



Assessment of the Cumulative Impacts of Desalination Brine Discharge on Marine Ecosystems

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Article Info	ABSTRACT
Article type: Research Article	Freshwater scarcity has intensified the need for desalination plants in coastal regions as a reliable alternative for water supply. However, the discharge of concentrated brine effluents into marine environments has raised serious environmental concerns. This study aims to review previous research on the cumulative impacts of desalination plant effluents and to examine their major environmental consequences on marine ecosystems and coastal water resources. This study was conducted using a descriptive–analytical and review-based approach. Relevant scientific literature concerning the cumulative impacts of desalination plant discharges was systematically reviewed. In addition, results from a numerical modeling study conducted in the Persian Gulf were analyzed to illustrate the significance of considering the simultaneous effects of multiple desalination facilities. The findings indicate that the continuous discharge of saline and warm effluents from desalination plants can lead to increased salinity and seawater temperature, deterioration of water quality, and adverse impacts on marine ecosystems. Numerical modeling results from the Persian Gulf further demonstrate that cumulative effects resulting from the operation of multiple desalination units may considerably intensify environmental pressures on coastal and marine environments. The study highlights the necessity of incorporating cumulative impact assessments into future planning, environmental evaluations, and management strategies for desalination projects. Considering the combined effects of multiple desalination plants is essential for ensuring the sustainable management of marine resources and minimizing long-term environmental risks.
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Introduction

Given the increasing population growth, increasing demand for fresh water, and limited fresh water resources in the world, the construction of desalination plants in coastal areas has been proposed as one of the main solutions for supplying water to these areas. The countries bordering the Persian Gulf, including Saudi Arabia, the United Arab Emirates, and Iran, currently meet a significant portion of their water needs through these units. However, the extensive and unplanned development of desalination plants has raised serious concerns about their environmental impacts. The most important aspect of the environmental impacts of desalination plants is related to the concentrated effluent (brine) that is discharged into the marine environment. This effluent, which has a salinity of 1.5 to 2 times the natural salinity of seawater and a temperature of 5 to 10 degrees Celsius higher than the surrounding water, also contains chemicals, heavy metals, and other pollutants. The continuous discharge of these brackish and warm effluents has raised concerns about cumulative impacts on the marine environment and coastal water resources. Existing knowledge gaps include (1) a lack of integrated studies that examine the simultaneous effects of multiple desalination units in a region, (2) insufficient attention to the synergistic effects of effluents in semi-enclosed areas such as the Persian Gulf where water exchange is limited, and (3) the lack of regional assessment frameworks rather than local and single-unit assessments. The main objective of this study is to review and analyze the cumulative impacts of desalination plant development on water resources and the marine environment, with emphasis on the Persian Gulf as one of the most important areas affected by this industry. The importance of the study is that by combining a systematic review of the literature and 3D numerical modeling, it provides a comprehensive picture of the cumulative consequences and highlights the need to revise approaches to environmental assessment and sustainable management of coastal water resources.

Method

This study employed a combined methodology integrating a systematic literature review and numerical modeling. In the review phase, relevant studies published between 2015 and 2025 were retrieved from international databases (ScienceDirect, Scopus, Web of Science, and Google Scholar) as well as Persian databases (SID, Magiran, and Civilica) using keywords related to desalination plants, brine discharge, cumulative impacts, and marine environments in both English and Persian. From an initial pool of 112 studies, 40 articles were selected based on relevance to quantitative effluent characteristics and applicability to semi-enclosed marine systems such as the Persian Gulf. In the modeling phase, the COHERENS 3D hydrodynamic model was applied to simulate the spatial distribution of salinity and temperature resulting from desalination effluents in the Persian Gulf. Input parameters included a 5 PSU increase in salinity and a 7°C rise in temperature relative to ambient seawater, along with site-specific data on plant location, capacity, and discharge volume obtained from international databases. Seasonal boundary conditions were incorporated based on winter circulation patterns, and simulations were conducted for both surface and bottom layers, with emphasis on winter conditions due to stronger density-driven accumulation. Unlike previous studies that examined desalination plants individually, this research simultaneously modeled multiple operational units to assess cumulative and synergistic impacts. A key limitation of the study was the lack of synchronized field measurements across all desalination facilities, necessitating reliance on averaged datasets and modeling assumptions, which were partially addressed through validation against comparable studies.

Results

A systematic review of the literature shows that research on desalination effluents can be grouped into two main categories: single-unit studies and a limited number of studies on cumulative impacts of multiple desalination plants. Single-unit studies generally report that brine salinity is about 1.5–2 times higher than natural seawater and discharge temperatures are approximately 5–10°C higher. In semi-enclosed seas such as the Persian Gulf, these discharges can gradually increase salinity in deeper layers, reduce dissolved oxygen, and disturb marine ecological balance. A key gap identified in the literature is the lack of studies addressing cumulative impacts in regions where multiple desalination plants operate in close proximity. In such conditions, the combined effect of multiple discharges becomes more significant than individual impacts. Numerical modeling results confirm that during winter conditions, lower temperatures and higher water density lead to accumulation of saline effluents in bottom layers. While surface waters experience relatively faster dilution due to currents, bottom layers show higher salinity accumulation and more extensive affected zones. Model results indicate that the highest salinity concentrations occur in the southern Persian Gulf, where desalination plants are densely located. Average salinity increases of about 2–3 PSU above natural levels were observed, effectively expanding the spatial extent of impacted areas compared to single-plant scenarios. The results also show that variations in individual plant discharge rates have limited influence on overall dispersion patterns, mainly affecting intensity rather than spatial distribution. From an economic and management perspective, these findings suggest that ignoring cumulative impacts may lead to reduced fishery productivity, decreased tourism income, and increased costs for marine infrastructure maintenance. Overall, the results emphasize the importance of considering regional-scale cumulative effects in environmental assessment and coastal planning.

Conclusions

A systematic review of the literature and numerical modeling results indicate that the simultaneous development of multiple desalination plants in coastal regions can generate more severe environmental impacts than single-plant scenarios due to cumulative effects. Gradual increases in salinity and temperature near brine discharge zones alter the physical and chemical properties of seawater, threatening sensitive marine ecosystems such as corals, mangroves, and benthic communities. These impacts are particularly critical in semi-enclosed seas like the Persian Gulf, where high evaporation rates and limited water exchange intensify the persistence and spread of saline and warm effluents, reducing dissolved oxygen levels and disrupting benthic life. The findings confirm that cumulative impacts of multiple desalination units are significantly greater than the simple sum of individual effects, highlighting the importance of considering synergistic interactions in environmental assessments. From a practical perspective, the results underscore the need to move beyond single-plant evaluation frameworks toward regional-scale assessment approaches. Key recommendations include adopting Integrated Coastal Zone Management (ICZM), applying 3D numerical modeling for predicting salinity and temperature distribution, implementing continuous environmental monitoring, optimizing brine discharge systems using deep-water diffusers, establishing regional standards for allowable salinity and temperature levels, and restricting the placement of new plants in environmentally sensitive areas. Future research should focus on climate change impacts, interactions among coastal pollutants, economic evaluation of environmental costs, and circular economy approaches for brine recovery. Overall, the study highlights that neglecting cumulative impacts in desalination planning can worsen environmental degradation and threaten the long-term sustainability of coastal water resources.

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