Sustainable seawater desalination in marine protected areas: Modelling and monitoring activity

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Abstract

This manuscript presents numerical simulations of the discharge from a desalination plant planned within a Marine Protected Area characterized by increasing freshwater demand. The modelling activity investigates the potential impacts of brine release on the coastal marine environment, with the aim of supporting environmentally sustainable design solutions. The proposed system adopts mitigation strategies based on the mixing of brine with treated wastewater, allowing the assessment of different dispersion scenarios under representative winter and summer hydrodynamic conditions. Results indicate that salinity variations remain limited and largely confined near the seabed, suggesting negligible effects on sensitive benthic habitats. The study highlights the role of green desalination solutions, supported by numerical modelling, as an effective approach to reconcile local water supply needs with the conservation of marine ecosystems in protected coastal areas.

Keywords

Marine protected area, green desalination, brackish water, sustainable water management

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Introduction

Climate change is profoundly disrupting historical precipitation patterns, altering the global distribution of water and reducing the reliability of traditional storage solutions such as dams, lakes, and underground reserves. These shifts are expected to intensify droughts and complicate the sustainable management of the world's freshwater resources, further destabilizing already imbalanced reservoirs and leading many regions to severe water shortages. Simultaneously, population growth, industrialization, and rising living standards are increasing water demand, while Earth's freshwater resources continue to dwindle.

Freshwater scarcity has thus emerged as one of the most pressing global challenges, particularly in arid and semi-arid regions with limited natural resources. According to Soni et al. (2025), approximately 66% of the global population experiences water shortage for at least one month each year, and many models forecast a sharp increase in freshwater scarcity in the near future due to longer drought periods, excessive freshwater withdrawals, and seawater intrusion that salinizes coastal aquifers.

To address these challenges, alternative and climate-independent water sources are essential for sustainable development. Desalination has become a practical and increasingly widespread solution to supplement traditional supplies, providing clean water in regions where natural sources are insufficient or overexploited. As an almost unlimited and climate-resilient resource, seawater desalination extends water availability beyond the constraints of the hydrological cycle, particularly benefiting coastal communities. Reflecting this potential, unconventional water resources—chiefly seawater desalination—have been recognized as critical for achieving the United Nations Sustainable Development Goal 6 (SDG 6): "Ensure availability and sustainable management of water and sanitation for all" (Ayaz et al., 2022).

In the past few decades, the global capacity of plants has expanded exponentially, surpassing 19,000 facilities by 2020 and producing around 99 million cubic meters of freshwater per day (Jones et al., 2019). However, this growing reliance on desalination raises concerns regarding the environmental impacts of brine disposal on marine and coastal ecosystems. Nevertheless, this practice generates dense hypersaline plumes that settle and spread along the seabed, altering the physical and chemical characteristics of receiving waters. Such changes can degrade water quality, affect local fisheries, and harm benthic organisms adapted to stable salinity conditions (Lattemann & Höpner, 2008).

To mitigate these impacts, desalination plant and outfall designs must be tailored to the local marine environment through comprehensive preliminary studies that assess hydrodynamics, wave conditions, and water quality. Mathematical modeling is often employed to predict brine dispersion, optimize outfall configurations, and minimize environmental harm (Roberts et al.; 2010; Palomar & Losada, 2011). Proper planning and advanced design methodologies are therefore essential to reduce ecological risks while ensuring a sustainable water supply. The desalination industry faces the dual challenge of producing new freshwater resources without increasing pressure on marine ecosystems and contributing to groundwater conservation (Hoepner, 2019).

Recently, research has explored alternative intake sources, such as coastal springs with relatively low salinity levels that require minimal desalination (De Serio et al., 2025). This innovative approach offers multiple advantages: it circumvents technical issues such as shell clogging, suspended solids from seasonal currents, and membrane

fouling; it substantially reduces the environmental footprint of brine discharge. The resulting effluent has much lower salinity, lessening stress on marine organisms, preserving the natural salinity gradient crucial for coastal ecosystems, and improving local biodiversity and dilution capacity. Consequently, this approach aligns closely with sustainable marine management principles and the goals of the United Nations Sustainable Development Goal 6 (SDG 6).
This study evaluates the case of the Tremiti Islands Marine Protected Area, which is affected by chronic potable water scarcity. Periodic crises occur when the submarine pipeline linking the islands to the mainland water supply network experiences failures. During such events, freshwater must be transported by ship from the mainland, highlighting the critical need to develop local, self-sustaining, and climate-resilient freshwater production systems. The present work aims to assess the environmental implications of brine discharge from a potential desalination plant in the Tremiti Archipelago, seeking to balance the demand for alternative water sources with the preservation of marine and coastal ecosystems.

