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Characterization of the water mass dynamic changes surrounding a seawater reverse osmosis desalination plant on the east coast of the Kingdom of Bahrain

Anwar Al-Osaimi[a], Thamer S. Ali[a,*], Waleed Al-Zubari[a], Humood Naser[b]

[a]*Department of Natural Resources & Environment, College of Graduate Studies, Arabian Gulf University, Bahrain, email: thamersa@agu.edu.bh (T.S. Ali)*

[b]*Department of Biology, Faculty of Science, University of Bahrain, Bahrain*

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ABSTRACT

Desalination in the Gulf Cooperation Council countries is essential in the provision of drinking water supply and in achieving the targets of the UN Sustainable Development Goals (SDGs), particularly SDG6.1 aiming at achieving access for all to safe drinking water. On the other hand, desalination process is associated with several environmental externalities that have adverse impacts on the coastal and marine environments. The aim of this research is to assess the dynamic changes of the water mass quality parameters resulting from a seawater reverse osmosis (SWRO) desalination plant located on the east coast of Bahrain, in relation to the tide cycle on seasonal basis. The evaluation is based on the spatial differences in water temperature and salinity in the surrounding areas of the plant outlet within about 2.5 km^2. Water samples were collected at 42 locations for both surface and bottom waters over high and low tide cycle during winter and summer. The results revealed an extreme elevation in temperature (>38°C) and hypersaline waters (>55‰) at locations nearby the discharge outlet as well as at bottom waters of depths >3 m in both seasons with exceptional levels in summer particularly during high tide cycle. Thermocline and halocline formations were noticeably occurred particularly during high tide in both seasons due to vertical differences in temperature (>3°C) and salinity (>1‰) at several locations associated with depths more than 3 m. The thermocline and halocline formations indicate the path by which the thermal and hypersaline water mass fluxed by the desalination plant sinking out towards the open water. The impacts of Al-Dur SWRO desalination need to be minimized to maintain the seagrass habitat around the coast to support the marine biodiversity, particularly the megafauna endangered species associated with seagrass, (dugongs, green turtles and dolphins) and other finfish and shellfish species.

Keywords: Environmental Impacts, Temperature, Salinity, Tide Cycle, Thermocline, Halocline, Al-Dur

1. Introduction

The Gulf Cooperation Council (GCC) countries are situated in an arid to semi-arid area and are characterized by high temperatures, low rainfall, and limited freshwater resources. In the past decades, these countries have experienced unprecedented social and economic development associated with rapid demographic and urbanization growth. To meet the water requirements for the rapidly expanding population under natural water scarcity, the GCC counties have relied essentially on desalination. This has been made possible by the availability of financial and energy resources the GCC countries possess. However, in addition to its financial and economic costs, desalination has several environmental externalities, which are manifested in its gaseous effluent, represented by greenhouse gasses emissions (CO_2, NOxs, SOxs, …), and liquid effluent, represented by the high concentration reject, or brines, of the desalination process, and in the case of thermal technology, thermal brine.

* Corresponding author.

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The production of desalination plants in the Arabian Gulf has increased from 0.04 million m^3/d in 1970 [1] to more than 21 million m^3/d in 2018 [2], which equivalent over 20% of total global [3]. The highest number of desalination plants and largest desalination capacity worldwide is found in the Arabian Gulf area; between 2000 to 2010 more than 64% of the world's total production capacity were reported in this region. Without exception, during the last three decades, desalination capacity in the GCC countries has increased substantially. This trend is expected to continue in the coming decades [4]. Desalination water production is supposed to increase from about 8,000 Mm^3/y to about 41,000 Mm^3/y by 2050 [5] and to 80,000 Mm^3 [6].

The Kingdom of Bahrain, like the rest of the GCC countries, have embarked on desalination projects to meet the municipal water requirement of rapidly increasing population and urbanization since the 1975, when it launched its first desalination plant in Sitra, Sitra MSF, located at the eastern coast of Bahrain island. This was followed by five desalination plants, all located on the eastern coastline of Bahrain: 1 MSF representing Al-Hidd, 2 MED including Al-Hidd and Alba, and 2 RO at Ras Abu Jarjur and Al-Dur [7]. Al-Dur desalination plant, the focus of this study, is designed to produce 220,000 m^3/d and was developed on a build-own-operate project (BOO) project basis, consisting of a combined power plant and a RO desalination plant.

While the socio-economic benefits of desalination plants and its key role in achieving sustainable development, particularly SDG6.1 concerned with the provision of safe drinking water supply to all population [8], the associated negative impacts related to desalination plants operation as a land-based source of pollution to the marine environment are of a major concern [9]. Namely, the main environmental concern is the impacts of the desalination brine discharge to the marine environment. The discharged brine water probably includes additional chemical pollutants, which possibly affect the chemical properties of both water and sediment quality.

The magnitude of this impact depends on the characteristics of the desalination plant and its reject brine. The rejected brine is characterized by extreme salinity, and in the case of thermal desalination it is also associated by extreme temperature. Thermal desalination plants usually discharge a temperature of 5°C–10°C above ambient seawater temperature [10]. Mann and Lazier [11] revealed that the highest temperature value in the surrounding area of the brine discharge is found very close to the mouth of the outfall diffuser. Abdul-Wahab [12] investigated the relationship between the temperature of seawater and the distance from the discharge site. The difference of temperature changes in the ocean water and the surrounding area of the discharge brine showed considerable fluctuation with a significant range from 10°C to almost 40°C, while the general ocean's temperature varies between 10°C to just under 25°C [13].

