water samples were collected from the same site and from three other locations: the intake bay, brine discharge of MSF plants and brine discharge of the SWRO plant. Control water and sediment samples were also obtained from an uninhabited beach at a distance of approximately 3 km north of the intake bay. Sediments were collected using a core sampler of 78.6 cm^2 area to a depth of approximately 10 cm.

Sediment and water samples were prepared for trihalomethanes determination according to EPA method 5021, and the analysis carried out according to EPA method 8260D (American Public Health Association (APHA), 1998). Trace metals of corrosion origin (iron, nickel, copper and chromium) were determined by atomic absorption (American Public Health Association (APHA), 1998).

2.8. Toxic effects

Static, acute toxicity tests were carried out with brine shrimp artemia (*Artemia franciscana*). Hatching rate of cysts and larval survival were compared in brine discharge and normal seawater for Jubail, Jeddah, Haql and for the Shuqaiq plants. Multi-well test plates were used for determining hatching success with continuous illumination (2100 lux) at 25 °C and larval survival rates were determined using the same plates following incubation in the dark at 25 °C for 72 h (MicroBioTests Inc, 2007). A quality control test was carried out using potassium dichromate provided with test kit and according to procedure described (MicroBioTests Inc, 2007). The concentration that gave a 24 h mortality close to 50% was reported.

2.9. Bacterial growth

Water samples from Jubail and Jeddah intake (normal seawater) and brine discharge were analyzed for the enumeration of culturable bacteria and calculate of growth rates (Saeed et al., 2000). The test results provided an indication of nutrient availability in the water and whether there were toxic effects in the discharge.

2.10. Total suspended solids

Total suspended solids (TSS) concentrations were determined by filtration of 1-l samples of seawater through tared, glass fiber filters. The filters were soaked in distilled water overnight, dried at 103–105 °C, cooled in a desiccator and weighed to a constant weight before use in the TSS filtration. These determinations were made at Jeddah, Haql and Jubail desalination plants.

3. Results and discussion

Results are presented below and discussed in an effort to ascertain whether effluents from desalination plants influenced measured water quality variables and fish trace metal concentrations or caused toxic effects. Increases in concentration of water quality variables and trace metal concentrations in fish from intake to discharge or greater toxicity in discharge than intake would suggest the possibility of negative impacts on coastal waters of the Red Sea and Gulf.

3.1. Physico-chemical parameters

In the Jubail plants intake bay, the temperature ranged from 16.0 °C at the start of the experiments in February to 27 °C at the conclusion of the experiments in June. The corresponding temperature values in the outfall were 21 °C in February and 36 °C in June. The pH values at the intake and outfall were similar, with a very narrow range from 7.9 to 8.1. The salinity range was 39–40‰ at the intake and 40–45‰ at the outfall. It is to be noticed that the Jubail plants intake bay has a wide mouth (300 m) to the open sea and there is a continuous flow of large volume of intake water (approximately 500,000 m^3/h). The large flow makes water characteristics in the intake bay similar to open sea opposite the plants shore (Saeed et al., 2002).

At the Jeddah plants, the temperature fluctuated by 4 °C from 27.8 to 31.7 °C. On any given sampling date, the difference in temperature between the intake and discharge sites (300 m from the discharge point) did not exceed 1 °C. The pH ranged from 8.1 to 8.3 while salinity varied between 39.3 and 39.9‰ at the intake and discharge sites respectively.

Marine biota in the Gulf tolerates a wide natural variation of water temperature of $\approx$15 °C in winter and $\approx$36 °C in summer. Fluctuations of water temperature in the discharge area are less than the naturally occurring winter-summer variation. At the discharge site, the temperature at the bottom is usually less than that of upper water column and might not be high enough to significantly affect the macrobenthos (Lin et al., 2018). Elevated temperature from discharge of a nuclear power plant on phytoplankton was found to increase phytoplankton density (Lo et al., 2004). There is a world-wide trend of membrane technologies dominating the market over thermal technologies. This dominance is best exemplified by the recent awarding of the 400,000 m^3/d SWCC Shoaiba SWRO plant in Saudi Arabia to a construction company (International Desalination Association (IDA), 2017). SWCC has also abandoned its MSF/power plant in Jeddah in favor of the new 240 m^3/d SWRO plant. Consequently, research will be geared more towards assessment of salinity effects. Marine biota are adapted to a saline environment and some species are euryhaline growing in a wide range of salinities such as the seagrass *Halodule* which can tolerate salinities up to 70‰, others such as *Syringodium* can only tolerate up to 40‰.

