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Evaluating the Environmental Impacts of Desalination Plant Brine Discharge using Marine Organisms as Bioindicators

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ABSTRACT

Desalination plants are an increasingly common solution to address water scarcity, particularly in arid and semi-arid coastal regions. However, the brine discharge from these plants can have significant impacts on the surrounding marine environment. This study investigated the use of biotic taxa as bioindicators to assess the environmental impact of desalination plant brine discharge. The study was conducted near a large-scale desalination plant in Dahab City on the Gulf of Aqaba, South Sinai, Egypt. The study area was divided into three distinct zones: Zone 1 (standard zone), Zone 2 (discharge zone), and Zone 3 (mixing zone). Water salinity and distribution of marine taxa as bioindicators were investigated during summer and winter seasons. Salinity recorded its highest value at zone (2), while, the lowest value was at zone (1). Seagrasses were recorded only in zone (1) and disappeared in other zones. Unexpectedly, the sea cucumber species have been recorded in abundance in zone (2) closer to the discharge pipe, where salinity is high. Echinoderms are potential sentinel taxon to gauge the impact produced by brine discharge. On the contrary, coral colonies particularly stony corals only appeared at zones (1) and (3), where the salinity was low. Corals are reputed to have a low tolerance to salinity fluctuations. The current study concluded that water discharged from desalination plants adversely affects coral reefs and seagrasses more significantly than other marine creatures.

INTRODUCTION

The worldwide need for freshwater is rising steadily due to population growth, urbanization, and climate change. Seawater desalination has emerged as a crucial technology to supplement limited freshwater supplies, especially in water-scarce coastal regions. While desalination can offer a reliable source of clean water, the hypersaline brine discharge from these plants can have harmful effects on the surrounding marine environment **(Jones *et al*., 2019)**.

Brine discharge from desalination plants can be evaluated for its impact on the environment using bioindicators, which are species whose presence, absence, or abundance can be used to determine the health of an ecosystem **(Riera *et al*., 2012)**. By studying the diversity, abundance, and community structure of bioindicator species, it can figure out the ecological impact of brine discharge and can provide guidance for successful mitigation.

There is a significant relationship between seawater salinity and the distribution of marine organisms. Furthermore, the distribution of marine organisms at desalination plant discharge sites varies from one species to another. Motile organisms such as fish, echinoderms, and plankton are better able to adapt to high salinity than other species. Coral reefs are highly sensitive to high salinity **(Al-Hammady, 2011)**. Salinity range of 32-34‰ is considered optimal for coral growth **(Vine, 1986)**. Higher salinities may lead to coral bleaching and low rates of growth, that accordingly affecting coral reef distribution **(Glynn, 1993)**. **Ammar and Nawar (1998)** reported that stressed salinity caused negative effect on hard and soft corals. **Peterson *et al*. (2018)** also reported similar findings: corals, along with their associated bacteria and algae, were significantly impaired by elevated salinity and antiscalant exposure, resulting in partial bleaching. Additionally, reduced salinity has been shown to cause rapid paling in corals and other symbiotic invertebrates **(Al-Hammady & Mahmoud, 2013)**. The surrounding benthic ecosystems may also be adversely affected by brine outfalls from desalination processes. These discharges can influence the distribution and diversity of benthic communities as well as the biogeochemistry of sediments. However, the spatial extent of such impacts is typically confined to a radius of approximately 10 meters, within a range of 1 to 30 meters from the outfall source **(Bianchelli *et al*., 2022)**.

This study investigated a range of potential environmental impacts associated with desalination plants. It serves as a case study of the main desalination plant at the Gulf of Aqaba, South Sinai, and the northern Red Sea, with a focus on assessing the ecological effects of brine discharge using bioindicators.

MATERIALS AND METHODS

1. Study site

The Dahab Desalination Plant (DAH) is located in South Sinai Governorate, Egypt, between the cities of Sharm El-Sheikh and Nuweiba, along the Gulf of Aqaba. It is situated at coordinates 28.477908° N and 34.489273° E (Fig. 1). The plant operates a reverse osmosis (RO) system with a maximum daily capacity of 15,000 cubic meters, supplying drinking water to the residents of Dahab City. Constructed between 2020 and 2021, the facility began operations in 2021.

DAH is equipped with two submerged pipelines: one intake pipe and one brine discharge pipe. Both are located 16 meters offshore and are submerged to a maximum depth of 6 meters. The intake pipe extends 170 meters from the shoreline to its open end, while the discharge pipe reaches 109 meters from the shoreline to its sealed terminus. The discharge outlet is positioned 125 meters east of Dahab's new marina and 820 meters west of Dahab Lagoon and its adjacent resorts.

The discharge pipe is fitted with seven multi-opening nozzles, each angled 60 degrees westward, collectively releasing approximately 1,428.5 cubic meters of brine per day (Figs. 2 & 3).

The surrounding marine environment consists primarily of sandy and sandy-muddy substrates, supporting a diverse distribution of seagrass beds, coral reef habitats, and associated marine fauna. Water depth gradually increases from shallow nearshore areas to deeper offshore zones (Figs. 2 & 3).

For the purposes of environmental assessment, the study area was divided into three distinct zones (Fig. 4):

- **Zone 1:** Reference zone located upstream of the discharge, representing baseline (pre-discharge) conditions
- **Zone 2:** Discharge zone where brine is released through the submerged nozzles
- **Zone 3:** Mixing zone where discharged brine mixes with ambient seawater.

