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Brine discharge from desalination plants: a modeling approach to an optimized outfall design

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Abstract

Desalination was for long considered a technology too expensive to adopt in most arid countries except those with large reserves of fossil fuels and affluent economies. Recent advances in desalination technology have abolished this old paradigm and have increased its market share in many arid and semi-arid countries. Nevertheless, the introduction of a desalination plant will inevitably be associated with several potential adverse environmental impacts particularly on the marine ecosystem as a result of effluent (brine) discharge. This paper focuses on simulating the dispersion of the brine plume in the marine environment by considering the heated effluent from a desalination-power plant in the Gulf region. Various scenarios were defined and simulated using the CORMIX model to compare the mixing behavior and efficiency of surface, submerged single-port as well as submerged multi-port outfalls taking temperature variations as an indicator. The simulations capitalized on the inadequacy of widely used surface channel discharges in achieving the required dilution rates capable of minimizing potential environmental impacts on the Gulf. A sensitivity analysis was conducted to identify most influencing input parameters on simulation results as well as evaluate management options to minimize adverse impacts of desalination-related marine discharge.

Keywords: Desalination; Brine discharge; CORMIX; Discharge outfalls; Sensitivity analysis

1. Introduction

In August 1999 the world human population exceeded the six billion mark signaling the ever-increasing pressure on available water resources. Today 40% of the world's population, most of whom live in arid countries, suffer from water shortage. This ratio is expected to increase to 60% by the year 2025, due to population growth, improvements in lifestyle, increased economic activity, and increased contamination of existing

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water supplies [1]. As a result, unconventional water resources such as desalination are increasingly becoming inevitable sources to alleviate water scarcity.

The introduction of desalination plants, however, has been associated with several potential environmental impacts, the most important of which is perhaps the open discharge of the concentrated brine into the marine environment. Limited efforts have targeted the characterization of the impacts of brine discharge on the marine environment. Using a two-dimensional advection-diffusion equation, Purnama et al. [2] concluded that discharging brine through a surface outfall adversely impacts coastal waters and promotes saltwater intrusion. Biodiversity monitoring data collected within an area 100–200 m away from the outfall of the Dhkelia RO plant in Cyprus revealed that littoral fauna and flora were affected by the brine discharge [3]. Conversely, a survey of the plankton community within the outfall bay of the Al-Jubail desalination plant in Saudi Arabia did not show significant change in the distribution of phyto and zooplankton, which was attributed to high dilution rates attained through the use of a 1.8 km long cascading channel [4].

The objective of the present study is to compare the effectiveness of various discharge outfalls on diluting the brine-blowdown generated from desalination plants by taking a power generation and water distillation station in the Gulf region as a case study. For this purpose, the brine characteristics and potential impact were first reviewed then the plants' operating conditions as well as the hydrodynamic characteristics of the area were defined. Various simulation scenarios accounting for surface discharge channels, single-port outfalls, as well as multi-port diffusers were assessed to determine the optimal outfall structure. A parametric sensitivity analysis was conducted to evaluate the effect of the various input parameters on the simulated results. Finally, management options were examined to determine their effectiveness in reducing environmental degradation. The general methodology adopted in the study is summarized in Fig. 1.

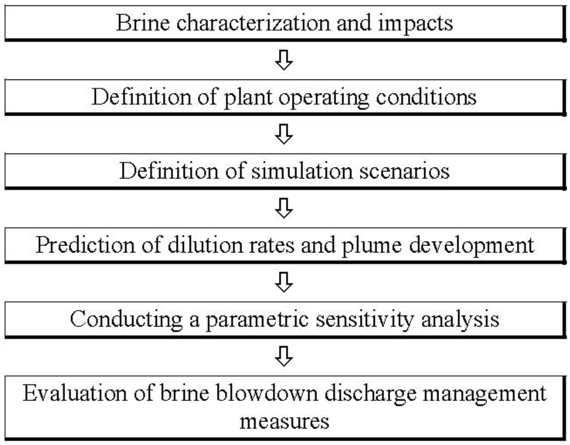

Fig. 1. Brine discharge assessment methodology.

2. Brine characterization and impact

The main waste stream resulting from the desalination process is the concentrated effluent that is referred to as brine or brine-blowdown. The brine is usually more saline than the raw seawater and above its ambient temperature although it reflects most of its chemical constituents. In addition to major constituents presented in Table 1, the brine usually contains corrosion products, halogenated organic compounds, oxygen scavengers, various acids, and a combination of anti-scaling/fouling/foaming/corrosion additives at relatively low levels depending on the desalination process involved [5].

Brine disposal has the potential to degrade the physical, chemical and biological characteristics of the receiving water body. The degree of degradation is highly dependent on the total volume of the brine being released, its characteristics, the dilution rate prior to discharge, and the characteristics of the receiving waters. The effect of the brine on the environment is also highly dependent on the geometric installation of the discharge

Table 1
Comparison between the chemical characteristics of the feed and brine water

Parameter	Um-Alnar Plant[a]		Taweela A Plant[a]		Abu Dhabi Plant[a]		Doha West Plant	
	Intake water	Brine water	Intake water	Brine water	Intake water	Brine water	Intake water	Brine water
Cations								
Magnesium (mg/l)	1,612	3,625	1,655	3,500	1,821	3,606	NR	NR
Sodium (mg/l)	11,806	21,750	13,250	26,142	12,103	22,437	NR	NR
Potassium (mg/l)	574	870	610	830	542	845	NR	NR
Calcium (mg/l)	516	1,850	659	1,775	563	1,818	NR	NR
Iron (ppb)	NR	NR	NR	NR	NR	NR	19.0	25.0
Copper (ppb)	NR	NR	NR	NR	NR	NR	4.3	8.0
Anions								
Chloride (mg/l)	26,921	37,223	28,113	38,821	27,135	37,779	25,134	41,748
Sulfate (mg/l)	3,723	4,560	3,227	4,319	3,115	4,321	NR	NR
Bicarbonate (mg/l)	115	190	131	187	126	185	NR	NR
TDS (mg/l)	45,340	70,278	47,737	71,689	45,490	71,204	46,710	79,226
pH	8.1	8.9	8.3	8.8	8.2	8.9	8.25	8.93
Temperature (°C)	40–44 reported for MSF plants operating in the Arabian Gulf [b]							

[a][6]. [b][7].
NR: Not reported.

outfall. In open and well-mixed environments, adverse impacts have been noticed mostly within 300 m from the discharge point [8]. Impacts are more pronounced in environments that are located in shallow and/or semi-closed bays. Areas inhabited by sensitive or high-value organisms are also considered to be highly vulnerable to brine discharge. Table 2 presents a brief overview of the characteristics, loads and environmental impacts of pollutants present in brine. Readers interested in a more detailed assessment of the chemical and physical characteristics of the brine should refer to Seawater Desalination: Impacts of Brine and Chemical Discharge on the Marine Environment [9].