The discharged brine represents a desalination externality that has a negative impact on the surrounding marine environment due to its influencing changes of the surrounding area's physical properties, such as salinity, temperature, and density and the remains of chemical additives or corrosion products [14]. With continuous desalination brine discharge into the ambient seawater, a localized hypersaline water, termed halocline, will be created [15]. In the case of thermal technologies, a localized high temperature zone will also be created (thermocline). The extent of the halocline and thermocline will depend on many parameters related to the desalination plant and the surrounding marine environment. These include desalination plant size, technology (i.e., thermal or membrane), and age [16]; the surrounding marine environment characteristics, such as depth, currents, morphology, and many other parameters.

Desalination plants in the Gulf typically use nearshore surface water intakes. Therefore, the potential impacts of impingement and entrainment were explored through a simple volume calculation that compared the predicted volume of water passing through desalination plants on an annual basis with the total volume of water in the Gulf between the shore and the 10 m depth contour [6]. The effect of desalination is based on a mixture of experimental, field and modelling studies to identify the physiochemical, biological and ecological impacts, which vary depending on location, type and capacity of desalination plant. The release of discharge plumes, particularly into confined water bodies, or areas where topography constrains hydrodynamic dispersal, potentially lead to an extreme concentration of brines that would be rapidly dispersed on an open coastline [17]. Similarly, the impact of intakes and outfall based on both configuration and design [18], and on the type and amount of water preconditioning chemicals used in each desalination plant [19].

An important first step to mitigate the impacts of the brine of an existing desalination plant on the coastal and marine environment is to characterize the extent of the created halocline and thermocline, if any, and their dynamic changes over seasons as well as over tide cycle. These characterizations are essential input to design the mitigation plan to reduce the impact of brine on the marine environment.

2. Materials and methods

2.1. Study area

The present study is conducted on the Al-Dur coast, east of Bahrain within the vicinity of the Al-Dur power and desalination plant (Fig. 1). The Al-Dur reverse osmosis desalination plant is located on the southeast coast of the Kingdom of Bahrain commissioned in February 2012 and was designed with a daily capacity of 220,000 m^3/d to meet the growing demand for drinking water and electricity in Bahrain as well. The plant was developed as a build-own-operate project (BOO) engaged in the private sector.

The tidal regime circulation along the Bahrain coasts is diurnal twice a day with a depth range between 0–7 m. The water intake at 1.5 km and the pip supplemented by two subsurface intake filters each consisted of four units. Total of 20 barrier fishing traps (locally known as Hadrah) are distributed along the Al-Dur coast. Further, fishing activities practiced by drift nets and wire metal traps (locally known as Gargoor).

2.2. Sampling

The monitoring sites have been positioned using Global Positioning System (GPS) of Trimble type into a network form located in the vicinity of the discharge path within a grid area represented in Fig. 2. The measurements were carried out during winter (February) and summer (August) 2017. The *in situ* measurements of temperature and salinity were conducted using Pro DSS multi-meter probe. The measurements in winter (27th February 2017) covered 36 monitoring locations during high tide and 42 monitoring locations during low tide. In summer (6th August 2017), a total of 40 monitoring locations has been selected during the high tide and 41 monitoring locations during the low tide.

3. Results

3.1. Water temperature

A seasonal variation found between winter and summer temperatures. The measurements in winter were ranged between 17.0°C and 21.8°C; however, in summer were varied between 35.4°C and 38.8°C. The minimum, maximum and average are presented in Table 1. The results showed that no differences observed between the surface and bottom in both seasons indicating well thermal mixing. However, the temperature during the low tide seems to be warmer than high tide.

Relatively, the temperature was differed on a spatial basis following to distance from desalination plant outlet. The maximum values found at stations closest to the outlet, those associated with depth less than 1m at which the range was varied from 21.2°C to 21.8°C in winter and from 37.4°C to 38.8°C in summer. The rest of the locations are with an average of 18.5°C in winter and 36.5°C in summer.

Slight variations could be noticed between temperatures during high tide and low tide cycle in summer (Fig. 3), however, no real variations observed in winter

Fig. 1. Location map showing the site of the Al-Dur power and desalination plant.

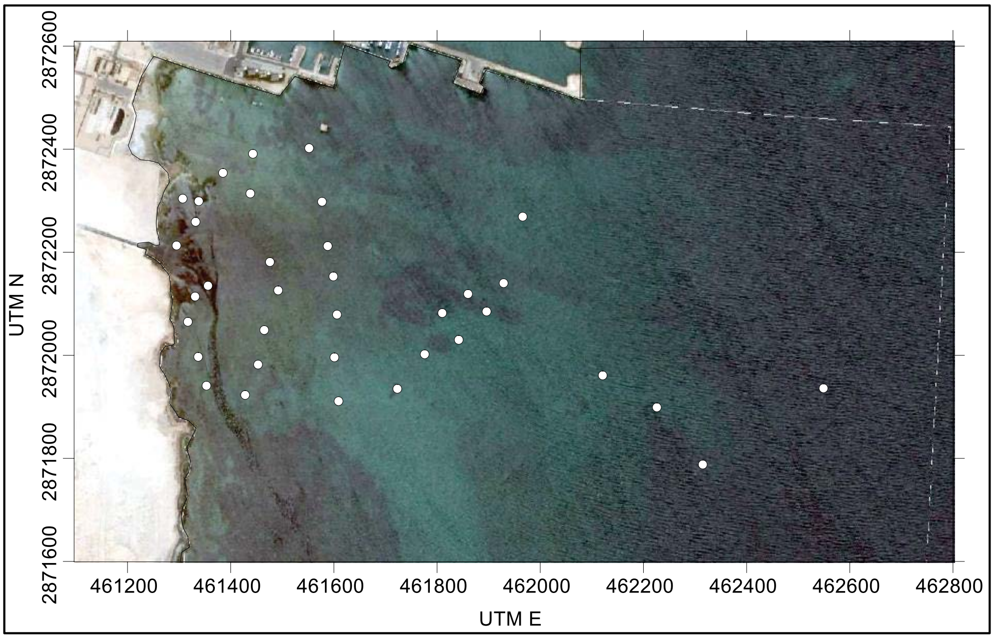

Fig. 2. Grid area of *in situ* water quality parameters.