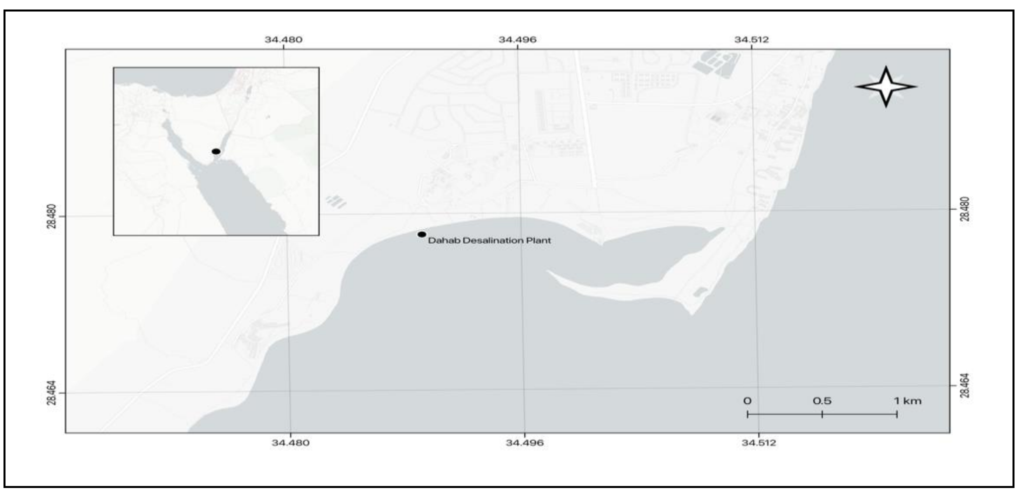

Fig. 1. The location of Dahab Desalination Plant, Gulf of Aqaba, South Sinai Government, Egypt