A six-year study testing for impacts and subsequent recovery of sessile marine invertebrates' recruitment near a SWRO plant outfall with high-pressure diffusers was carried out (Clark et al., 2018). The ecological impacts were found disproportionate to the relatively minor changes in salinity, suggesting a mechanism other than salinity. It was

Table 2
Phytoplankton density and chlorophyll-*a* concentration at different desalination plants on the Red Sea and Arabian Gulf coasts (n = 7).

Location	Parameter	
	Phytoplankton (Cell/m^3)[1]	Chlorophyll-*a* (mg/m^3)[1]
Jeddah (Red Sea mid-section):		
Intake site	$1.05 \times 10^5 - 9.87 \times 10^5$ (a)	0.38 − 2.20[a]
Brine discharge site	$1.19 \times 10^5 - 1.60 \times 10^6$ (b)	0.51 − 3.90[b]
Haql (Northern Red Sea):		
Intake site	$1.98 \times 10^5 - 3.87 \times 10^5$ (a)	0.18 − 1.3[b]
Brine discharge site	$2.09 \times 10^5 - 4.23 \times 10^5$ (a)	0.17 − 1.7[b]
Jubail (Arabian Gulf coast):		
Intake site	$1.20 \times 10^5 - 2.93 \times 10^5$ (a)	0.45 − 1.60[a]
Brine discharge channel	$0.90 \times 10^3 - 1.30 \times 10^5$ (b)	0.00 − 1.70[b]
Brine discharge site	$2.80 \times 10^3 - 3.40 \times 10^5$ (c)	0.50 − 2.5[c]

[1]Lowest and highest readings obtained during any season (spring, summer, fall or winter).
[a,b,c] Means (not shown in favor of ranges) with same letter superscript for each location/plant and same parameter are not different while those with different letter superscripts are different.
Analysis of variance and paired t-tests (P ≤ 0.05).

proposed that impacts were partially driven by changes in hydrodynamics caused by the diffusers. A study of benthic community at the discharge site of a SWRO plant showed that the benthic community in the discharge site is more abundant and diverse than adjacent areas of normal salinities (Vega and Artal, 2013). Therefore, any deviation from the norm exhibited by any biological parameter is not necessarily a direct effect of a variation in temperate and salinity due to the brine discharge.

3.2. Phytoplankton, chlorophyll, nutrients and total organic carbon

Phytoplankton densities and chlorophyll *a* concentrations are shown in Table 2. There were significantly more phytoplankton and greater chlorophyll *a* concentrations at the discharge area than at the intake site for the Jeddah plants located within the mid-section of the Red Sea. At the Haql plant (northern Red Sea), phytoplankton counts and chlorophyll *a* concentrations were similar in intake and discharge waters. The Jubail plants located on the Gulf had greater phytoplankton abundance and higher chlorophyll *a* concentrations in the discharge than at the intake as in Jeddah (Table 2). However, phytoplankton abundance and chlorophyll *a* concentration in discharge channel was lower than at the intake and discharge site.

Inorganic nutrient levels are less in the discharge water than in intake water of Jubail reflecting utilization by more phytoplankton population (Tables 2 and 3). At the Jeddah plants, concentrations of inorganic nutrients were similar between intake and discharge site, but there is not a defined discharge channel at Jeddah as there is at the Jubail plants. Silicate concentrations were not detectable at either desalination facility. Nutrient analyses were not made at the Haql plant.

Concentrations of ammonia, nitrite, nitrate and phosphate at Jubail plants declined sharply in the brine discharge channel compared to intake water. Ammonia could be volatilized during the discharge cycle while nitrite could be oxidized as a result of vigorous mixing and replenishment of dissolved oxygen in the discharge channel. It is not clear why nitrate and phosphate concentration decreased in the discharge channel, but the most likely reasons for the declines in these nutrients were the hydrodynamic and elevated temperature conditions. The inorganic nutrient data do not agree well with the phytoplankton abundance and chlorophyll *a* concentration data. The discharge area at the Jubail plants has greater phytoplankton abundance than the intake even though nutrient concentrations at the discharge is less. At Jubail, it appears that phytoplankton are actively growing in the discharge site and reducing levels of nutrients. This is not the case at the Jeddah plants where, despite an order of magnitude greater phytoplankton density in the discharge site compared to the intake site, the nutrient levels were similar at both sites. There are two possible reasons for this. One reason is fortification of the discharge with plankton from the cooling water system. Another reason could be that nutrients level is above the replication threshold for plankton growth. In addition, it is possible that nutrients from external sources reach coastal areas of the desalination plants at Jeddah (Saeed et al., 2007).