3. Area characteristics

The Gulf area houses the highest density of desalination and power plants in the world generating a total of 15,000 MW of electric power and 11.99×10^6 m^3/day of desalinated water [36,37]. These installations discharge their effluents directly to the Arabian Gulf, which is a shallow semi-enclosed and highly saline water body that has a water residence time of 2 to 5 years. The seawater characteristics of the Arabian Gulf differ from the world's ocean waters in many aspects including high salinity levels and elevated water temperatures that could exceed 45°C. While the gulf is characterized with a very productive and diverse ecology, these harsh natural conditions stress the existing biota and often expose them to conditions at the edge of their tolerance limits. The uncontrolled discharge of brine blowdown can negatively affect the marine fauna and flora by compounding on the existing harsh conditions resulting in the loss of important sheltering, nursing, and feeding sites.

Table 2
Environmental impacts of brine constituents on the marine environment

Discharged pollutants	Pollutant source characteristics and discharged load	Potential environmental impact
Corrosion products (heavy metals)	• Mainly resulting from the corrosion of copper alloy tubing used in MSF plants and increases significantly under high temperature operations typical of such plants • The main corrosion products in the desalination industry are copper, iron, nickel, chromium, zinc and molybdenum [1,5–7,10–13]. • Copper is the most significant heavy metal discharged from desalination. Reported copper concentrations in the effluent can exceed 0.02 ppm (200 times higher than natural marine concentrations) [5]. • Estimates indicate that desalination is responsible to the input of 2 to 13% of the natural copper load in the Arabian Gulf [9]	• Heavy metals accumulate in sediments and tissues of aquatic organisms [6, 5, 14, 19] • Heavy metals can redistribute the trace metals in an area and change the existing phytoplaktonic and fish communities in an area [15]
Antiscaling additives	• Used to remove the scale formations on the plant's tubing • The main antiscalants used in the desalination industry are orthophosphate, and biodegradable polymeric additives based on maliec anhydride or polyacrylate [9, 14, 15] • Reported dosing rates for polymeric additives do not exceed 0.53 mg/L [16]. • Anti-scaling additive concentrations at the point of discharge of MSF plants range between 0.53 and 1 ppm [9]	• The use of orthophosphate enhances the primary productivity in oligotrophic seas and increases the occurrence of acute red and green algae blooms which in turn depletes the dissolved oxygen levels [5,11,14] • While polymeric additives are not linked with toxic hazards their potential to cause biogenic and/or abiogenic toxicity has not been completely analyzed [5,11]
Antifouling additives	• Used to hinder the potential of bacterial, algal and other marine organisms to foul the desalination plant • Chlorine or hypochlorite are the main antifouling agents in use • Chlorine dosing ranges between 2 and 5 ppm, while shock chlorination can reach up to 8 ppm [7, 17] • Chlorine concentrations at the point of discharge of MSF plants range between 0.2 and 0.5 ppm [18]	• Transforms stable bromides to reactive bromines • Forms halogenated hydrocarbons some of which are known carcinogens and mutagens [5,12,] • Forms chloroamines and bromoamines which are toxic stable compounds [5] • Results in the formation of hypochlorite ions that disrupt normal enzymatic and biological processes in organisms [11] • Can induce the migration of intolerant species from the affected area [11,20]

Table 2 (continued)

Discharged pollutants	Pollutant source characteristics and discharged load	Environmental impacts
Halogenated organic compounds	• Formed as a result of the reaction of residual chlorines and bromines with natural and anthropogenic organic sources • Main source of organic compounds in the Arabian Gulf is anthropogenic releases of oil [21]	• Stresses marine organisms even at low concentrations • Many are known carcinogens and mutagens • Impacts the reproductive organs of oysters [22] • Significantly increase the mortality rate of larval oysters [23] • Some halogenated organic compounds can bioaccumulate in tissue [24]
Antifoaming additives	• Used to prevent foam formation in MSF units • Main antifoaming additives are polyglycol blends [9] • Typical dosing rates are around 0.1 ppm • 90 % degradation is expected before discharge • Polypropylene glycol concentrations at the point of discharge of MSF plants range between 0.04 and 0.05 ppm [9]	• Disrupts the intracellular membrane system in marine organisms • Can react with halogens to form carcinogenic and mutagenic compounds [5]
Oxygen scavengers	• Used to reduce corrosion especially in MSF plants • Sodium sulfite is the most widely used oxygen scavenger [5]	• Can slightly reduce the levels of dissolved oxygen in the discharge area [25]
Acid	• Used mainly as an antiscalant • Acid washing can produce effluents with pHs as low as 2	• Changes the chemistry of the seawater in the vicinity of the outfall [11] • Can result in the migration of organisms from the affected area thus reducing biodiversity [25]
Concentrate	• Usually reflects the chemical constituents of the feedwater • MSF effluents are 1.1 times more concentrated than the original feedwater [16] • Seawater RO effluents can be 2 times more concentrated than the original feedwater	• Can have lethal impacts on some aquatic organisms [7,19,27, 28] • Can retard hatching of fish eggs [28] • Can affect the morphological characteristics of some species [28] • Monitoring of biodiversity within an area 100–200 m from the outfall of the Dhkelia RO plant in Cyprus showed that littoral fauna and flora were impacted by salinity increase [3]
Reject heat	• MSF plants have effluents 8 to 15°C above ambient • RO plants do not contribute to thermal pollution	• Reject heat decreases the ability of water to hold oxygen, increases the rate of chemical reactions, changes the available biodiversity, increases the metabolic rate of cold-blooded animals [29, 30, 6, 31, 32, 33, 11, 34, 35]

MSF = multi-stage flash distillation plants. RO = reverse osmosis.

In the area proper of the desalination plant under study, seven coastal sites have been developed to produce distilled water and electrical energy. The total current installed nominal capacity reaches to 1.4×10^6 m^3/day at an operating temperature of 90°C. Most plants discharge their brine blowdown into a narrow bay via ordinarily surface and near-shore outfalls as is the case in most desalination plants operating in the Gulf region [5]. The closed nature of the bay and the restricted hydraulic circulatory currents hinder the mixing and dilution processes and may result in the recirculation of the discharged pollutants [38]. This situation is especially exacerbated at the plant site due to the shallowness of its area within the bay and characterized with more limited circulation patterns and is mostly composed of intertidal mud beds. This shallow bay is utilized to discharge the resulting brine blowdown after mixing with the once-through cooling water (the plant follows a combined distillation-power cogeneration and its exact coordinates are kept anonymous at the request of the plant management; it is of the MSF type and was built in the early 1980's to supplement the area's increasing power and water demands).