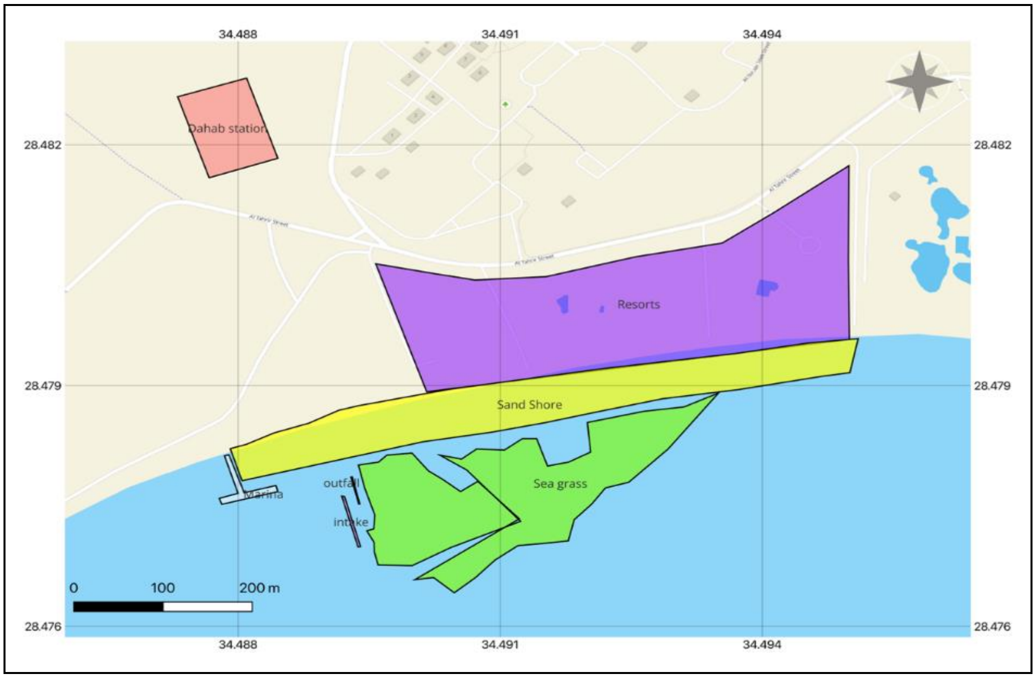

Fig. 1. The location of the pipeline and marine habitat in the study

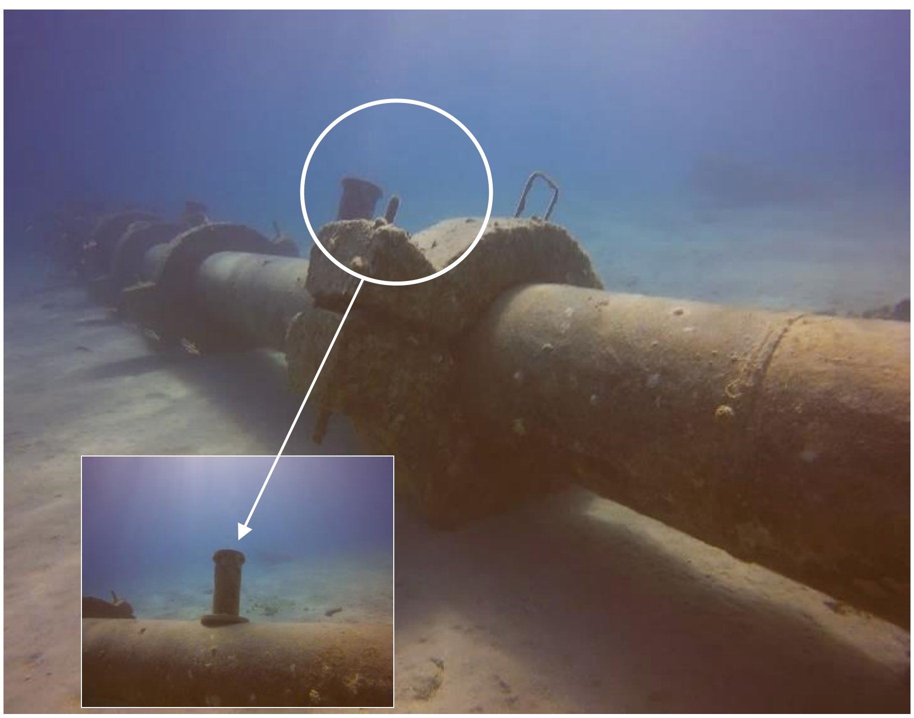

Fig. 2. Underwater outfall pipeline and nozzles

2. Filed survey

Sea water salinity was measured directly in the field using a portable refractometer. Salinity was measured at the three different zones during summer and winter seasons according to low and high tidal amplitudes in the Red Sea **(Edwards, 1987)** and expressed as ppt.

Biological indicators of marine environments have been investigated and determined using line intercept transect (LIT) and quadrat transect (QT) according to **English *et al*. (1997)**. SCUBA diving and snorkeling have been used to assess, sample, and collect data from the study area. All collected and surveyed biota were identified based on standard references and textbooks as **Randall (1986)** for fishes, **Veron (2000)** for corals, **Rusmore-Villaume (2008)** for mollusks, and **El-Shafai (2011)** for seagrasses.

To obtain models for the studied area, DELFT3D modeling software has been used with delft dashboard v02.04.18042, Global Mapper Pro v24.1, Autodesk AutoCAD 2022.1.2 and Google Earth Pro (v 7.3.6.9796). In addition, The GEBCO dataset was used to obtain the bathymetry in the selected studied areas. Also, the manual method was used to validate the online bathymetry data. The data were stored using Microsoft Excel and analyzed using R studio 1.0.15 and SPSS (V. 23.0.0). All maps were created using QGIS (V 3.32.2) and all graphs were illustrated using GraphPad Prism (V.8.0).

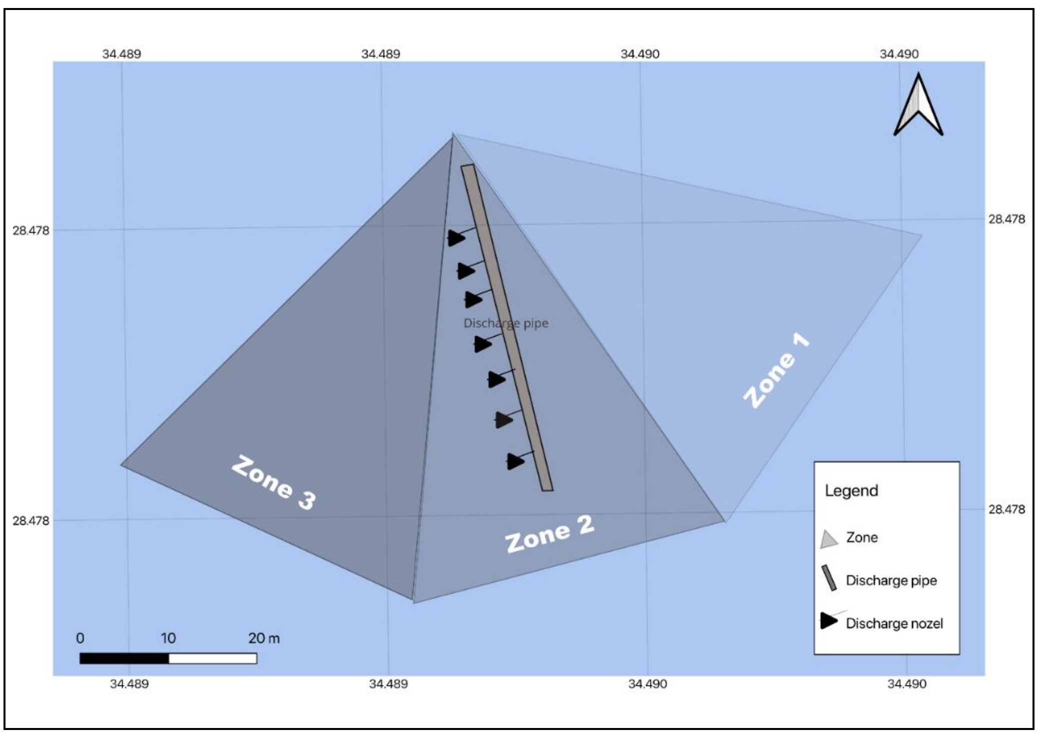

Fig. 3. Sketch map showing study area zones (zones "1, 2, and 3")

RESULTS

The depth of the study area increases progressively from 0 to 10 meters in the west-south direction. The outfall nozzles discharge brine at depths ranging between 4 and 6 meters. This discharged brine then mixes with ambient seawater in the mixing zone located to the west, where the depth ranges from 6 to 10 meters (Fig. 5).

The results of the present study indicate that seawater salinity varied significantly across zones and seasons (Table 1). The discharge zone (Zone 2) exhibited the highest salinity, reaching 49.86ppt, while the standard zone (Zone 1) recorded the lowest salinity at 39.2ppt. Additionally, salinity levels were higher during the summer season compared to winter (Table 1 and Figs. 6 & 7).

A one-way ANOVA revealed statistically significant differences in salinity between the zones (P = 0). Furthermore, a two-way ANOVA showed significant differences in salinity due to both zone and seasonal effects (P = 0), confirming that salinity is influenced by spatial and temporal factors in the study area.