Intake water chlorination, elevated temperature and turbulence may have negatively affected phytoplankton abundance in the discharge channel of Jubail plants. Laboratory experiments have shown that chlorine in concentrations similar to those in cooling water of the Jubail plants has caused 10% mortality in three copepod groups (Ershath et al., 2018).

Concentrations of dissolved sugars and protein (but not total organic carbon) are higher at the discharge site than in the intake water at Jubail. This is the result of organic decomposition caused by chlorination. There are no significant differences in dissolved sugars and protein or TOC values between intake and discharge waters at Jeddah. The dissolved sugars and protein represent microbially available carbon sources, while the TOC concentration is a measure of all carbon fractions in water and is an index of the organic load in water rather than a nutrient index. Low TOC concentrations reveal that oil and other pollutants (e.g. sewage) are not present in intake water samples, and also suggest that desalination plants discharge is not a source of organic pollution to coastal waters.

Table 3
Concentration levels of nutrients in the intake and discharge sites of Jubail (Gulf) and Jeddah (Red Sea) desalination and power plants (n = 7).

Nutrient	Jubail			Jeddah	
	Intake	Discharge channel	Discharge site	Intake	Discharge site
A. A. Inorganic nutrients (μg-at/l)					
1. Ammonia –N	0.79–8.30[a]	0.01–0.02[b]	0.53–0.70[c]	1.39–4.59[d]	1.70–3.50[d]
2. Nitrite –N	0.30–1.49[a]	0.07–0.09[b]	0.05–0.09[b]	0.02–0.20[d]	0.03–0.23[d]
3. Nitrate-N	1.49–4.99[a]	0.30–1.90[b]	0.51–2.00[b]	0.54–0.86[c]	0.20–1.18[c]
4. Phosphate-P	1.72–5.20[a]	0.09–0.18[b]	0.10–0.20[b]	0.03–0.23[d]	0.05–0.25[d]
5. Silicate –S	BDL[a]	BDL[a]	BDL[a]	BDL[b]	BDL[b]
B. Organic nutrients (mg/l)					
1. Dissolved sugars	BDL - 0.10[a]	0.60–1.40[b]	3.90–5.0[c]	0.29–0.39[d]	0.17–0.25[d]
2. Dissolved protein	0.01–0.02[a]	0.90–1.90[b]	4.90–6.1[c]	0.02–0.05[d]	0.02–0.03[d]
3. TOC	1.52–2.41[a]	1.6–2.40[a]	2.90–3.50[a]	1.95–2.95[b]	1.90–2.90[b]

BDL = Below Detection Limit: (Silicate < 0.1μ-at/l; sugars 0.027 mg/l).
[a,b,c.d]Means (not shown in favor of ranges) with same letter superscript for each location/plant and same nutrient are not different while those with different letter superscripts are different in intake and discharge. Analysis of variance and paired t-tests (P ≤ 0.05).

Table 4a
Concentration of corrosion metals in the intake and discharge waters of Jubail (Gulf), Jeddah (mid Red Sea) and Haql (northern Red Sea) desalination plants (n = 4).

Metals	Locations and sampling sites Concentrations (μg/l)[1]						
	Jubail			Jeddah		Haql	
	Intake	Discharge channel	Discharge Site[2]	Intake	Discharge site	Intake	Discharge site
1. Iron	BDL –5.9[a]	BDL – 6.2[a]	BDL – 7.0[a]	2.9–3.9[c]	3.9–4.2[c]	0.40–4.0[d]	0.50–4.9[d]
2. Nickel	BDL[a]	BDL[a]	BDL[a]	BDL – 1.0[c]	BDL – 1.2[c]	0.10–0.42[d]	0.10–0.49[d]
3. Copper	1.0–3.0[a]	4.0–6.0[b]	2.6–6.0[b]	1.0–1.0[c]	1.0–1.1[c]	0.07–0.15[d]	0.10–0.17[d]
4. Chromium	BDL –0.1[a]	BDL[a]	0.0–0.1[a]	BDL[c]	BDL –0.1[c]	BDL[d]	BDL[d]

BDL = Below Detection Limit of (0.3 μg/l for Iron, 0.01 μg/l for Copper and 0.1 μg/l for each of Nickel and Chromium).
[a,b,c,d]Means (not shown in favor of ranges) with same letter superscript for each location/plant and same metal are not different while those with different letter superscripts are different in intake and discharge. Analysis of variance and paired t-tests (P ≤ 0.05).
[1] Lowest and highest readings obtained during any season (spring, summer, fall or winter).
[2] General Presidency of Meteorology and Environment Protection (GPMEP) of Saudi Arabia ambient water quality standards for waters of the Arabian Gulf are: Fe – not reported and 50 μ/l for each of Ni, Cu and Cr. Maximum allowable discharge water quality standards for these metals as set by GPME are: Fe – not reported, Ni 0.5 mg/l, Cu 0.5 mg/l, and Cr 1.0 mg/l [GPMEP, 2006].