Table 1
Surface and bottom water temperature during high and low tide cycle in summer and winter

Temperature	Summer				Winter			
	High tide		Low tide		High tide		Low tide	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Min.	35.1	35.2	36.6	36.7	17.3	17.4	18.3	18.5
Max.	38.8	38.7	40.4	40.3	21.5	21.3	23.1	23.3
Average	36.5	36.5	37.9	37.9	18.3	18.6	19.5	20.1

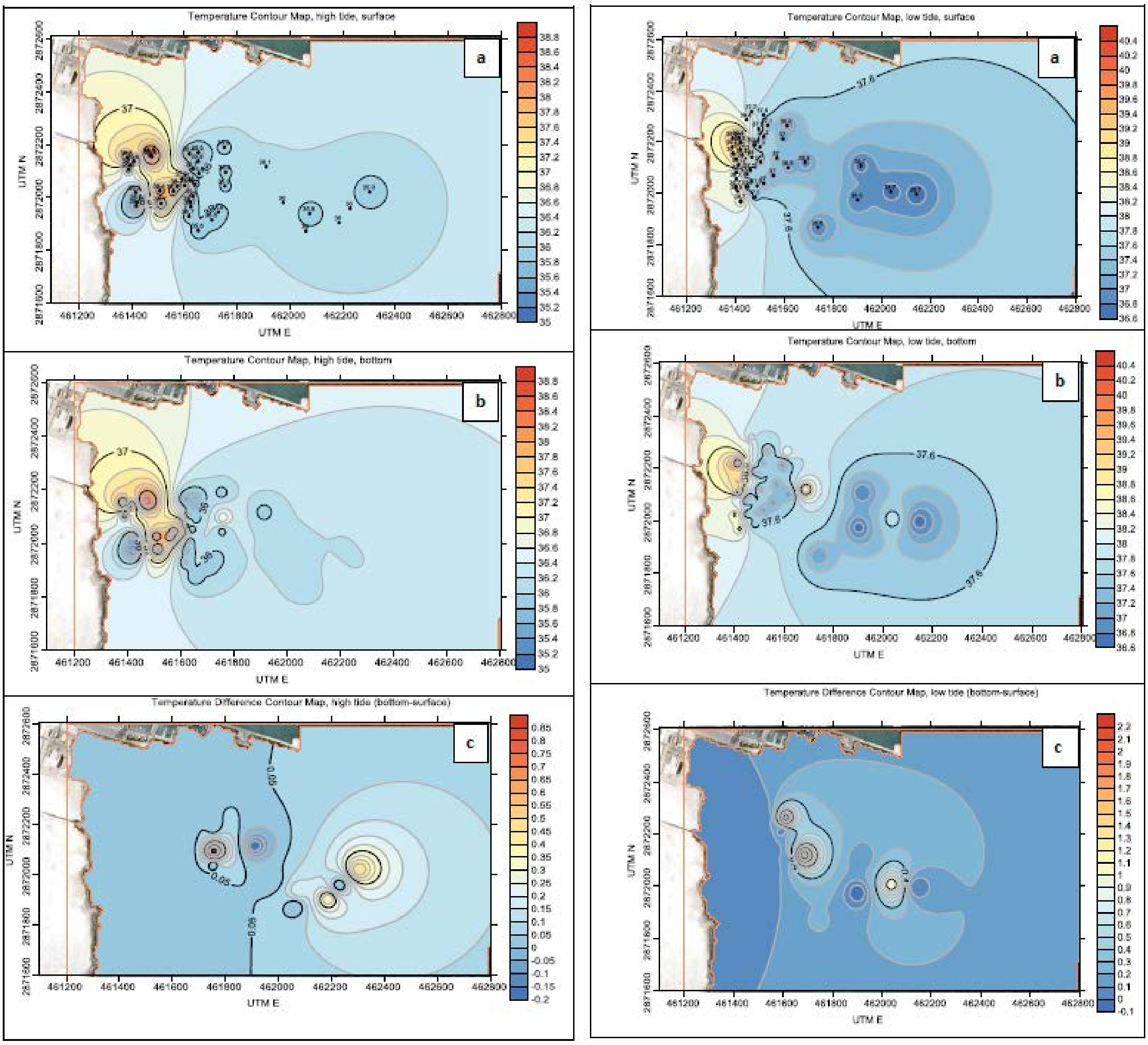

Fig. 3. Water temperature during high (left) and low (right) tide cycle in summer (a) surface, (b) bottom and (c) difference between surface and bottom.

(Fig. 4). A considerable thermocline was observed in winter where the bottom layers characterized by higher temperature mostly at stations characterized by depth more than 3–4 m. The other sampling locations exhibited marginal fluctuations on a vertical basis between surface and bottom layers mostly with less than 2°C (Fig. 5). In summer the water column seems to be thermally well mixed.