Table 1. Average seawater salinity for each zone among two seasons

Seasons	Zones	Salinity (ppt)
Summer	Zone 1	40.35
	Zone 2	49.18
	Zone 3	46.77
Winter	Zone 1	39.35
	Zone 2	46.13
	Zone 3	42.70

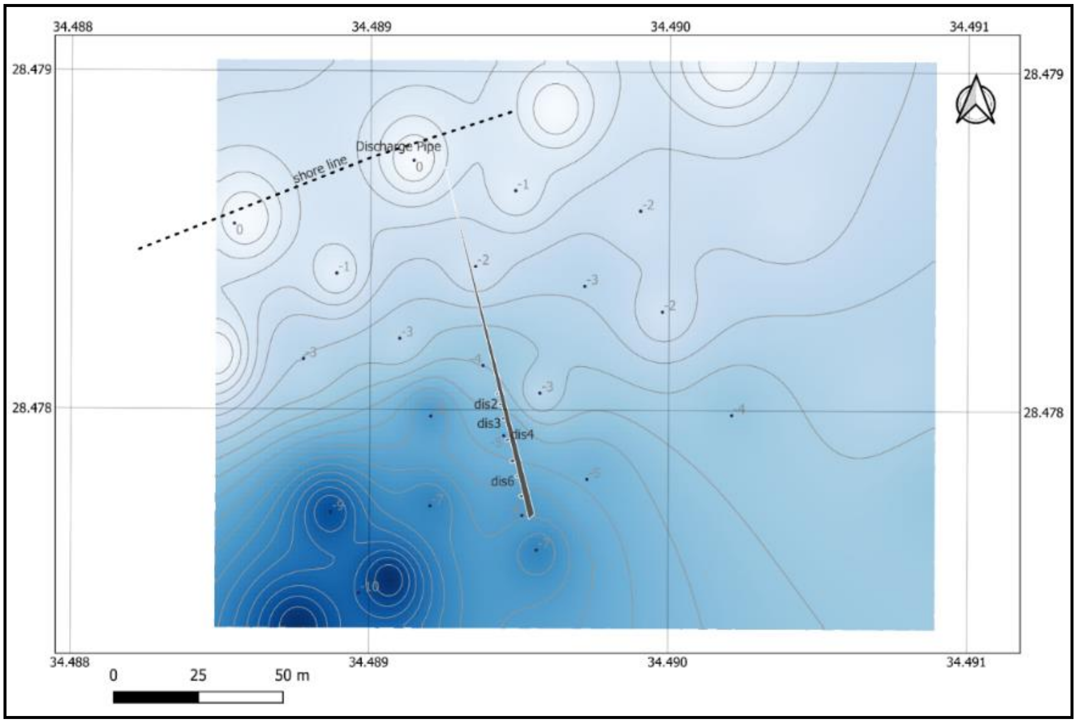

Fig. 4. Bathymetry map of the study site

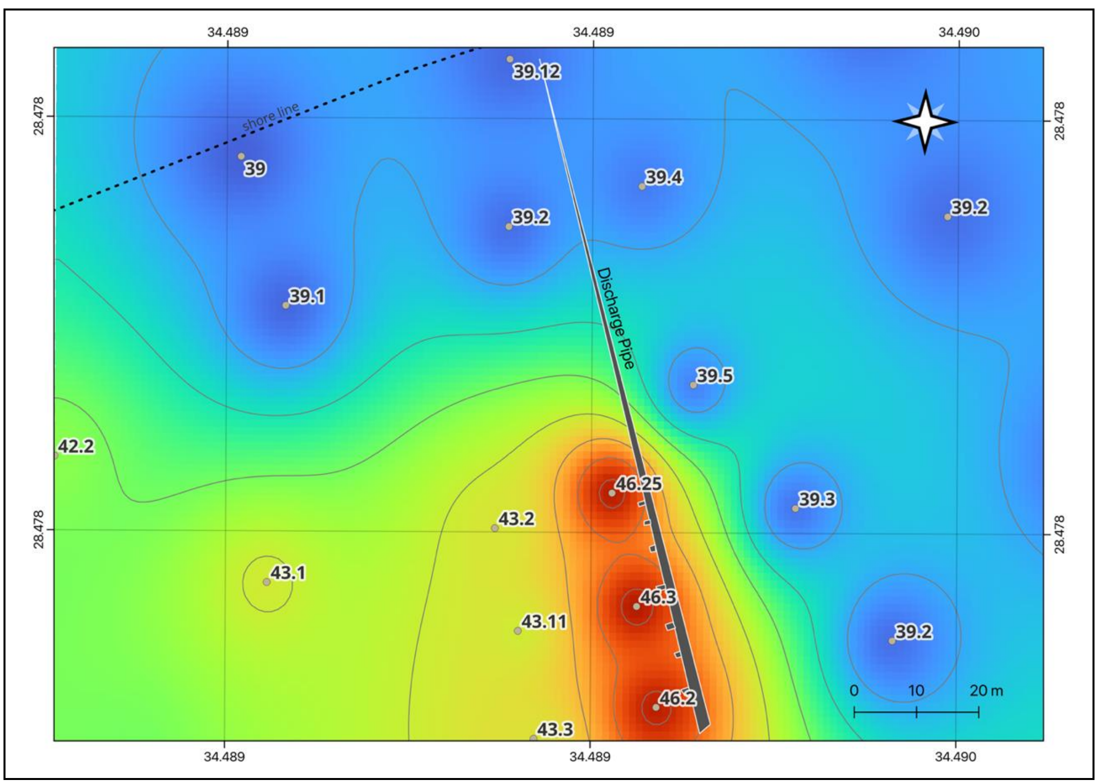

Fig. 5. Distribution map of salinity in winter

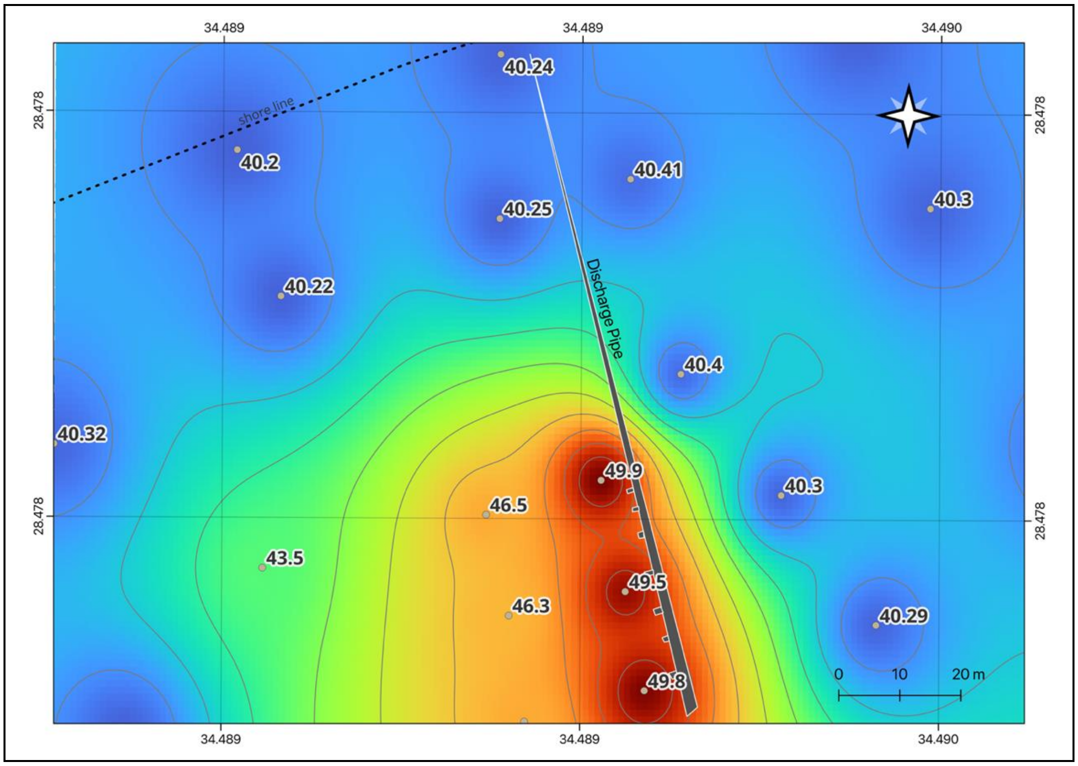

Fig. 6. Distribution map of salinity in summer

In the current study, seagrass distribution was limited at zone (1), while sea cucumbers and shells were recorded at zone (2). Coral reefs were distributed between zone (1) and zone (3). The percent cover of marine habitat at zone (1) was 26% seagrass, 3% live corals, and 71% sand-muddy substrate. Where at zone (2) the majority of percent cover was only sand-muddy substrate (100%) with complete absence of coral reefs and seagrass. In contrast, sand-muddy substrate represents 95% in zone (3), 2% live coral, and 3% dead coral (Figs. 8, 9, 10).

During this study, it was noticed that shells and sea cucumbers (Fig. 11) appear in high density in the vicinity of the discharge pipeline at zone (2). Three different species of sea cucumbers (Holothuroidea: Echinodermata) were recorded (*Holothuria edulis, Holothuria atra, and Holothuria argus*) with an average density of 3 individuals /m^2. Moreover, the gastropod mollusks (*Lambis truncata* and *Cerithium adansonii*), and bivalve (*Anadara antiquate*) were recorded at the same zone (2). In contrast, *Halophila stipulacea* belong to seagrasses is presented only in zone (1) and covered an average of 26 % of sea bottom; while coral reefs were recorded at zones (1) and (3) with cover percentages averaged 3 and 2% respectively. The recorded coral species included *Stylophora* sp., *Acropora* sp., *Pocillopora* sp., *Porites* sp. from hard corals, and *Sarcophyton* sp. from soft corals (Figs. 12-15).

During this study, certain species of fish (Fig. 15) have been recorded all over the discharge pipe in zone 2. These fishes comprised four different species including *Amphiprion bicinctus*, *Amphiprion* sp. (anemone fish), *Dascyllus trimaculatus,* and *Pomacanthus imperator*.