4. Standards and regulations

In general, the development of specific and comprehensive standards regarding the discharge of brine concentrate to water bodies is still lacking because the desalination industry-regulatory interface is relatively new and in developmental stages [10,39,40]. Current regulatory attempts focus on defining plant-specific mixing zones at the point of discharge. These zones take into account the capacity of the receiving water to dilute the effluent and limit aquatic degradation spatially and temporally.

The adopted mixing zone standard in this study was proposed by Khordagui [7]. This standard restricts the increase in the weekly average temperature to a mixing zone of 300 m from the point of discharge beyond which the heated discharge is expected to decrease to less than 1°C above the ambient temperature. The standard also stipulates that the effluent should not exceed the summer maxima nor the daily frequency and amplitude of the ambient temperature cycle beyond the 300 m mixing zone [8].

5. Brine discharge modeling

5.1. Model description

The CORMIX–GI model was used to simulate the development of the brine plume resulting from the continuous discharge of the brine blowdown from the MSF desalination power plant. CORMIX is a United States Environmental Protection Agency (USEPA) approved simulation and decision support system that has been adopted for assessing the environmental impacts resulting from point source discharges within their mixing zones [41]. The model is subdivided into three separate sub-systems namely: CORMIX 1 for the analysis of submerged single port discharges, CORMIX 2 for the analysis of submerged multi-port diffuser discharges and CORMIX 3 for the analysis of buoyant surface discharges. It is capable of predicting the effluent dilution rate and the plume trajectory from the point of release into the far-field by analyzing and combining the solutions of several flow patterns [42].

5.2. Simulation scenarios

Three basic scenarios were examined to compare the mixing behavior and efficiency of surface, submerged single-port as well as submerged multi-port outfalls into shallow waters typical of the Arabian Gulf, with the subject plant as a case study (Table 3). The first scenario, S1, evaluates the adequacy of surface discharge outfalls widely used in most desalination plants along the

Table 3
Simulated scenarios and sub-scenarios

Scenario	Module	Description of scenario	Sub-scenario
S1	CORMIX-3	Simulates current brine discharge conditions practiced in the plant, i.e. surface discharge into the bay at an average depth of 0.6 m, an ambient velocity 0.182 m/s, and a heat loss rate of 40 $W/m^2/°C$	
S2	CORMIX-1	Simulates discharge of brine through a single-port submerged outfall extended deep into the bay 4 m from the nearest bank at a depth of 20 m, an ambient velocity 0.182 m/s, and a heat loss rate of 40 $W/m^2/°C$	
S3	CORMIX-2	Simulates discharge of brine through a multi-port submerged outfall extended to the bay, at an average depth of 5 m, an ambient velocity 0.182 m/s, and a heat loss rate of 40 $W/m^2/°C$	S3.1: Staged multi-port submerged outfall S3.2: Vertical multi-port submerged outfall S3.3: Alternating-fanned multi-port submerged outfall

Table 4
Characteristics of the simulated outfall structures

Parameter	Outfall type				
	Surface (flush type)	Single port	Vertical	Staged	Alternating fanned
Port discharge velocity (m/s)	18 m/s	5	5	5	5
Distance to nearest bank (km)	0	4	2	2	2
Angle of discharge (°)	90	NA			
Alignment angle (°)	NA		90	90	90
Vertical angle (°)	NA	90	0	0	NA
Relative orientation angle (°)	NA	NA	90	0	NA
Horizontal angle (°)	NA	0	0	90	NA
Diffuser length (m)	NA	NA	1,464	813	1,342
Number of ports	1	1	244	125	244
Port spacing (m)	NA	NA	6	6.5	5.5
Port(s) diameter (m)	13[a]	6	0.38[b]	0.53[b]	0.38[b]
Port height (m)	0	1	0.7	0.7	0.7
Discharge depth (m)	0.6	20	5	5	5

[a]Port width. [b]Diameter of diffusers. NA, not applicable since the angles vary from one port to another.

Arabian Gulf. In the case of the subject plant, discharge occurs through a channel located within the inter-tidal zone of the bay. The second scenario, S2, examines the development of the brine plume through the use of a single-port submerged outfall. In this scenario, the brine is discharged deep into the bay 4 km away from the coast. The third scenario, S3, evaluates the dilution rates experienced through the adoption of multi-port diffusers. It is divided into three sub-scenarios: S3.1 to determine the dilution rates generated through the use of a staged multi-port