3.3. Trace metals in water and fish tissues

Metals that are mostly common in alloys of desalination plants are iron, nickel, copper, and chromium. They could reach the brine discharge as corrosion product. These metals originate from thermal plants and from metal parts of SWRO plants (Green et al., 2018). Concentrations of these metals in the intake and discharge water samples of Jubail, Jeddah and Haql desalination plants are given in Table 4a. Further data from the Jubail plants are shown in Table 5. Concentrations of copper were greater in the Jubail discharge channel than at either the intake or discharge sites. This phenomenon presumably results from corrosion at the MSF desalination facility at the Jubail plant. The levels of trace metals, especially copper, do not appear to be of concern as far as results presented here as they were not accumulated significantly in the fish tissues (Table 4b) and there were no toxic effects on brine shrimp (Section 3.5). Further, the copper concentrations in the discharge area are within the normal range of 0.19–10.4 μg/l for Gulf coastal waters (Center for Environment and Water and King Fahd University of Petroleum and Minerals Research Institute, 2007) and the ambient water quality limit of 50 μg/l of copper set by the General Presidency of Meteorology and Environmental Protection (GPMEP) of Saudi Arabia for Gulf water is not exceeded (General Presidency of Meteorology and Environmental Protection (GPMEP) of Saudi Arabia, 2006). It is still important to note that copper concentrations in coastal waters of the Gulf (Center for Environment and Water and King Fahd University of Petroleum and Minerals Research Institute, 2007) often exceed the copper concentration range of 0.03–0.9 μg/l for normal seawater (Anthoni, 2006).

Copper concentration in the discharge area (and in the Gulf in general), nevertheless, was higher than reported for normal seawater. It would seem prudent that long-term accumulation of copper in bottom sediments of the discharge area and its effect on benthic community be monitored.

Concentrations of corrosion trace metals in fish tissues were greater in liver than in muscles (Table 4b). This is a normal occurrence in fish tissue samples, because the liver filters blood from the digestive tract and removes or detoxifies potentially harmful substances. The liver actually prevents metals from reaching and accumulating in other tissues. Metal concentrations in fish tissue, like their concentrations in water samples, did not differ between intake and discharge areas. Moreover, moribund fish collected following a fish mortality event at the Jubail plants did not have higher concentrations of metals than fish held in cages. Desalination plants do not appear to be a source of metal contamination in fish tissue. All fish survived in the cages for 5 days suggesting that the discharge water is not toxic.

Table 4b
Concentration of corrosion metals in fish from the intake and discharge waters of Jubail (Gulf), Jeddah (mid Red Sea) desalination and power plants (n = 3).

Metals	Locations and sampling sites Concentrations (mg/Kg wet weight)									
	Jubail						Jeddah			
	Intake		Discharge site		Moribund[1]		Intake		Discharge site	
	Muscle	Liver	Muscle	Liver	Muscle	Liver	Muscle	Liver	Muscle	Liver
1. Iron	8.39 ± 1.91[a]	12.99 ± 6.1[b]	9.31 ± 0.97[a]	13.81 ± 5.60[b]	7.90 ± 0.81[a]	11.98 ± 4.35[b]	3.73 ± 0.79[c]	39.00 ± 9.82[d]	4.31 ± 1.50[c]	41.62 ± 11.09[d]
2. Nickel	0.20 ± 0.04[a]	0.89 ± 0.59[b]	0.21 ± 0.03[a]	0.96 ± 0.55[b]	0.15 ± 0.05[a]	0.09 ± 0.02[b]	1.69 ± 0.6[c]	3.86 ± 1.20[d]	1.73 ± 0.81[c]	3.79 ± 1.04[d]
3. Copper	0.32 ± 0.19[a]	12.81 ± 3.11[b]	0.36 ± 0.18[a]	14.0 ± 4.00[b]	0.28 ± 0.11[a]	10.00 ± 2.91[b]	0.40 ± 0.29[c]	2.90 ± 0.90[d]	0.48 ± 0.0.31[c]	3.10 ± 1.20[d]
4. Chromium	BDL[a]	0.001[b]	BDL[a]	0.001[b]	BDL[a]	0.001[b]	BDL[c]	0.001[d]	BDL[c]	0.001[d]

[a,b,c,d]Means (not shown in favor of ranges) with same letter superscript for each location/plant and same metal are not different while those with different letter superscripts are different in intake and discharge. Analysis of variance and paired t-tests (P ≤ 0.05).
BDL for Chromium is < 0.001 mg/kg.
[1] Collected in lethargic condition during a sudden fish mortality case in coastal waters of the Jubail plants.