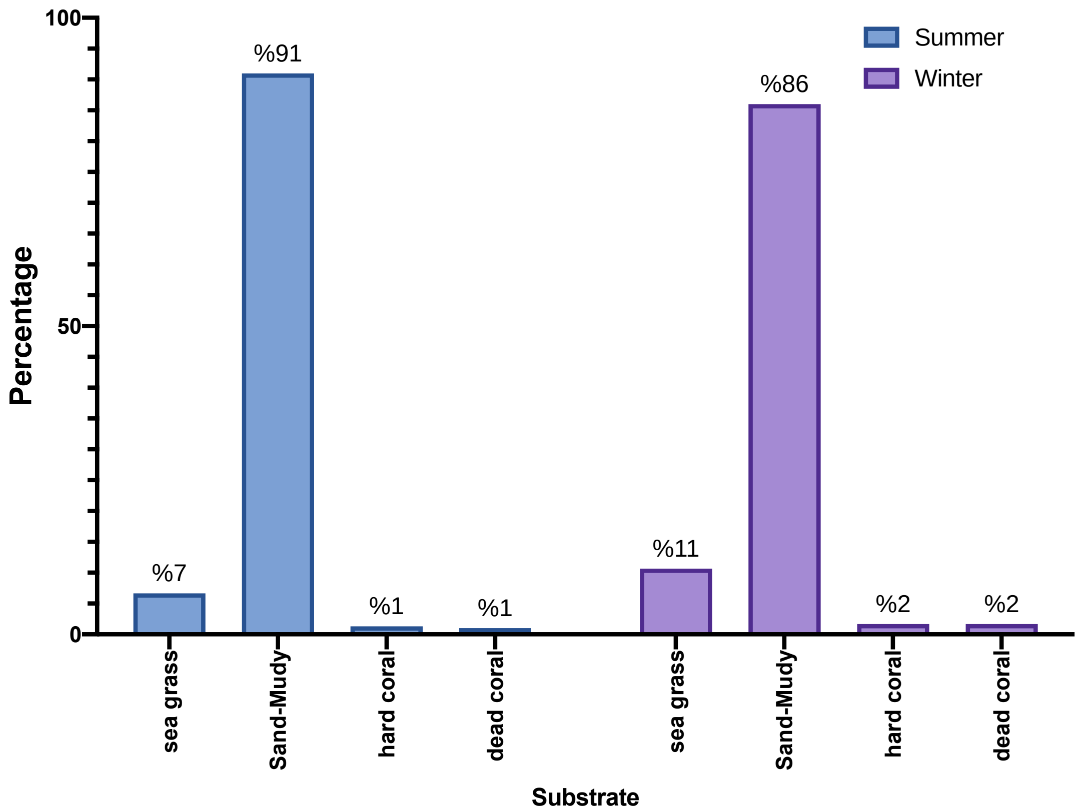

Fig. 7. Substrate percentages during summer and winter at the study area

The one-way ANOVA showed some significant variances in different substrates between among zones only and there are no significant variances among seasons. One-way ANOVA showed significant variance between different zones in seagrass (*P* value=0.01), sand-muddy substrate (*P* value=0.01), hard coral (*P* value=0.05), and dead coral (*P* value=0.01).

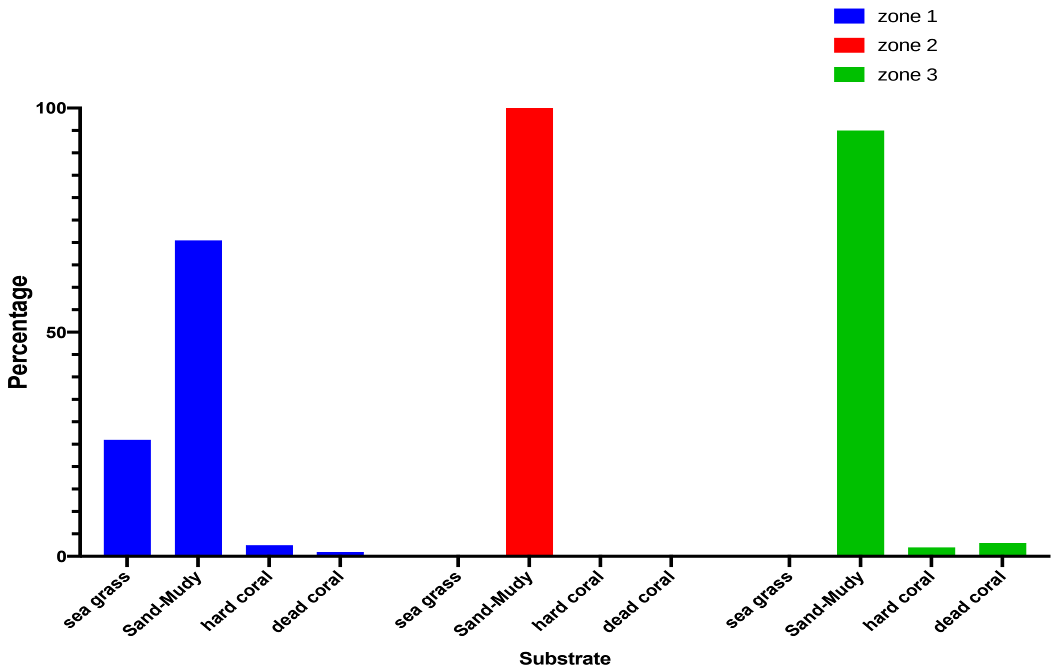

Fig. 8. Substrate percentages among different zones

Fig. 11. Sea cucumber A- (*Holothuria edulis*)

B- Sea cucumber (*Holothuria atra*)

Fig. 11. Gastropods, bivalves, and mollusk shells

Fig. 10. Seagrass (*Halophila stipulacea*)

Fig. 12. Different fish around the discharge pipe

Fig. 13. Some coral reefs at zone-1

The dispersion model was developed by first creating a computational mesh of the study area. Relevant input data were then incorporated into the model, including bathymetric profiles, outfall salinity, ambient seawater salinity, as well as local current and wind speeds. The model was simulated under various scenarios, accounting for different seasonal and environmental conditions, to assess brine dispersion patterns under a range of circumstances.

Simulation results indicated that the mixing zone—where outfall brine blends with ambient seawater—extends across a radius of approximately 200 to 400 meters. The relatively broad extent of this mixing area is primarily attributed to site-specific factors, including the shallow depth of the discharge location and weak local currents (Fig. 16).