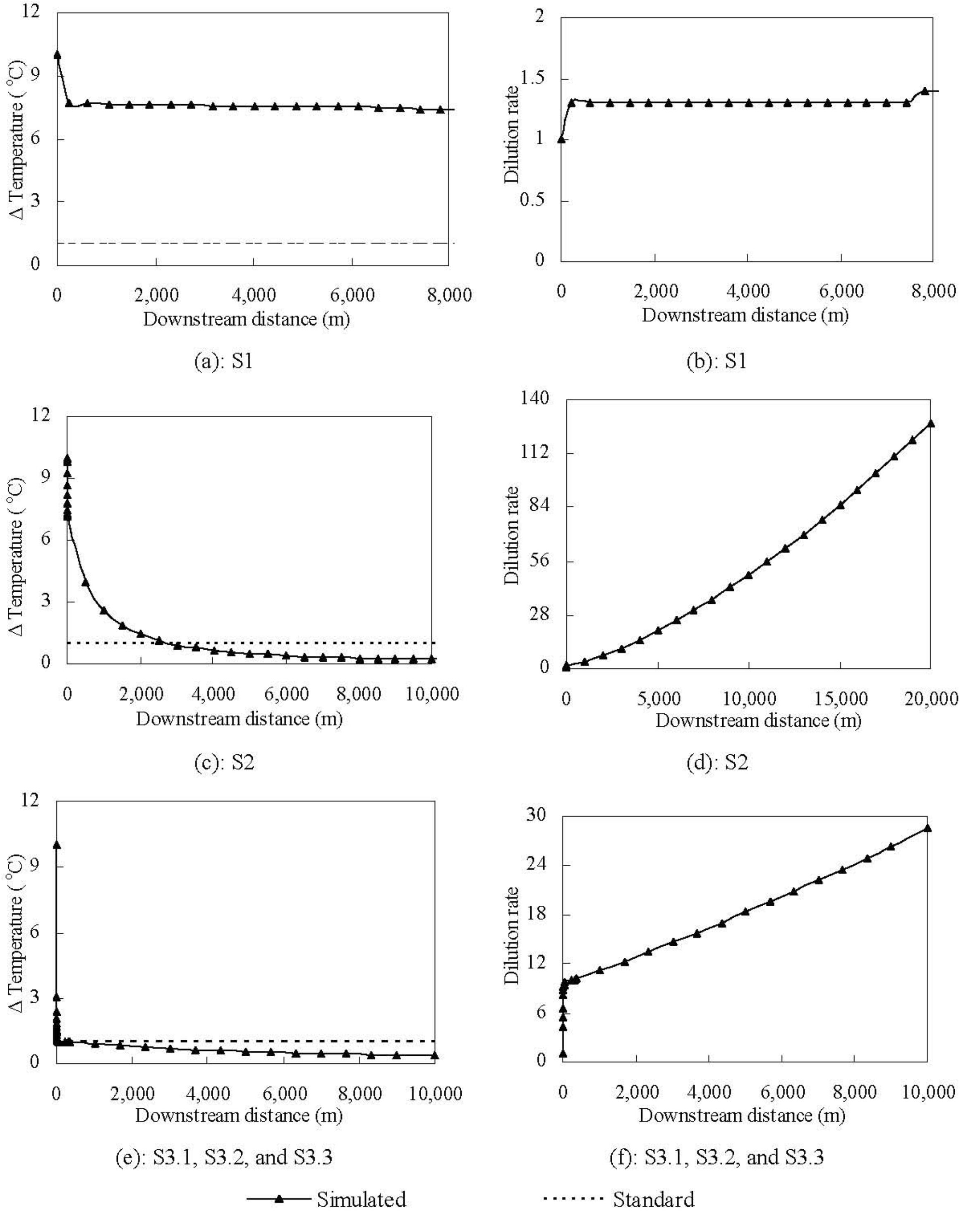

Fig. 2. Achieved plume temperature drop and dilution rates for the simulated scenarios.

submerged diffuser; S3.2 to assess the effect of a vertical multi-port submerged diffuser; and S3.3 to assess the adequacy of an alternating-fanned multi-port submerged diffuser for brine dilution. The spatial orientation of the adopted discharge ports is presented in Table 4.

The elevated temperature of the brine blowdown was selected as an indicator for simulating the dilution and mixing rates of the brine upon discharge. The temperature was selected since it is a conservative pollutant that has no side interactions with other pollutants thus providing an accurate description of the dilution and mixing processes.

5.3. Simulation results and analysis

Simulation results in terms of achieved dilution rates and the spatial drop in plume temperature are presented in Fig. 2. The results indicate that the use of a surface discharge outfall fails to achieve the required dilution rates within a mixing zone of 300 m under conditions typical of the bay (Fig. 2a, 2b). The low dilution rates are due to the dynamic attachment of the plume to the downstream bank resulting in the formation of a zone in which the effluent undergoes recirculation. In addition, the shallow nature of the bay leads to the bottom attachment of the plume upon discharge thus blocking the ambient current and reducing dilution potential. The use of a single port submerged outfall increased dilution rates significantly but still failed to achieve the required dilution rate within the adopted mixing zone, whereby the plume temperature profile reaches the differential 1°C standard after 2,685 m downstream of the initial point of discharge (Fig. 2c, 2d). The highest dilution rates were obtained under the three sub-scenarios S3.1, S3.2, and S3.3, which were able to accomplish the required dilution rates and hence minimize potential environmental damage (Fig. 2e, 2f). The length of the diffuser line being an important parameter affecting the total cost of multi-port outfalls renders sub-scenario S3.1 an economically desirable option to adopt since it achieves the required temperature drop with the shortest diffuser line (813 m). Fig. 3 compares the plume temperature drop under the three considered scenarios S1, S2, and S3. Evidently, the single and multi-port outfalls offer more effective alternatives in attaining the desired temperature drop with S3 being the optimum alternative.

5.4. Sensitivity analysis

The parametric sensitivity analysis focused on the effect of varying model parameters on

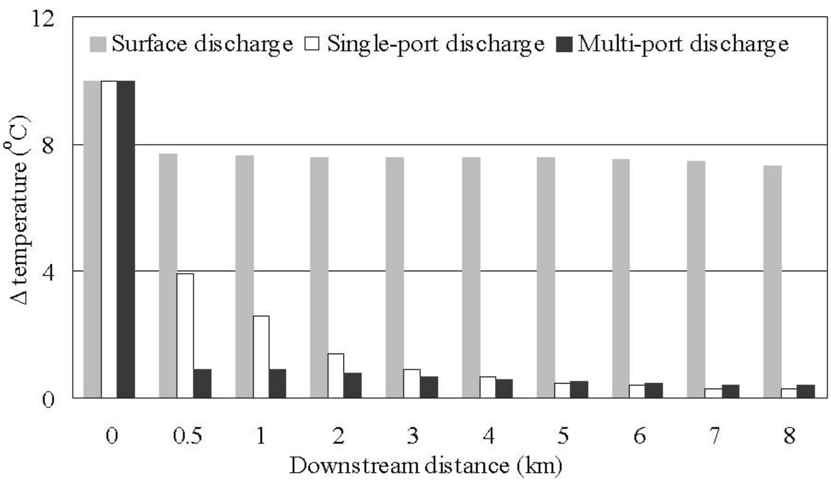

Fig. 3. Comparison of the plume temperature drop under scenarios S1, S2 and S3.

Table 5
Sensitivity analysis of CORMIX1, 2 and 3 to input parameters

Parameter	Base case	Variation range	Observations
Average depth/ discharge depth (m)			Increasing the depth of the water in the vicinity of the outfall will decrease the temperature of the plume by increasing the dilution rates, reducing bottom attachment and increasing the interaction of the plume with the receiving water body. Multi-ports exhibited the highest sensitivity to depth changes.
Surface discharge	0.6	1–5	
Single port	20	15–30	
Multi-port	5	3–10	
Current ambient velocity (m/s)		0.06–1.5	Increasing the velocity of currents will enhance mixing and hence moderately decrease plume temperatures and increase the dilution rate in the case of surface and multi-port discharge arrangements. Single-port discharges showed a decrease in dilution rates and a subsequent increase in temperatures as the ambient velocity was increased.
Surface discharge	0.182		
Single port	0.182		
Multi-port	0.182		
Manning's *n*	0.08	0.05	Changes in Manning's n affected the temperature profile of surface discharge only. Decreasing the roughness of the channel in the case of the surface discharge decreased the friction between the plume and the bottom thus resulting in a slight decrease in the reported temperatures. Single and multi-port simulations did not show any change while varying the friction coefficient.
Flow rate (m^3/s)		69.5–277.8	Decreasing the flow rate reduces the temperature profile of the plume significantly by reducing the heat load and its respective discharge velocity. Flow rate variations affect mostly the dilution rates of the single and multi-port submerged outfalls.
Surface discharge	138.9		
Single port	138.9		
Multi-port	138.9		
Indicator concentration (°C)		8–15	Increasing the temperature of the effluent affects its dissipation greatly by increasing the load being discharged. In all three discharge cases, decreasing the effluent temperature by 2°C reduced the simulated concentrations by 20 % while increasing the effluent temperature by 5°C increased the simulated concentrations by 50 %.
Surface discharge	10		
Single port	10		
Multi-port	10		
Distance to bank (m)			Changing the distance of the outfall with respect to the nearest bank does not affect the drop in temperature until the plume attaches to the bank. Increasing the distance to the bank would retard attachment and thus is expected to enhance the dilution rate. However, changing the distance to the nearest bank did not significantly affect drop in temperature in scenarios S2 and S3, while increasing the distance in case of S1 significantly enhanced dilution rates.
Surface discharge	0	1–5	
Single port	4,000	2,000–5,000	
Multi-port	2,000	1,000–4,000	
Angle of discharge[a] (°)	90	0–45	Reducing the angle of discharge between the surface discharge outfall centerline and the ambient current slightly increased temperatures along the plume centerline.
Width of outfall[a] (m)	12	3–10	Decreasing the width of the surface discharge outfall increased the discharge velocity thus enhancing mixing and reducing centerline temperatures.
Area of outfall[b] (m^2)	27.8	17.4–46.3[d]	Changes in the area of the single port outfall did not affect the mixing process and the simulated centerline temperatures remained the same.