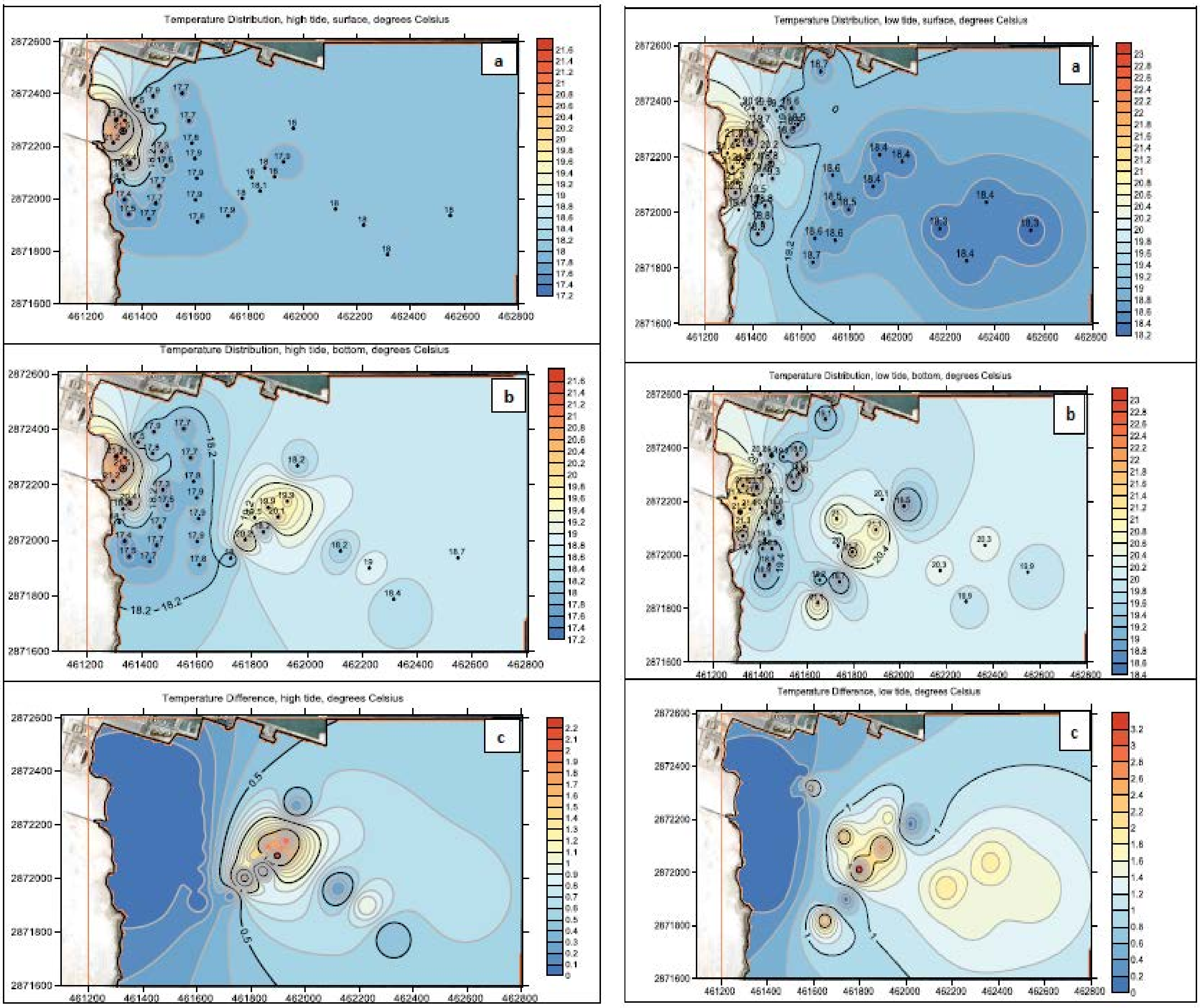

Fig. 4. Water temperature during high (left) and low (right) tide cycle in winter (a) surface, (b) bottom and (c) difference between surface and bottom.

The spatial variation of temperature considering the tide cycle in summer showed a heterogeneity distribution during the high tide at which three contours were formed characterized by different temperatures. However, during the low tide the water mass was spatially more homogenized within the outlet vicinity. In winter, different pattern has been observed indicating thermal stratification as visible contours were occurred representing high temperature at bottom in comparison with surface specifically at depths 3–5 m.

3.2. Salinity

The salinity levels throughout the study area were varied between 44‰ to 59‰ in summer 42‰ and 60‰ in winter (Figs. 6 and 7). The results presented in Table 2 revealed that no real differences on seasonal basis were observed between summer and winter measurements. The salinity levels at bottom are relatively higher than surface with a slight tendence to high concentration during low tide cycle.

Spatially, the salinity showed clear variations based on a distance from the desalination outlet during summer and winter (Figs. 6 and 7). Extreme salinity levels (58‰–60‰) were found at stations located nearest to the outlet at depth less than 1m. However, the salinity levels at other locations were ranged between 42‰ to 49‰.

The salinity levels during the high tide cycle found to be slightly higher than relevant ones during the low tide cycle. Halocline (salinity stratification with a difference >1‰) was observed at all sampling locations except stations located nearby the outlet associated with shallow depths (<1 m). Stations located at depth 3–4 m were found to be the most saline stratified where the difference was >5‰ during the high tide and >10‰ during the low tide (Fig. 8). The vertical differences in salinity in summer were slightly lower than those that occurred in winter.