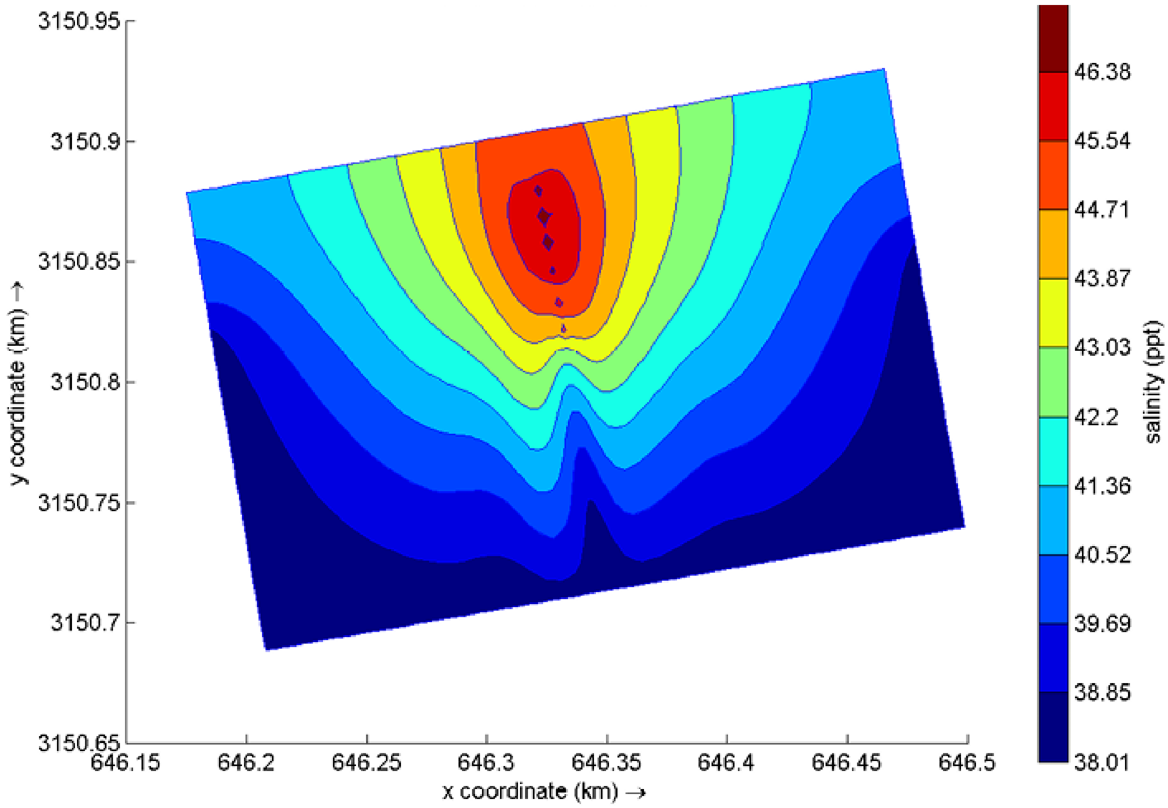

Fig. 14. The dispersion model of salinity

DISCUSSION

Understanding the ecological impact of desalination plant discharge into marine environments has become increasingly important for biologists and ecologists, particularly given the rapid global expansion of desalination facilities **(Chang, 2015)**. Despite this, limited data exist regarding the specific effects of brine discharge—particularly elevated salinity—on marine ecosystems, including the physiology of reef-building corals.

In the present study, seawater salinity varied noticeably across zones. The discharge zone (Zone 2) recorded the highest salinity (49.86ppt), while the standard zone (Zone 1) showed the lowest salinity (39.2ppt). This disparity may be explained by the dilution effect of brine, which occurs approximately 20 meters from the discharge outfall. At greater distances (up to 1km), salinity generally stabilizes within the natural range for marine environments **(Talavera & Quesada Ruiz, 2001)**.

Seagrass distribution was limited to Zone 1, located furthest from the discharge. The small seagrass *Halophila stipulacea*, native to the Red Sea **(Forsskål, 1775; Lipkin, 1975)**, is known for its broad salinity tolerance. Its invasive potential has been linked to its adaptability to varied environmental conditions, including temperature, light, nutrients, and salinity **(Por, 1971**; reviewed in **Gambi *et al.*, 2009; Sharon *et al.*, 2009, 2011)**. Most seagrass species thrive in salinities between 20 and 40ppt, which may explain their presence only in Zone 1, where salinity did not exceed 39.2ppt. However, **Flowers and Colmer (2008)** noted that seagrasses, as halophytes, can survive salt concentrations that are lethal to 99% of plant species. Consequently, brine discharge may have wide-ranging impacts on the community structure of seagrasses, invertebrates, soft-sediment infauna, and corals, varying from negligible changes in microbial and plankton communities to significant ecological disruptions **(Roberts *et al.*, 2010**; cited in **Van der Merwe *et al.*, 2014)**.

Three species of sea cucumbers—*Holothuria edulis*, *H. atra*, and *H. argus*—were recorded in Zone 2 (high-salinity area), with an average density of 3 individuals/m². This finding is supported by **Vidolin *et al.* (2002)**, who reported that sea cucumbers exhibit hyper-osmotic regulation in high-salinity environments and hypo-osmotic regulation in low-salinity conditions, likely through decreased permeability of the body wall. The gray sea cucumber (*H. grisea*) has been observed to regulate coelomic fluid osmolarity temporarily. Salinity has been shown to affect the morphological and biochemical characteristics of target organs in echinoderms and other marine animals **(Brunelli & Tripepi, 2005; Bernabò *et al.*, 2008; Putranto *et al.*, 2014; Xu *et al.*, 2015)**. Osmoconformity and ion regulation mechanisms, including extracellular isosmotic regulation, play critical roles in their response to salinity stress **(Geng *et al.*, 2016)**. However, these findings contrast with those of **Yuan *et al.* (2010)** and **Bai *et al.* (2015)**, who concluded that mature sea cucumbers tolerate salinities between 20 and 39ppt, with optimal growth at 30 ± 2ppt **(Setiawati *et al.*, 2023)**.