Table 5 (continued)

Parameter	Base case	Variation range	Observations
Port height[b] (m)	1	0.5–2.0	Changes in port height of the single port outfall did not affect the mixing process
Outfall orientation[b]			Variations of the outfall orientation resulted in the generation of unstable mixing conditions that limited the simulation efforts and the sensitivity analysis
Single port			
Horizontal angle (°)	0	0–45	
Vertical angle (°)	90	0–270	
Alignment angle[c] (°)		0–135	All alignment angles considered for the multi-port outfalls resulted in an increase in the centerline temperatures indicating that a perpendicular alignment is the most suitable alignment to enhance mixing and dissipate the excess temperature in the effluent in the three cases.
Staged	90		
Vertical	90		
Alternating fanned	90		
Nozzle alignment[c] (°)			Changing the nozzle alignment of the multi-port outfalls had a minimal effect on the mixing and dilution processes.
Staged	NA	NA	
Vertical	Same direction	Fanned	
Alternating fanned	Fanned	Same direction	

[a]Applicable only for surface discharge (CORMIX-3)
[b]Applicable only for single port discharge (CORMIX-1)
[c]Applicable only for multi-port discharge (CORMIX-2)
[d]Areas that translate into discharge velocities between 3 and 8 m/sec, recommended to reduce deposition, pipe scouring, and outfall plugging.
NA: Not applicable

Table 6
Results of parametric sensitivity analysis for surface and single-port diffusers expressed in percent variation from base case (CORMIX-1 and 3)

Parameter	Downstream distance (Km)												
	Surface outfall					Single-port outfall							
	0.5	1	3	5	7	0.5	1	3	5	7	10	15	20
Average depth													
1 m	−10.5	−11.2	−11.6	−12.1	−13.9	NA	NA	NA	NA	NA	NA	NA	NA
5 m	−76.4	−77.1	−77.8	−78.0	−78.8	NA	NA	NA	NA	NA	NA	NA	NA
15 m	ND	ND	ND	ND	ND	+9.1	+14.7	+22.7	+26.4	+27.8	+29.1	+30.8	+30.6
30 m	ND	ND	ND	ND	ND	−13.4	−18.9	−26.7	−28.9	−30.2	−31.1	−31.5	−32.1
Current ambient velocity	-18.5	-22.8											
0.06 m/s			ND[1]	ND	ND	−12.9	−25.3	−35.2	−37.9	−39.2	−30.6	−25.2	−18.2
1 m/s			ND	ND	ND	+23.2	+41.3	+77.6	+93.7	+102.4	+110.2	+118.0	+121.5
1.5 m/s			−14.9	ND	ND	−20.0	+0.8	+55.0	+85.0	+103.9	+21.8	+140.2	+149.7
Manning's *n*													
0.05	−6.6	−6.7	−6.6	−6.5	−6.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Flow rate													
69.5 m^3/s	−3.3	−5.5	−7.0	−7.7	−11.0	−23.2	−31.7	−41.9	−44.7	−46.2	−47.6	−48.0	−48.5
277.8 m^3/s	+2.2	+2.5	+3.4	+3.6	ND	+21.2	+35.1	+62.5	+73.2	+79.2	+84.0	+89.7	+92.1
Indicator concentration													
8°C	−20.1	−20.0	−19.9	−19.9	−20.1	−20.0	−20.1	−20.0	−19.9	−19.9	−20.4	−19.7	−20.0
15°C	+50.0	+50.3	+50.4	+49.7	+50.1	+50.0	+50.2	+49.6	+50.0	+49.9	+49.5	+50.4	+49.8
Distance to bank (m)													
1	−10.5	−11.2	−11.6	−12.1	−13.9	NA	NA	NA	NA	NA	NA	NA	NA
5	−76.4	−77.1	−77.8	−78.0	−78.8	NA	NA	NA	NA	NA	NA	NA	NA
2,000	NA	NA	NA	NA	NA	+0.3	−3.1	−4.5	−0.8	+0.9	−1.5	+0.9	+7.3
5,000	NA	NA	NA	NA	NA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Angle of discharge		6.3	7.4	7.7	8.7								
0°	ND					ND	ND	ND	ND	ND	ND	ND	ND
45°	+0.8					ND	ND	ND	ND	ND	ND	ND	ND
Width of outfall (m)													
3	−9.1	−8.9	−8.3	ND	ND	NA	NA	NA	NA	NA	NA	NA	NA
5	−4.3	−3.9	−3.4	ND	ND	NA	NA	NA	NA	NA	NA	NA	NA
10	−0.5	−0.5	−0.1	−0.4	−0.7	NA	NA	NA	NA	NA	NA	NA	NA

NA: Not applicable; ND: Not determined due to the generation of unstable mixing conditions that stop further simulations.

Table 7
Results of parametric sensitivity analysis for multi-port diffusers expressed in percent variation from base case (CORMIX-2)

Parameter	Multi port diffuser	Downstream distance (km)							
		0.3	1	3	5	7	10	15	20
Average discharge depth (m)	Vertical	17.5	14.5	15.6	16	14.1	15	16.5	16.7
	3								
	10								
	Staged	0.4	1.2	2.8	3.8	5.3	6.6	8.4	11.7
	3								
	10								
	Alternating−fanned	16.9	16.3	15.1	16.8	17.7	16	16.4	16.6
	3								
	10								
Current ambient velocity (m/s)	Vertical	11.4	−33.7	−91.5	−109	−104	−97.5	−87.1	−93.7
	0.06								
	1								
	1.5								
	Staged	−126				−99.4			
	0.06		−5.6	−10.5	−4.7		ND	ND	ND
	1		−64.5	−57.3	−50.5		−35.0	−21.7	−10.1
	1.5		−75.5	−69.9	−64.2		−50.7	−38.2	−26.1
	Alternating−fanned	10.5	−30.6	−89.4	−105	−102	−94.9	−89.2	−94.3
	0.06								
	1								
	1.5								
Flow rate (m^3/s)	Vertical								
	69.5	−49.9	−50.5	−49.5	−50.3	−49.6	−50.4	−50.0	−50.0
	277.8	+100	+98.0	+102	+99.6	+102	+98.6	+100	+100
	Staged								
	69.5	−28.4	−30.4	−34.4	−37.0	−38.8	−40.7	−43.0	−39.9
	277.8	+26.4	+6.5	+1.5	ND	ND	ND	ND	ND
	Alternating−fanned								
	69.5	−49.9	−50.0	−49.9	−49.8	−50.1	−50.1	−50.0	−49.8
	277.8c	+100	+100	+100	+101	+100	+99	+100	+100

ND: Not determined due to the generation of unstable mixing conditions that stop further simulations.