Materials and Methods

Study area

The focus of this study is the Tremiti Islands Archipelago, located in the Adriatic Sea off the northern coast of the Gargano Promontory (southern Italy), approximately 12.5 nautical miles from the nearest mainland point at Torre Mileto. This small archipelago consists of the islands San Nicola, San Domino, Capraia, and the islet of Cretaccio. The islands are aligned along a northeast–southwest (NE–SW)

axis and are separated from each other by only a few hundred meters.
Since 1989, the Tremiti Islands have been designated as a Marine Protected Area (MPA), within which three management zones have been established (Fig. 1).

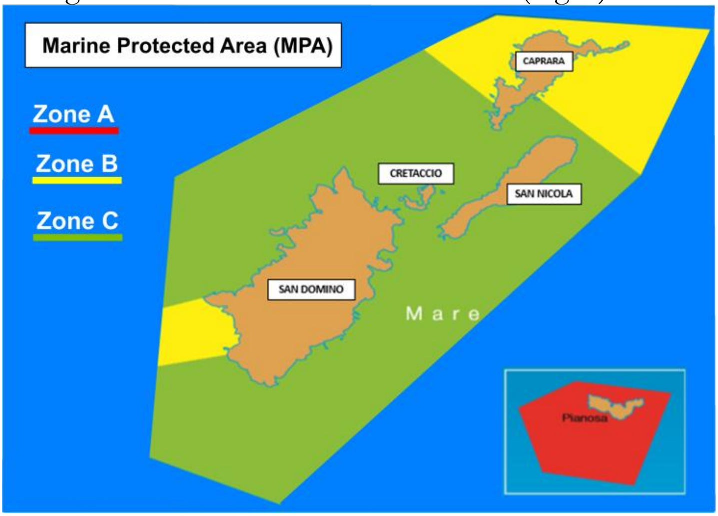


Figure 1 - Target area: Marine protected area.

The marine environment of the Tremiti Islands is considered one of the most ecologically valuable and scenic ecosystems of the Mediterranean Basin, often described as a true "underwater sanctuary." Scientific studies have identified 17 distinct habitat types and associated benthic assemblages that characterize the seafloor within the Marine Protected Area (Chimienti et al., 2020, 2021; De Padova et al., 2024).
From 2003 to 2016, the Tremiti Islands experienced a paradox: surrounded by the sea yet forced to rely on tanker ships for their water supply (Fonzi, 1984). For years, a direct connection to the mainland has been under discussion: an underwater pipeline approximately 22–25 kilometers long, capable of supplying up to 2,000–3,000 cubic meters per day. This would be a stable, low-maintenance solution, but the

risks of anchor damage, strong currents, and significant impact on the seabed have so far hindered any project. In Italy, islands have addressed this issue using two main models: underwater pipelines or desalination plants. The choice depends on distance, seabed conditions, and environmental constraints (Giacomelli & Baldi, 2023; Parada et al., 2023).

Today, the most feasible solution for the Tremiti Islands is represented by a modular reverse osmosis desalination plant on San Nicola Island, funded by the PNRR. It is a small plant with a capacity of 12 l/s, designed to serve only the archipelago's inhabitants. Funded under the PNRR "Green Islands" initiative, it is conceived as both a solution for local needs and a pilot model for other minor islands or isolated coastal communities.

Habitat mapping

The study of the seabed characteristics and benthic communities potentially affected by the discharge from the desalination plant was undertaken in the area of the existing wastewater treatment plant outfall. Six video transects were planned and conducted using the ROV Ageotec Perseo aboard the vessel Kiya (Fig. 2).