Coral reef presence was restricted to Zones 1 and 3, and absent entirely from Zone 2, likely due to hypersaline conditions. Corals are highly sensitive to salinity fluctuations **(Al-Hammady, 2011)**. The optimal salinity for coral growth lies between 32 and 34ppt **(Vine, 1986)**, and elevated salinities can lead to coral bleaching, reduced growth, and altered reef distribution **(Glynn, 1993)**. **Ammar and Nawar (1998)** documented the negative effects of salinity stress on both hard and soft corals. Similarly, **Peterson *et al.* (2018)** found that elevated salinity and antiscalants impaired corals, as well as their symbiotic algae and bacteria, resulting in partial bleaching. Conversely, reduced salinity can also cause rapid paling in corals and other symbiotic invertebrates **(Al-Hammady & Mahmoud, 2013)**. Salinity stress alters coral metabolism, photophysiology, and algal symbiont function **(Muscatine, 1967; Chartrand *et al.*, 2009)**. Tolerance to salinity stress varies among coral species, depending on their native environments and ability to regulate osmotic balance **(Mayfield & Gates, 2007)**. Interestingly, **Whitmarsh *et al.* (2021)** suggested that desalination discharges may not significantly affect certain fish assemblages, indicating potential resilience in some marine communities.

High shell densities were observed near the discharge pipe in Zone 2, likely due to adaptive mechanisms in bivalves. These organisms have evolved to survive wide environmental stresses over millions of years. **Sokolova *et al.* (2019)** confirmed that bivalves are osmoconformers capable of regulating both extracellular and intracellular hemolymph salinity. Their sedentary nature, wide distribution, and sensitivity to environmental change make them ideal bioindicators. Sudden salinity shifts can severely impact mollusk physiology, leading to mortality and economic loss **(Gajbhiye & Khandeparker, 2017)**. A common defense mechanism in bivalves under salinity stress is shell closure, isolating internal fluids from the external environment **(Solan & Whiteley, 2016)**. This response helps maintain stable salinity within the pallial cavity **(Chaparro *et al.*, 2009)**.

CONCLUSION

This study demonstrates the effectiveness of using various marine organisms—including seagrass, coral reefs, sea cucumbers, fish, and mollusks (gastropods and bivalves)—as bioindicators for assessing the environmental impact of desalination plant brine discharge. The observed reductions in seagrass cover and coral reef presence indicate that hypersaline effluent negatively affects these sensitive ecosystems. These findings underscore the importance of incorporating bioindicator-based monitoring into environmental impact assessments and management strategies for desalination facilities located in coastal regions.

The results contribute to a broader understanding of the ecological consequences associated with desalination and offer valuable guidance on the use of bioindicators to monitor and mitigate brine discharge in marine ecosystems. Understanding these impacts is essential for developing sustainable water management practices that meet increasing freshwater demands while preserving vulnerable marine habitats.

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الملخص العربي

تقييم التأثيرات البيئية لتصريف المياه المالحة من محطة تحلية المياه باستخدام المؤشرات الحيوية

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تعد محطات تحلية المياه حلا لمشكلة الطلب المتزايد على المياه العذبة وندرتها، لا سيما في المناطق الساحلية القاحلة وشبه القاحلة. ومع ذلك، يمكن أن يكون لتصريف راجع هذه المحطات تأثيرات كبيرة على البيئة البحرية المحيطة. في هذه الدراسة تم دراسة المؤشرات الحيوية في البيئة البحرية المحيطة لتقييم التأثير البيئي لتصريف راجع هذه المحطات. أجريت الدراسة بالقرب من محطة تحلية في مدينة دهب على خليج العقبة، البحر الأحمر، بجمهورية مصر العربية. تم تقسيم منطقة الدراسة إلى ثلاث مناطق مختلفة، المنطقة 1 (المنطقة الضابطة أو القياسية)، المنطقة 2 (منطقة التصريف)، والمنطقة 3 (منطقة الخلط). تم قياس درجات ملوحة المياه وتوزيع البيئات البحرية كمؤشرات حيوية خلال فصلي الصيف والشتاء. سجلت أعلى درجة ملوحة في المنطقة (2)، بينما كانت أدنى قيمة في المنطقة (1). تم تسجيل الأعشاب البحرية فقط في المنطقة (1) بينما اختفت في المناطق الأخرى بشكل غير متوقع، بينما تم تسجيل خيار البحر بكثرة في المنطقة (2) بالقرب من أنبوب التصريف حيث تكون الملوحة عالية. لذا استخدمت شوكيات الجلديات استخدمت كمؤشر لقياس التأثير الناتج عن تصريف مياه الراجع. وعلى العكس من ذلك، سجلت الشعاب المرجانية فقط في المنطقتين (1 و 3)، حيث تكون الملوحة أقل. مما يؤكد عدم على التواجد في المناطق عالية أو ذات التغير الواسع منخفضة التحمل لتقلبات في الملوحة. وخلصت هذه الدراسة إلى أن المياه التي يتم تصريفها من محطات تحلية المياه تؤثر سلبا على الشعاب المرجانية والأعشاب البحرية بشكل أكبر من الكائنات البحرية الأخرى.