Table 7 (continued)
Results of parametric sensitivity analysis for multi-port diffusers expressed in percent variation from base case (CORMIX-2)

Parameter	Multi-port diffuser	Downstream distance (Km)							
		0.3	1	3	5	7	10	15	20
Indicator concentration (°C)	Vertical								
	8	-19.9	-20.9	-19.2	-20.3	-19.4	-20.7	-20.0	-19.9
	15	+50.3	+47.9	+50.9	+49.4	+51.3	+50.0	+50.0	+50.0
	Staged								
	8	-20.0	-20.0	-20.0	-19.9	-19.5	-20.2	-20.2	-19.8
	15	+50.0	+49.5	+50.4	+50.2	+50.1	+49.6	+49.6	+49.8
	Alternating-fanned								
	8	-20.0	-20.0	-20.0	-19.9	-19.5	-20.2	-20.2	-19.8
	15	+50.5	+49.5	+50.4	+50.2	+50.1	+49.6	+49.6	+49.8
Distance to bank (m)	Vertical						7.1	12.3	0.9
	1000	0.0	0.0	-0.9	-0.2	-0.4			
	4000	0.0	0.0	0.0	0.0	0.0			
	Staged								
	1000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+5.9
	4000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Alternating-fanned						7.1	12.3	0.9
	1000	0.0	0.0	-0.9	-0.2	-0.4			
	4000	0.0	0.0	0.0	0.0	-0.2			
Alignment angle (°)	Vertical	203	95.1	68.6	51	41.9	25.2	15.8	9.2
	0								
	45								
	135								
	Staged								
	0	+67.8	+59.7	ND	ND	ND	ND	ND	ND
	45	+66.8	ND	ND	ND	ND	ND	ND	ND
	135	ND	ND	ND	ND	ND	ND	ND	ND
	Alternating-fanned	229	114.6	83.8	105.9	84	34.8	18.6	12.5
	0								
	45								
	135								
Nozzle direction	Vertical	NA	NA	NA	NA	NA	NA	NA	NA
(Fanned/same direction)	Staged, fanned	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Alternating-fanned								
	Same direction	+10.1	+9.3	+7.6	+6.4	+5.8	+4.8	+2.3	+1.8

NA: Not applicable; ND: Not determined due to the generation of unstable mixing conditions that stop further simulations.

simulated temperature drop and/or dilution rates. The simulations were conducted by varying one parameter at a time while holding the rest constant. Table 5 summarizes the effect of input parameters on simulated temperatures with respect to downstream distance. The temperature variations at different downstream locations are reported in the form of percent change from base case and presented in Tables 6 and 7. Note that variations in wind speed and in the heat loss coefficient did not affect concentrations and dilution rates and thus were not reported. The results indicate that the adopted flow rate, ambient current velocity, discharge depth, indicator level and the alignment angle of multi-port outfalls were the most significant parameters affecting the development of the plume, while the roughness of the seabed and the distance of the outfall from the bank seemed to have the least significant effect on model simulation results.

6. Management options

6.1. Brine disposal

The mitigation of environmental implications of concentrate disposal is most closely related to the means through which it is managed. Several means for disposal of the concentrate are practiced worldwide including: direct surface water discharge, discharge to a sewage treatment plant, deep well disposal, land application, evaporation ponds, brine concentrators as well as mixing with the cooling water or sewage treatment effluents prior to surface discharge. Table 8 outlines advantages and disadvantages of various brine disposal methods. Evidently, brine discharge into surface water bodies is the most commonly used and least expensive disposal method in practice today [10,40,43]. Minimal adverse impacts are expected if rapid mixing and dilution are ensured in the discharge zone [5,44]. These optimal mixing conditions can be attained by the careful design and construction of outfalls that account for local circulation patterns, hydrographic currents, and the hydrodynamic characteristics of the discharge area. Outfalls should avoid lagoons, shallow water and inter-tidal areas with limited circulations and look for rather exposed coastal stretches with strong flushing capabilities [5,7,8, 15]. In fact, the USEPA prohibits the discharge of any effluent in shallow near-shore water bodies and requires the construction of offshore outfalls. In Cyprus, the new Larnaca RO plant (capacity 54,000 m^3/day) was required to be equipped with an outfall exceeding 1 km in length and discharging at least 10 m below sea surface to limit brine impact on existing biota [3]. Submerged discharge outfalls however are more costly, particularly in the Gulf region since the distance required for laying down the pipes is relatively long due to the shallowness of the Arabian Gulf. The adoption of submerged multi-port diffusers is expected to be cheaper than single-port submerged outfalls in the case of the Arabian Gulf since multi-ports are capable of ensuring rapid mixing even in shallow water bodies thus reducing the costs associated with placing pipes over long distances. This is attributed to the presence of a multitude of nozzles in the diffuser that increase the plume's contact area with the ambient water, increase initial mixing rates, and reduce the downstream distance traveled by the plume before meeting the environmental regulatory requirements [45,46].

Based on the simulation results presented in this study, Table 9 outlines design recommendations that can enhance the dilution rates of the discharge and reduce the pollutant concentrations for direct surface, single-port and multi-port outfall discharges. The adoption of surface channels for brine discharge in shallow areas with limited circulation is not adequate to achieve acceptable mixing and dilution rates. Mitigation of adverse impacts of the direct surface discharge of brine on the local marine environment can be achieved either by the construction of several long single port outfalls or a multi-port diffuser.