Three to four main salinity contours could be observed during the high tide in summer indicating a clear variation on a spatial basis, however, the water mass seems to be more homogenized during the low tide where the water mass

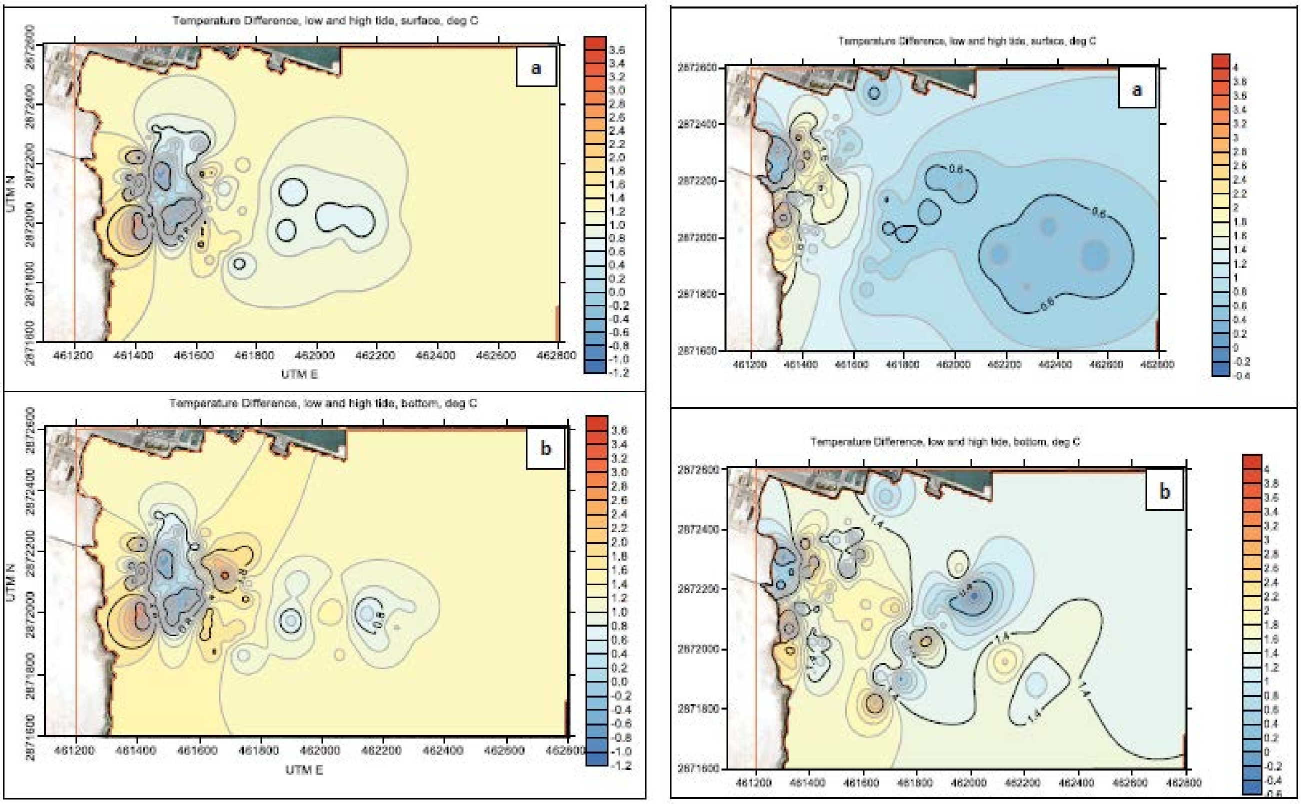

Fig. 5. Water temperature differences between high and low tide cycle of surface and bottom waters in summer (left) and winter (right).

well-mixed throughout the outlet area. The trend of salinity gradient was different in winter where a noticeable difference was obtained throughout the water column among the monitoring locations, particularly at stations associated with depths 5–6 m in which obvious halocline was observed. In general, the vertical distribution of salinity was more stratified in comparison with temperature during summer and winter.

4. Discussion

There is visible effect and impact due to the release of the brine water from Al-Dur desalination to the local water around the outlet of the desalination discharge. At the area facing the outfall high increase of water temperature extended to different distances following to tide cycle on a daily periodical basis as well as seasonal basis identified throughout the monitoring locations. The predicted scenarios in the Sitra desalination plant study showed that there is temporal variation in temperature during winter and summer as obtained by Saleh [20]. Similar findings indicated in the present study on the Al-Dur desalination plant. Palmer [21] proposed enforcement of national guidelines and standards for the brine discharge to minimize the environmental impacts. The Arabian Gulf is a highly stressed area due to the desalination activities and increasing capacity for providing fresh water. In addition to the environmental impacts expected to occur from climate change [5].

Al-Dur plant is one of the RO desalination plants in Bahrain. The trend of the desalination technology over the last 15 y indicated that the RO technology is expected to be the most common in the future capacity. However, although this technology type RO does not directly generate heated brine, the RO process will generate warm water typically discharged to the sea by the power stations, due to the associated energy production required unless very large-scale renewable energy sources are deployed [22].