Table 5
Concentration of trace metals and trihalomethanes in sediments (dry weight) and water in the Jubail Desalination and Power Plants (n = 3).

Parameters		Location						
		Discharge Site		Control beach		Brine		Intake Bay
		Sediments (mg/kg)	Water (μg/l)	Sediments (mg/kg)	Water (μg/l)	MSF (μg/l)	SWRO (μg/l)	Water (μg/l)
Trace Metals[a]	Iron	2590–2639	25–27	230–287	5.0–12.0	2.0–5.9	14–25	0.01–5.5
	Nickel	10.0–14.0	0.1–1.5	4.0–8.0	0.1–0.15	BDL	BDL	BDL
	Copper	13.0–15.0	2.0–5.0	1.0–1.8	0.6–1.8	3.0–5.0	0.1–0.3	1.0–3.0
	Chromium	10.2–15.4	1.0–2.0	3.0–4.5	0.9–1.9	BDL	BDL	BDL
THM[b]	DCBM	BDL[c]	BDL	BDL	BDL	BDL	BDL	BDL
	Bromoform	0.27–0.33	22–28	BDL	BDL	60–74	25–35	BDL
	Chloroform	0.050–0.055	BDL	BDL	BDL	BDL	BDL	BDL
	DBCM	BDL	BDL	BDL	BDL	BDL	BDL	BDL

[a] General Presidency of Meteorology and Environment Protection (GPMEP) of Saudi Arabia ambient water quality standards for waters of the Arabian Gulf are: Fe – not reported and 50 μg/l for each of Ni, Cu and Cr. Maximum allowable discharge water quality standards for these metals as set by GPMEP are: Fe - not reported, Ni - 0.5 mg/l, Cu - 0.5 mg/l, and Cr - 1.0 mg/l. Sediment quality guidelines for trace metals (mg/kg) as set by GMP: Fe - Not regulated, Nickel - 16 copper - 18 and Chromium - 52 [GPMEP, 2006].

[b] THM = Trihalomethanes; DCBM = Dichlorobromomethane; DBCM = Dibromochloromethane.

[c] BDL = Below Detectable Limit in water (0.3 μg/l for iron, 0.01 μg/l for copper, 0.1 μg/l for each of nickel and chromium and 2 μg/l for each of trihalomethanes compounds), and in sediments (0.5 mg/kg dry weight for each trace metal, 50 μg/kg for each of the trihalomethanes compounds).

3.4. Sediment analysis

Sediment analysis for trace metals of corrosion origin (iron, nickel, copper and chromium) and trihalomethane compounds in comparison with concentrations of these parameters in water samples are presented in Table 5. Trace metals in water are below ambient water quality standards set by the General Presidency of Meteorology and Environment Protection (GPMEP) of Saudi Arabia for waters of the Gulf (General Presidency of Meteorology and Environmental Protection (GPMEP) of Saudi Arabia, 2006). They are also below limits set by GPMEP for discharge water (General Presidency of Meteorology and Environmental Protection (GPMEP) of Saudi Arabia, 2006). The Australian and New Zealand Environment and Conservation Council (ANZECC) sets guidelines trigger values for these metals as: nickel 4.5 μg/l, copper 1.3 μg/l and chromium 4.4 μg/l. While nickel and chromium were below the ANZECC trigger value, copper concentration exceeds trigger value (Australian and New Zealand 2000). The ANZECC trigger values are the concentrations below which there is a low risk of adverse biological effects. Although the ANZECC guidelines cannot be adopted to Gulf waters, due to the special nature of the Gulf, there is a precautionary need to ascertain the effect of cooper on benthic biota. It will be seen in sediment analysis results below that there is accumulation of all corrosion trace metals in sediments of the brine discharge site in Jubail.