Table 8
Advantages and disadvantages of brine disposal options [44, 7, 10, 42, 40, 47]

Disposal method	Advantages	Disadvantages
Direct surface water discharge	• Least expensive • Can accommodate large volumes	• Depends on natural circulation patterns and hydrographic currents in the area
Discharge to a sewage treatment plant	• Lowers the BOD of the resulting effluent • Dilutes the brine concentrate	• Can inhibit bacterial growth • Can hamper the use of the treated sewage for irrigation due to the increase in TDS and salinity of the effluent • Overload the existing capacity of the sewage treatment plant
Deep well disposal	• Viable for inland plants with small volumes of brine • No marine impact expected	• Expensive • Needs a structurally isolated aquifer • Increases the salinity of groundwater
Land applications	• Can be used to irrigate salt tolerant species • Viable for inland plants with small volumes of brine • No marine impact expected	• Requires large parcels of land • Can affect the existing vegetation • Can increase the salinity of groundwater • Can increase the salinity of underlying soil
Evaporation ponds	• A viable option for inland plants in highly arid regions • Can commercially exploit the concentrate • No marine impact expected	• Expensive option • Can increase salinity of groundwater • Can increase salinity of underlying soil • Needs dry climates with high evaporation rates • Requires large parcels of land with a level terrain • Needs regular monitoring
Brine concentrators/zero discharge	• Can produce zero liquid discharge • Can commercially exploit concentrate • No marine impact expected	• Expensive • High energy consumption • Production of dry solid waste
Mixing with the cooling water discharge	• Achieve dilution of both effluents prior to discharge • Combined outfall reduces the cost and environmental impacts of building two outfalls • Necessary to reduce salinity if disposing in fresh water bodies	• Dependent on the presence of a nearby thermal power plant
Mixing with the sewage treatment effluent	• Achieve dilution of brine effluent prior to discharge • Does not overload the operational capacity of sewage treatment plant • Necessary to reduce salinity if disposing in fresh water bodies	• The brine could enhance the aggregation and sedimentation of sewage particulates that can impact benthic organisms and interfere with the passage of light in the receiving water body

Table 9

Design recommendations for brine discharge

Discharge type	Design recommendation [a]
Surface discharge	Increasing the width of the channel coupled with reducing its depth is expected to increase the dilution process of the plume and enhance its ability to spread horizontally
Single-port outfall	Splitting the effluent flow rate between 2 or more outfalls that are adequately spaced is expected to enhance the dilution process
Multi-port outfall	Adopting a perpendicular alignment of the diffuser line with respect to the ambient velocity is expected to enhance the dilution process

[a]Relevant to conditions similar to those simulated and should not be implemented to discharges under different conditions without prior verification.

Table 10

Environmental concerns and the possible mitigation measures resulting from brine discharge into a surface water body [10,15]

Environmental impact	Desalination process	Mitigation measure
Low pH	Mainly SWRO	Raise pH prior to discharge
Residual chlorine	MSF	Dechlorination prior to discharge; improved chemical control
Increased temperature	MSF	Blending; using diffusers; using cooling pond or cooling tower prior to discharge
Metal ions	MSF	Blending; improved chemical control, using different equipment materials (polyethylene or titanium rather than copper nickel pipes)
High salinity	SWRO and MSF	Using diffusers; blending

SWRO = Seawater reverse osmosis; MSF = multi-stage flash.

6.2. Reducing pollutant load

The effects of brine can also be minimized prior to the discharge phase by reducing the pollutant load of the effluent. Pollutant specific mitigation measures that are most commonly practiced in the desalination industry are presented in Table 10.

7. Conclusions and limitations

The disposal of the brine blow-down is one of the major environmental concerns associated with the desalination industry. The blow-down contains a variety of environmental pollutants that may impact the receiving water bodies. Simulations of the brine plume dispersion from a desalination-power plant in the Gulf region revealed the inadequacy of using surface discharge outfalls for brine disposal. Using multi-ports proved to be adequate to enhance dilution rates and limit the potential environmental impacts, whereby a tenfold dilution rate was achieved within a 300 m mixing zone. Like all models, CORMIX has several inherent limitations. One major limitation results from the use of hydrodynamically significant length scales to determine the flow class of the effluent and its subsequent dilution, spatial and temporal development in the receiving water body. As such a small change in an input variable may result in the identification of a different flow class with quite different predictions leading to a sharp shift in the simulated trajectory and mixing rates causing potential in discontinuities in the prediction results [45]. Another limitation common to all three CORMIX modules is the need to describe the actual cross-section of the water body as a rectangular straight uniform channel that may be bound laterally or unbound and where the current velocity is assumed to be uniform thus simplifying the prevailing hydrodynamic regimes within an area. A limitation inherent to the CORMIX-3 module is its inability to simulate negatively buoyant discharges thus limiting its applicability for brine dispersion [42]. Furthermore, the CORMIX model exhibited a limited capability for simulating the discharge of large flow volumes in shallow areas. Finally, model simulations could not be verified with field measurements since data concerning pollutant concentrations along the brine plume were not available.

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References

[1] ESCWA (Economic and Social Commission for Western Asia) and UNEP (United Nations environmental program). Proc. Expert Group Meeting on the Implementation of Agenda 21 for the integrated water management in the ESCWA region. United Nations, New York, 1996.

[2] A. Purnama, H.H. Al-Barwani and M. Al-Lawatia, Modeling dispersion of brine waste discharge from a coastal desalination plant. Desalination, 155 (2003) 41–47.

[3] R. Einav, K. Harussi and D. Perry, The footprint of the desalination processes on the environment. Desalination, 152 (2002) 141–154.

[4] P.K. Abdul-Azis, I.A. Al-Tisan, M.A. Daili, T.N. Green, A.G.I. Dalvi and M.A. Javeed, Chlorophyll and plankton of the Gulf coastal waters of Saudi Arabia bordering a desalination plant. Desalination, 154 (2003) 291–302.

[5] T. Höpner, A procedure for Environmental Impact Assessment (EIA) for seawater desalination plants. Desalination, 124 (1999) 1–12.

[6] H.A. Abu Qdais, Environmental impacts of desalination plants on the Arabian Gulf. Proc. International Desalination Association World Congress on Desalination and Water Reuse, Vol. 3, San Diego, 1999, pp. 249–260.

[7] H. Khordagui, Environmental aspects of brine reject from desalination industry in the ESCWA region. Groundwater recharge from treated wastewater. Expert group meeting on development of non-conventional water resources and appropriate technologies for groundwater management in the ESCWA member countries, Manama, 1997.

[8] ESCWA (Economic and Social Commission for Western Asia). Water desalination and wastewater reuse: Review of technology, economics and application in the ESCWA region. Expert group meeting on development of non-conventional water resources and appropriate technologies for groundwater management in the ESCWA member countries, Manama, 1997.

[9] S. Latteman and T. Höpner, Seawater desalination: Impacts of brine and chemical discharge on the marine environment. Balaban Desalination Publications, Italy, 2003.

[10] M. Mickeley, Environmental considerations for the disposal of desalination concentrates. Proc. International Desalination Association World Congress on Desalination and Water Sciences, 37 (1995) 351–368.

[11] A.M. Shams El Din, S. Aziz and B, Makkawi,

Electricity and water production in the Emirates of Abu Dhabi and its impact on the environment. Desalination, 97 (1994) 373–388.

[12] F.M.A. Al-Awadhi, The year of the ocean and its crucial importance to the Gulf. Desalination, 123 (1999) 127–133.