The results on salinity gradient revealed that the effect of the brine water release is relatively high near the area of the outlet. The effect varied with the distance between 500–800 m from the discharge point. Such increase is continued through the whole period of investigation due to the continuous disposal of the brine water to the sea area. Since there is no standard for the salinity gradient in the Kingdom of Bahrain, a comparison made with the quality standard set by the Kuwait environment public authority for the release of cooling water to the sea area. The comparison has indicated that the salinity concentrations at most of the sampling locations were higher than effluent discharge standards with a mean ranging between 2.5‰–9.0‰. The effect of high salinity concentration may potentially reflect on benthic species composition indicated by [23]. Salinity can play a significant role in the growth and size of aquatic life and marine species disturbance mostly the migratory species as for common commercial fish species such as silver Pomfret and his shad that Kuwait environment

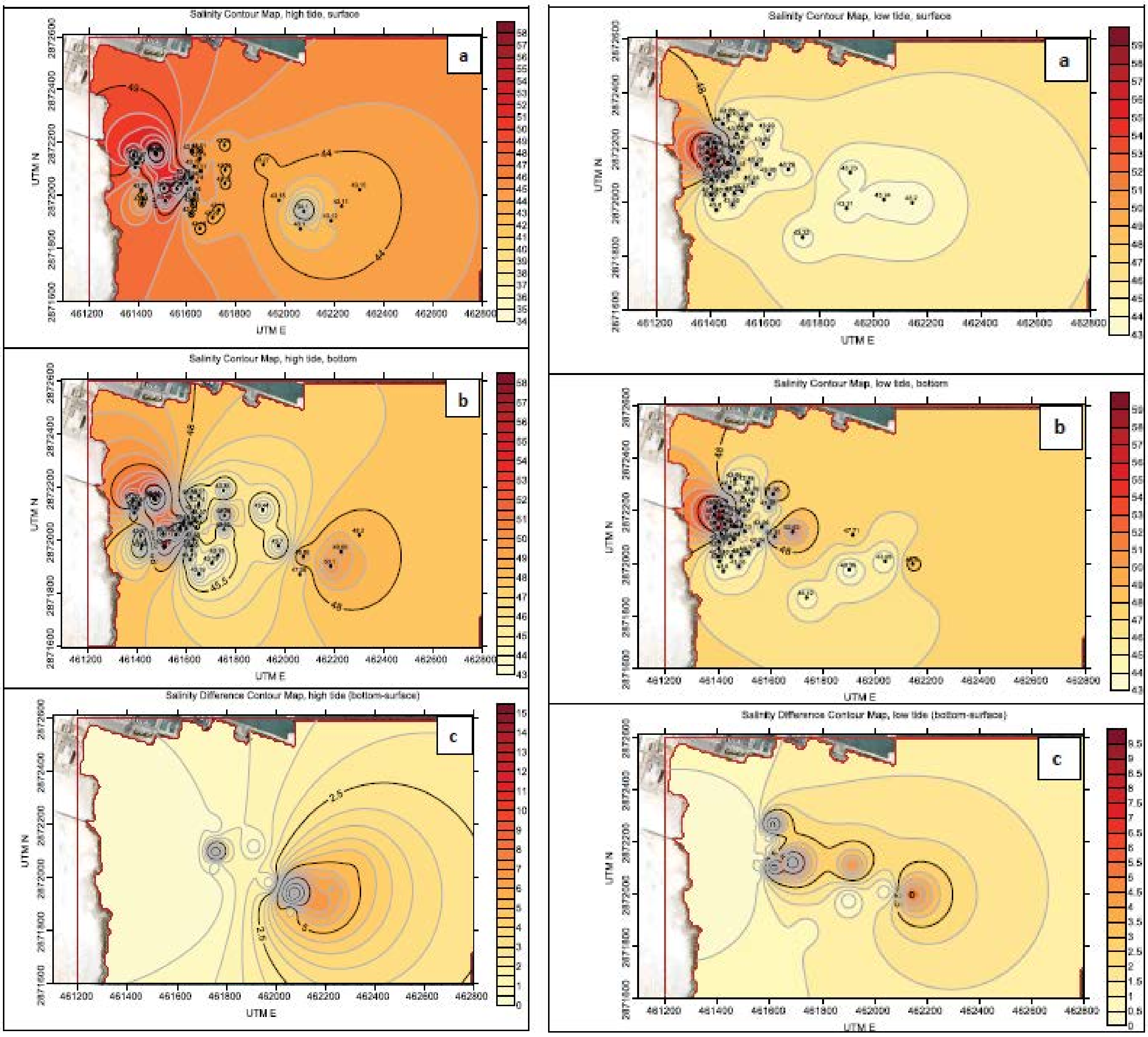

Fig. 6. Salinity gradient during high (left) and low (right) tide cycle in summer (a) surface, (b) bottom and (c) difference between surface and bottom.

is part of their migration cycle. The optimum seawater salinity (35‰), which may increase up to 70‰ characterize low water quality for marine living biodiversity [24]. In terms of physical scale of impacts, salinity increases >2‰ are rarely observed beyond a 400 m radius of outfalls [25] although may extend to several km's in some cases [26]. Studies concerning with the environmental impacts of seawater desalination suggest that impacts typically occur over spatially limited areas close to desalination plants [17,25,27], including the Arabian Gulf [28].

Al-Dur desalination plant is located adjacent to the seagrass habitat that extends from the east of Bahrain across Fasht al-Adam to Hawar Islands. Thermal tolerance of the seagrass beds in the Arabian Gulf showed that seagrass growth is reduced above 37°C, and temperatures above 40°C for an extended period are considered lethal limit [29], suggesting that discharge areas are likely inhospitable environments for seagrasses during summer. Some EIA reports suggest that at salinities greater than 58‰ affect the seagrass growth in the Arabian Gulf, while at salinities of more than 67‰, a location is not suitable for any seagrass species [29]. The present study indicated extreme salinity levels within the outlet vicinity with a tendence of high concentration at bottom, which may potentially affect the seagrass growth associated with Al-Dur coastal area. Al-Osaimi et al. [30] found that the infauna species in Al-Dur coast is considerably affected by salinity where the lowest species diversity was associated with locations characterized by high salinity difference between surface and bottom salinity.