The concentration of Cr in the discharge site is similar to that in the control site. The metals Fe, Ni and Cu are present in the seawater at the discharge site at higher concentrations than in the seawater at the control site. The maximum levels of these metals found at the discharge site are higher than those at the control site by factors ranging from 2.3-fold (Fe) to 10-fold (Cu). Copper is known to remain in solution phase because of its low affinity to sediment particles (Nguyen et al., 2005). It is suggested that a copper concentration of 15 μg/l in brine effluents of desalination and power plants not a high risk to aquatic life because of dispersion and dilution in receiving water (Hoepner and Latteman, 2002). In any case, because of advances made in pretreatment and energy recovery SWRO technology will dominate over thermal technologies in the near future and corrosion products will be greatly diminished. There is accumulation of trace metals in sediments at the discharge site are higher than concentrations in the control sediments and the maximum levels of metals found at the discharge site are higher than the control cite by factors ranging from 1.8-fold (Ni) to 9.1-fold (Fe). Coastal sediments are considered to be a major sink for contaminants such as trace metals which are, unlike other pollutants, not biodegradable and can accumulate in sediments over time. Dissolved metals in the discharge plume can be complexed by humic substances, adsorbed to suspended matter and deposited in calm water in sediments where they may reach a level that is toxic to aquatic life. Still, concentration of trace metals in water and sediments of the brine discharge site are well below maximum discharge water quality standards and sediment quality guidelines (General Presidency of Meteorology and Environmental Protection (GPMEP) of Saudi Arabia, 2006). Of particular interest is iron concentration in the brine discharge site which is approximately one order of magnitude higher than other trace metals. Iron concentration in the brine reject of the SWRO plant is also exceptionally higher than other trace metals. There appeared to be leakage of the coagulant ferric chloride from the dual media filters to the brine reject. In addition, the dual media filters backwashing solution which is dumped with brine is saturated with ferric chloride. Although no guideline values are available for iron, it could exert negative effects on benthic organisms (e.g. fouling of nest sites and interfering with respiration and filter feeding). New SWRO plants are now provided with waste treatment facilities. Backwashing waste from filters (dual media filter in particular) and waste of membrane cleaning that used to be dumped with brine is now treated and separated into sludge and clear liquid. The amount of total suspended solids reaching coastal waters is now drastically reduced. In addition, metals present in backwashing water and membrane cleaning waste are mostly adsorbed and removed in the sludge. Considering the effective removal of metals in the solid phase of the backwashing and membrane cleaning processes and the large dilution ratio of any residual metals remaining in the liquid phase of the backwash by the brine stream, contamination of the coastal receiving water with metals should not occur.

Little research has been undertaken to elucidate the formation and toxic effects of chlorination by-products in marine environment (Kim et al., 2015). In the present study, THMs were present in the form of bromoform THM (tribromomethane) with chloroform THM (trichloromethane) concentrations at their below detection limit and only in sediments and not in water samples. (Table 5). The source of these disinfection by-products is chlorine disinfection as no THMs are measurable in the control beach or the intake bay of the Jubail desalination and power plants. Chlorination significantly increases THMs content of seawater (Abdel-Wahab et al., 2010). Bromoform was found to dominate over other THMs species in seawater samples from Jubail desalination and power plants treated with chlorine in the laboratory as it constituted above 80% of the total THMs (Mayankutty et al., 1995). The reason for bromoform dominance was attributed to the presence of

Table 6
Comparison of bacterial counts and generation times in the discharge and intake waters of the Jubail and Jeddah desalination and power plants (n = 10).

Sampling Location	Bacterial Counts (CFU/ml)[1]		Generation time (h)[4]
	0-h[2]	24-h[3]	
Jubail:			
Intake	$(1.33 \pm 0.53)^a \times 10^4$	$(3.33 \pm 0.97)^a \times 10^5$	5.16 ± 1.02^a
Brine discharge channel	$(3.06 \pm 0.39)^b \times 10^3$	$(3.60 \pm 0.89)^a \times 10^5$	3.43 ± 0.89^b
Discharge site	$(1.48 \pm 0.29)^a \times 10^4$	$(3.95 \pm 0.95)^a \times 10^5$	5.01 ± 0.98^a
Jeddah:			
Intake	$(1.21 \pm 0.66)^c \times 10^4$	$(2.66 \pm 0.25)^b \times 10^5$	2.89 ± 0.09^c
Discharge site	$(1.16 \pm 0.69)^c \times 10^4$	$(2.94 \pm 0.73)^b \times 10^5$	3.02 ± 0.13^c

[1]Pour plate count in marine agar and incubation at 30 °C in a thermostatically-controlled incubator.
[2]Intial count.
[3]Count after 24-h incubation.
[4]Generation time (h) = $\Delta t\, k/(\ln Nt - \ln Nt_0)$: where t is incubation time, K is a constant and equals 0.693, Nt is bacterial count after 24-h incubation, and Nt_0 is the initial bacterial count (Saeed et al., 2000).
[a,b,c,d]For the same parameter (vertical columns) and for each plant means with same letter superscript are not different; means with different letter superscripts are different (Analysis of Variance and Tukey test, P ≤ 0.001).