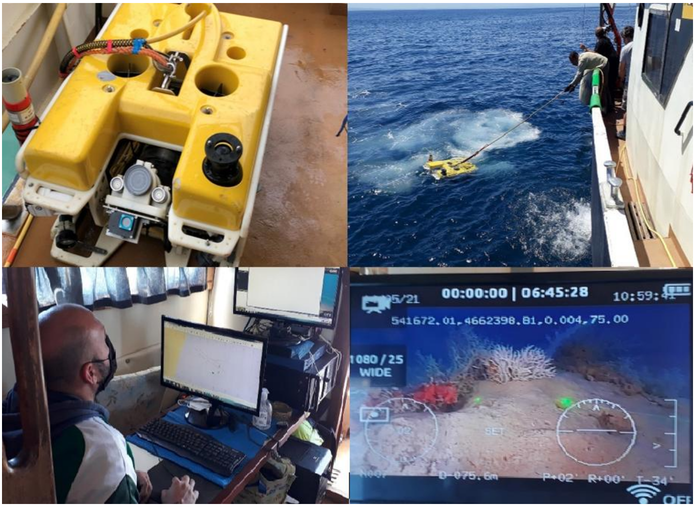


Figure 2 - Tools and instruments used.

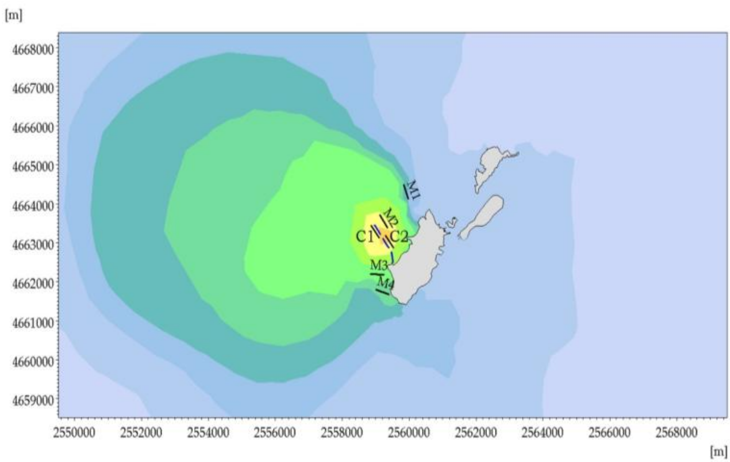


Figure 3 - Transects carried out for the study of the seabed (C1, C2, M1, M2, M3, M4) and the benthic communities that will be affected by the discharge from the desalination plant.

Two transects (C1 and C2) were aligned with the outfall, one offshore and one onshore, while the remaining four (M1–

M4) were executed on adjacent seabeds following a cross-shore pattern (Fig. 3).

Numerical model and implemented runs

The aim of the modeling activity carried out in this study was to analyze using the 3D numerical model MIKE 3 Flow Model FM provided by the Danish Hydraulic Institute (DHI, 2016), the wave and current regime, as well as the dispersion process of the waters discharged from the desalination plant's submarine outfall.
The MIKE 3 FM HD model is based on the numerical solution of three-dimensional incompressible Reynolds-averaged Navier–Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure. Consequently, it solves the conservation equations for mass, momentum, temperature, and salinity, as well as the turbulence closure equation. Using a sigma-type vertical coordinate system, it accounts for variations in the free surface, and the model employs an unstructured computational mesh to ensure maximum flexibility in representing complex geometries. In order to achieve fine resolution in the area of interest, allowing for the visualization of local circulation, a coarse mesh was used in the region of deep waters and appropriately refined near the coast of the Tremiti Islands for domain discretization. The nodes of this mesh represent the calculation points of the model. Vertical discretization in the model is carried out using the so-called sigma layers, which follow the terrain's variations, ensuring a constant number of calculation points along each vertical (Fig. 4).