In general, the water mass within the outlet vicinity showed a relative homogeneity throughout the water column during the low tide cycle compared with the high tide cycle where the temperature and salinity showed more stratified formation.

A pre-treatment process needs to be implemented for brine waters before its direct discharge to mitigate its impacts on physical, chemical and biological properties around the vicinity extent and buffer zone. It suggested to

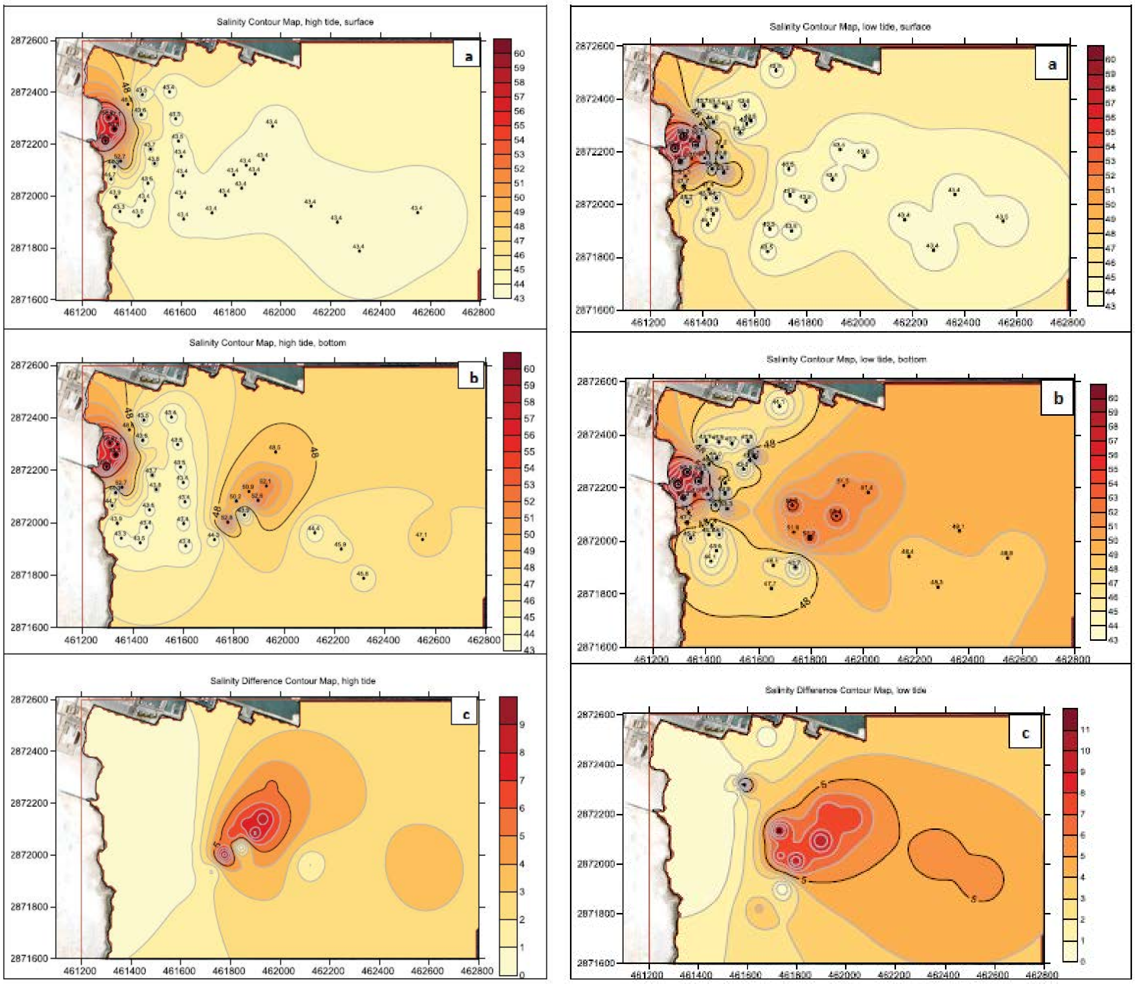

Fig. 7. Salinity gradient during high (left) and low (right) tide cycle in winter (a) surface, (b) bottom and (c) difference between surface and bottom.

Table 2
Surface and bottom salinity levels during high and low tide cycle in summer and winter

Salinity	Summer				Winter			
	High tide		Low tide		High tide		Low tide	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Min.	34.1	43.2	42.6	42.8	43.3	43.4	43.4	43.6
Max.	58.2	58.3	58.7	58.9	59.3	59.5	60.0	60.0
Average	46.7	47.8	46.9	47.8	45.6	47.3	46.9	49.2

pass the discharged waters through a long channel before releasing to the coastal environment or extend the discharge pipe to deep water by diffuser lines. That promotes better mixing of the brine and seawater where the high current will improve the mixing process of the outlet. Moreover, it is of great importance to establish regional standards for the brine discharge from the desalination plant in the GCC countries.