[13] I.D. McGregor, A.H. Sultan and A. Al-Radif, Fifty common misconceptions in the desalination industry. Proc. International Desalination Association World Congress on Desalination and Water Sciences, Abu Dhabi, 1995, pp. 185–195.

[14] M. Abdel-Jawad and M. Al-Tabtabaei, Impact of current power generation and water desalination activities on Kuwaiti marine environment. Proc. International Desalination Association World Congress on Desalination and Water Reuse, San Diego, 3 (1999) 231–240.

[15] California Coastal Commission. Seawater desalination in California, 1993. Available from: http://ceres/ca.gov/coastalcomm/web/desalrpt/dtitle.html.

[16] A.J. Morton, I.K. Callister and N.M. Wade, Environmental impacts of seawater distillation and osmosis processes. Desalination, 108 (1996) 1–10.

[17] H.K. Khordagui, A conceptual approach to the selection of a control measure for residual chlorine discharge in Kuwait Bay. Environ. Management, 16(3) (1992) 309–316.

[18] T. Höpner and S. Lattemann, Chemical impacts from seawater desalination plants — a case study of the northern Red Sea. Desalination, 152 (2002) 133–140.

[19] T. Höpner and J. Windelberg, Elements of environmental impact studies on coastal desalination plants. Desalination, 108 (1997) 11–18.

[20] G.L. Seegert, Observation on fish distribution below sewage treatment plants in relation to chlorinated effluents. Water chlorination-environmental impact and health effects. Ann Arbor Science, Ann Arbor, Michigan, 1979.

[21] R. Golob and E. Brus, UNEP Regional Seas Reports and Studies, 1984, p. 7.

[22] M.Y. Ali and J.P. Riley, The distribution of brominated methanes in desalination plants in Kuwait. Water Res., 23(9) (1989) 1099–1106.

[23] M.E. Stewart, W.J. Biogoslawski, R.Y. Hsu and G.R. Helzz, Marine Pollution Bull., 10 (1979) 166, cited in Saeed et al., 1999.

[24] G.L. Scott, D.P. Middaugh, A.M. Crane, N.H. McGlothin and Eatabe, in: Jolley, R.L., Brungs, W.A. and Cumming, R.B. eds., Water Chlorination: Environmental Impact and Health Effects, Vol. 3, Ann Arbor Science, 1980, pp. 501–516, cited in Saeed et al., 1999.

[25] A.M. Altayaran and I.M. Madany, Impact of a desalination plant on the physical and chemical properties of seawater, Bahrain. Water Res., 26(4) (1992) 435–441.

[26] B. Mabrook, Environmental impact of waste brine disposal of desalination plants, Red Sea, Egypt. Desalination, 97 (1994) 453–465.

[27] R.A. Kryzhanovsky, Effectiveness of processing resources of the continental shelves of world oceans. Nedra, Leningrad, Russia, 1989. Cited in Abu Qdais, 1999.

[28] S. Iso, S. Suizu and A. Maejima, The lethal effect of hypertonic solutions and avoidance of marine organisms in relation to discharged brine from a desalination plant. Desalination, 97 (1994) 389–399.

[29] R.A. Hinrichs and M. Kleinbach, Energy Its Use and the Environment, 3rd ed., Harcourt College, Philadelphia, 2002.

[30] GESAMP (Group of Experts on the Scientific Aspects of Marine Environmental Protection). IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP joint group of experts on the scientific aspects of marine pollution, thermal discharges in the marine environment. Report Study GESAMP, Number 24, 1984. Cited in Altayaran and Madany, 1992.

[31] L. Jensen, R. Davies, A. Brooks and C. Meyers, The effects of elevated temperatures upon aquatic invertebrates. Johns Hopkins University, Cooling Water Research Project, Report No. 4, Edison Electric Institute, New York, 1969. Cited in Altayaran and Madany, 1992.

[32] C. Coutant, Biological aspects of thermal pollution. Entrainment and discharge canal effects. In Brook A.J., ed., CRC Critical Review of Environmental Control Union, Carbide Corp, Oak Ridge, Tennessee, 1970, pp. 341–381. Cited in Altayaran and Madany, 1992.

[33] R.M. Davies and L. Jensen, Effects of entrainment of zooplankton at three Mid-Atlantic power plants. Report No. 10, Electrical Power Research Institute, Cooling water discharge research project (RP-49),

Palo Alto, California, 1974. Cited in Altayaran and Madany, 1992.
[34] J. Baum, Environmental impacts and regulatory issues from seawater desalination: Meeting the needs of California’s coastal communities, seminar, University of California at Santa Barbara (USCB), 1991. Cited in California Coastal Commission, 1993.
[35] R.O. Smith, Ecology and Field Biology, 5th ed., Addison Wesley, Longman, Menlo Park, California, 1996.
[36] P. Azoury, Power and desalination in the Arabian Gulf region: an overview. Proc. Institution of Mechanical Engineers, 215(A) (2001) 405–419.
[37] IDA (International Desalination Association), The biggest turnout for WSTA 6th water conference. IDA News, 12(3–4) (2003) 6–8.
[38] T. Saeed, H. Khordagui and H. Al-Hashash, Contribution of power/desalination plants to the levels of halogenated volatile liquid hydrocarbons in the coastal areas of Kuwait. Desalination, 121 (1999) 49–63.
[39] R.L. Doneker, Personal communication. Department of Environmental Science and Engineering, OGI School of Science and Engineering, Oregon Health and Science University, 2002.
[40] J.V. Del Bene, G. Jirka and J. Largier, Ocean brine disposal. Desalination, 97 (1994) 365–372.
[41] R.L. Doneker and G.H. Jirka, CORMIX-GI systems for mixing zone analysis of brine wastewater disposal. Desalination, 139 (2001) 263–274.
[42] G.H. Jirka, R.L. Doneker and S.W. Hinton, User’s Manual for CORMIX: A hydrodynamic mixing zone model and decision support system for pollutant discharges into surface waters. DeFrees Hydraulics Laboratory, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, 1996.
[43] D. Squire, Reverse osmosis concentrate disposal in the UK. Desalination, 132 (2000) 47–54.
[44] M. Ahmed, W.H. Shayya, D. Hoey, A. Mahendran, R. Morris and J. Al-Handaly, Use of evaporation ponds for brine disposal in desalination plants. Desalination, 130 (2000) 155–168.
[45] L.R. Davis, Fundamentals of Environmental Discharge Modeling. CRC Press, Boca Raton, Florida, 1999.
[46] H.B. Fischer, E.J. List, R.C.Y. Koh, J. Imberger and N.H. Brooks, Mixing in Inland and Coastal Waters. Academic Press, Boston, 1979.
[47] J. Truesdall, M. Mickley and R. Hamilton, Survey of membrane drinking water disposal methods. Desalination, 102 (1995) 93–105.