bromides in high concentrations in seawater (Mayankutty et al., 1995). Chlorinated water samples from Jeddah desalination and power plants contained chiefly bromoform to the exclusion of other chlorination by-products (Mayankutty et al., 1991). The concentration of bromoform in water of the brine discharge site is only 25 μg/l. However, bromoform accumulated in sediments to a concentration of 330 μg/kg which is approximately 13 times greater than its concentration in the water column above the sediments. Concentrations of THMs in brine or in water at the intake site were negligible considering regulatory limits of THMs in drinking water. The WHO set regulatory THMs limits for drinking water in μg/l as: trichloromethane 100, tribromomethane 100, dichlorobromomethane 60, and dibromochloromethane 100 (WHO, 2011). The concentration of bromoform in sediments is 0.33 mg/kg (Table 5).

The 25 μg/l concentration of bromoform in water of the brine discharge site is far below concentrations that are reported lethal for some marine organisms. The 96 h LC_{50} for bromoform was reported for certain marine organisms in mg/l as follows: *Skeletonema* sp. (marine diatom algae) 11.5–12.3, *Mysidopsis bahia* (marine mysid shrimp) 24.4 (EPA, 1980) and *Crassostrea variegatus* (oyster larvae) 1.0 mg/l (Hsu and Helz, 1999). It can be noted that chronic effects of bromoform on adult oysters were observed at 25 μg bromoform/l (HSDB, 2001). Chronic exposure value for embryo and larval stages of the salt water fish *Cyprinodon variegatus* is 6.4 mg/l (EPA, 1980). The concentration of bromoform in sediments is 0.33 mg/l (Table 5). Assuming that this concentration is roughly equivalent to 0.33 mg/l of water, then this concentration is well below the 96 h LC_{50} reported for the mentioned marine organisms, particularly the shrimp and oyster larvae which can be benthic. However, the effect of long-term exposure of benthic organisms to THM needs to be ascertained.

3.5. Toxic effects

Toxicity tests showed that the hatching rate of artemia cysts was ≥95% in both intake and brine discharge water samples from the four desalination plants. No larval mortality occurred 24 and 48 h after hatching in either intake or brine discharge water samples. Different concentrations of potassium dichromate were used as quality control. A 300 mg/l solution resulted in a 24 h larval mortality of close to 50% and was thus reported. The 300 mg/l potassium dichromate solution resulted in a hatching rate of 60–65%, a 24 h larval mortality of 45–55% and a 48 h larval mortality of 70%. Therefore, brine discharge is not acutely toxic to the brine shrimp *A. franciscana*. A study of the intake and outfall bay of Jubail plants showed Arthropoda, (with copepods and larvae being their main representatives) forming the largest zooplankton community in the outfall bay, with Protozoa forming the second largest zooplankton group (Abdul Azis et al., 2003). The food web consists of bacteria, unicellular algae, protozoa, copepods, artemia and fish in a relatively balanced assemblage that is likely stable and sustainable.

At Jubail, the brine discharge channel contained trace levels of residual chlorine which were tolerated by brine shrimp. Chlorine is generated electrochemically from chlorine generators on land and dosed in a concrete intake pits just before intake pumps. There are five such intake pits. The brine discharge channel of the Jubail plants is located below the individual discharge lines of the desalination units. Thus, individual discharge lines empty with slope and associated turbulence into the main discharge channel. The expulsion of chlorine is associated with replenishment of oxygen and dissipation of temperature. This will help in alleviation of potential harmful effects of chlorination. In desalination plants, the design of the brine discharge structures into open and especially shallow coastal waters should carefully be studied as it could influence the impact of the discharged brine on coastal ecosystems.

3.6. Bacterial growth

Initial bacterial abundance (0-h counts) and the 24-h counts in the discharge and intake waters of the Jubail plants did not differ indicating similar growth conditions. The same is true for the corresponding generation times that ranged from about 3 to 5 h (Table 6). Initial bacterial abundance in the brine discharge channel was one order of magnitude lower than either the intake or discharge sites. The intake water is chlorinated through electrochemical generation of chlorine from seawater, and chlorine residuals reduced bacterial abundance in the initial sample from the discharge channel. Trace levels of chlorine in the Jubail plants brine discharge channel were found to inhibit light emission from a bioluminescent bacterium in a previous study (Saeed and Al-Nomazi, 2013). However, chlorination stress did not occur in the bacterial culture of the present study, and after 24 h, densities of bacteria in cultures incubated from the discharge channel matched those from the final discharge area (Table 6). The quick recovery of bacteria from the brine discharge channel is reflected by their accelerated 24-h growth rate/generation time of 3.43 h compared to 5.16 and 5.01 h for the intake and discharge sites water samples, respectively (Table 6). As observed at Jubail, the bacterial counts and generation times in water samples from the intake and discharge sites of Jeddah (Red Sea) desalination and power plants are similar indicating no harmful effect of the brine discharge.