An agreement was signed in March 2019 for Al-Dur 2 IWPP, an independent water and power project occupies an area of approximately 192,500 m^2 immediately south of the existing Al-Dur1 IWPP plant. The new plant shall be developed to generate 1,500MW of Power based on Combined Cycle Gas Turbine (CCGT) technology and produce 50MIGD of water through same technology seawater reverse osmosis (SWRO) of Al-Dur1. The plant is expected to be fully operational by the second quarter of 2022. Usually, during the planning of new plants, the intake system as well as the outfall system is carefully chosen to maintain water quality for plant operation and to minimize the potential impacts

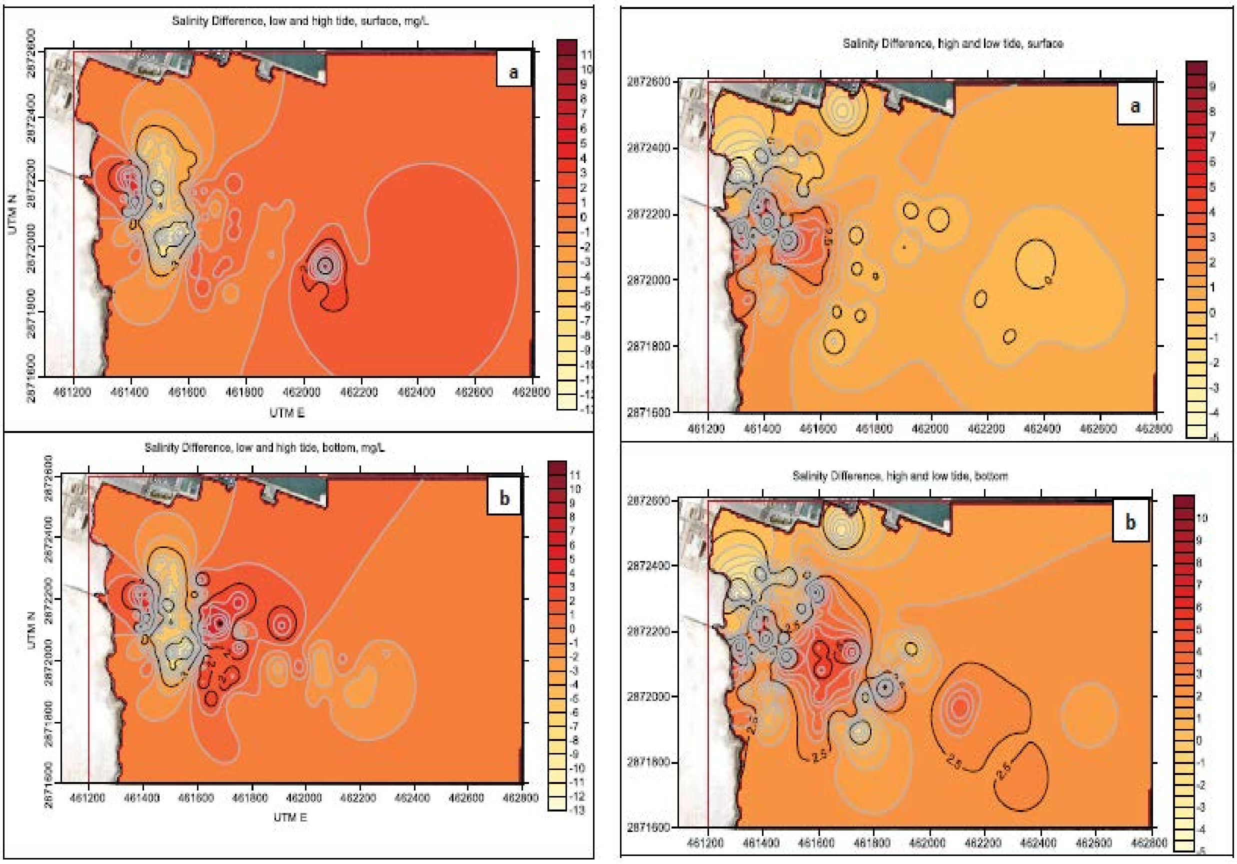

Fig. 8. Salinity difference between the high and low tide cycle of surface and bottom waters in summer (left) and winter (right).

of the discharged effluent on the surrounding marine area as well as the impact on the plant intake area. Therefore, Al-Dur coast will be vulnerable to further thermal pollution associated with hypersaline discharge. The extent of the additional impacts will be generated by the new plant need to be identified specifically for seagrass beds and benthic species associated with such habitat.

5. Conclusions

As a result of the lack of sufficient natural freshwater resources, the Kingdom of Bahrain depends heavily on desalination plants to provide sustainable needs for drinking freshwater. Consequently, utilization of seawater through desalination represents a coastal process activity in Bahrain. However, desalination plants could have several impacts on the surrounding marine environment. The impact's extent was varied concerning dynamic changes based on physical and chemical features considering the tide cycle associated with residual chemicals used in the pre-treatment process.

Analysis of available information regarding future scenarios of desalination capacity development and the impacts of desalination indicate that by 2050, desalination acting in combination with climate change, could have significant adverse impacts on the marine environment. There are several regulatory mechanisms that can be applied to control water demand and desalination activity, and these are tied in with technological development and practical reality. In terms of demand for water, regulation can be applied to control or limit water use or place demands on sectors to maximize water use efficiency.

The desalination outputs located adjacent to critical vulnerable habitats, for instance seagrass beds, may potentially impact the species diversity and ecosystem's function. In the southeast coast of Bahrain, the impacts will be complicated by further outlet of a new desalination plant (Al-Dur2) will be in place adjacent to the current one (Al-Dur1). On the other hand, the short-term observations, usually associated with monitoring program around power stations or desalination plants will not provide the opportunity to find out the impact trend on long-term scale for either temperature or salinity behaviour. Consequently, the current monitoring program implemented by the Supreme Council for Environment on seasonal basis needs to cover further monitoring locations representing the vicinity of each desalination plant. Moreover, a hydrodynamic modelling is required to assess the extent impact could be dispersed in relation to the seagrass beds.

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