3.7. Total suspended solids

The concentration of total suspended solids (TSS) was nearly 5 mg/l greater at the discharge than at the intake of the Jubail plants (Table 7). The TSS concentration increased between the intake and discharge channel and was the same in discharge channel and discharge area. At the Jeddah and Haql plants, TSS concentration did not differ between intake and discharge areas. The TSS concentration is an important water quality parameter that can effect community structure of an aquatic ecosystem. Suspended solids cause light attenuation and limit phytoplankton production. These effects may impact both the food chain and the type and magnitude of biofouling communities through marine shell fouling of plant structures. Increased TSS load can also lead to pretreatment filtration problems at SWRO plants.

Concentrations of TSS are similar (Red Sea plants) or comparable (Gulf Plants) between intake and discharge water samples. However, TSS concentrations at intake and discharge areas were higher at the

Table 7
Concentration of total suspended solids in intake and brine discharge of the Jubail, Jeddah and Haql desalination plants (n = 8).

Location	TSS (mg/l)		
	Intake	Discharge Channel	Discharge Site
Jubail	(20.6 ± 1.04)[a]	(24.50 ± 1.9)[b]	(25.1 ± 0.95)[b]
Jeddah	(14.89 ± 3.04)[c]	NA	(14.80 ± 2.95)[c]
Haql	(22.3 ± 0.85)[d]	NA	(23.1 ± 0.79)[d]

NA = No open discharge channel.
[a,b,c,d] For the same location means with same letter superscript and not different. Means with different letter superscripts are different (analysis of variance and paired test *E-tests;* (P ≤ 0.01).

Jubail and Haql plants than at the Jeddah plants. This apparently results from shallow water columns at the discharge sites at Jubail and Haql that could easily be disturbed. At the Jubail plants, it was noted that water in the discharge channel has TSS concentration similar to that of the discharge site and more than the intake site. There is no dilution effect in the discharge site. This could possibly be due to turbulent mixing between discharged brine and receiving water in the discharge site that makes TSS load similar in discharge channel and discharge site irrespective of dilution. The brine discharge channel at Jubail having more TSS than the intake possibly a result of ingress of suspended matter from soil along the open discharge channel and from frequent dust storms.

Another source of suspended solids in the brine discharge of SWRO plants is the backwash water from membranes and filters. Sludge resulting from the backwashing is traditionally disposed with brine. This trend is now changing and waste treatment is now incorporated in new plants design e.g. the new Ras Al-Khair, Gulf coast of Saudi Arabia 307,000 m^3/d SWRO plant. The sludge resulting from the pretreatment phase (e.g. dissolved air flotation and dual media filter units) is dewatered and disposed of at an authorized landfill. The treatment process, designed to achieve removal of ~90% of the suspended solids retained at the filters, comprises of flocculation, sedimentation, thickening and a final sludge de-watering process. The clarified water is discharged to the sea with the brine stream with no solids.

4. Conclusions and recommendations

1. It is difficult to trace the fate of most of chemicals used (probably with the exclusion of coagulation metals) in desalination processes in the marine environment. It was necessary to base the assessment of their impacts on environmental changes and toxic effects on representative marine organisms.
2. The variables measured in this study indicate the effect of brine discharge on adjacent coastal waters of the Red Sea and Gulf to be minimal. This is because: a) most of the components of discharge from desalination plants are not harmful to the marine environment; b) most plants are dual purpose, producing drinking water and generating electricity, and the huge quantity of cooling water from electricity production dilutes salinity and minimizes the temperature increase of the brine from desalination; c) the majority of large size thermal plants are collocated with SWRO plants and the brine from SWRO plants helps in further minimization of temperature increase from thermal plants; d) The cooling water of the distillation plants dilute the high salinity effluent from SWRO plants.
3. Given the need for potable water in extremely arid lands of the Arabian Peninsula, the effects noted with the discharge zone (the zone where temperature and salinity are elevated above ambient) seem acceptable. Based on phytoplankton counts and chlorophyll production there appeared to be no significant effect of entrainment.
4. Entrainment effect needs more specific evaluation and further studies are recommended to investigate accumulation of any contaminants in biomonitors.
5. Seawater desalination plants should seek to establish a legal coastal discharge zone beyond which water and sediment quality parameters returned to ambient conditions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2019.02.005.

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