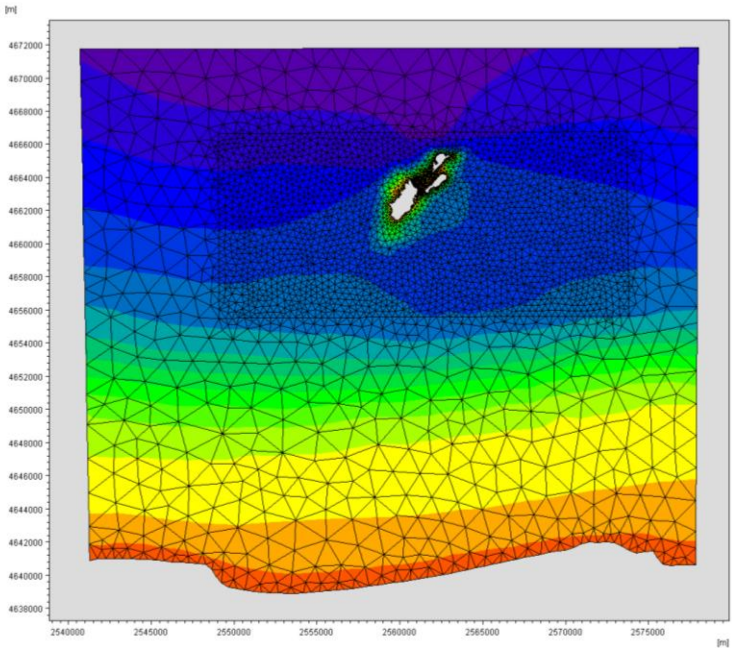


Fig. 4: Computation domain used for numerical simulations.

Simulations were executed by adopting a Smagorinsky coefficient (Cs), a seabed roughness and a wind drag coefficient (Cd) equal to 0.6, 0.1 m and 0.002 respectively, according to recent sensitivity analysis, and a wind drag coefficient Cd equal to 0.002, based on earlier studies (Armenio et al., 2016, 2017a, 2017b, 2018a, 2018b; 2019; De Padova et al., 2023, 2024).

Two seasonal mean circulations were generated, respectively, for winter and summer, to evaluate the diffusion process of groundwater under typical seasonal conditions and thus within more limited time intervals and with more distinct forcings. Specifically, the hydrodynamic module of the model was driven by three different inputs: a homogeneous and steady wind field, a semi-diurnal tidal motion and wave motion.

For the average winter condition, the input consisted of a wind field that was representative of the season, namely a wind coming from the NNO with an intensity ranging from 11 to 17 knots, estimated to be an average of 7 m/s. This homogeneous and steady wind field in space was imposed for the entire duration of the run (i.e., 7 days, ensuring a stationary condition is reached). This generates average current patterns, which can naturally be modified by intense but brief transient events, and then return to the representative average condition.

For the average summer condition, the input consisted of a wind field that was representative of the season, namely a wind coming from the ONO with an intensity ranging from 7 to 11 knots, estimated to be an average of 4.5 m/s.

The representative values of radiation stress for the average winter and summer conditions were the output of the MIKE 21 SW wave model. Specifically, the representative wave motion for the winter condition, as reported in the Regional Coastal Plan for Apulia, is defined by a direction of 336° NW.

The representative wave motion for the summer condition, as reported in the Regional Coastal Plan for Apulia, is defined by a direction of 333° NW.

The tide, considered to be generally invariant between winter and summer periods, was imposed as a variation in the free surface along the open boundary of the domain. It is of a semi-diurnal type, characterized by an amplitude of 0.15 m (height 0.30 m) and a period of 12 hours.

Two scenarios were analyzed under both average winter and summer conditions to evaluate the effectiveness of mixing the brine with the treated wastewater discharged through the existing outfall system at the outfall point (2559009.934E 4663240.072N) (Fig. 5).

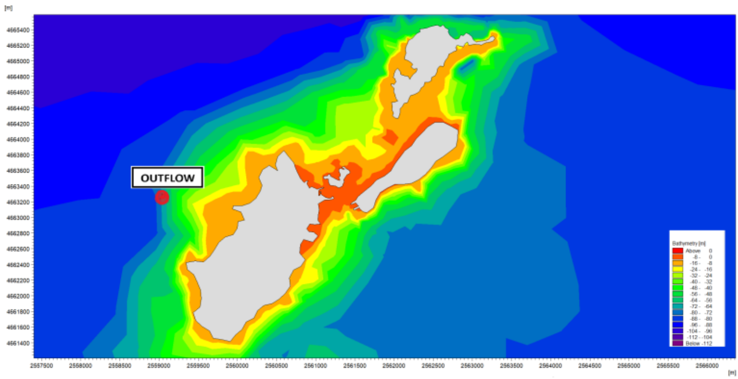


Figure 5 - Location of the outflow.

In the first configuration only the treated wastewater discharge was regarded, characterized by a salinity of approximately 0.05 PSU and a flow rate of 500 m³/h, for both the average winter and summer conditions (T1A and T1B).
In the second configuration (High Salinity), the discharge consisted of a mixture of brine and treated wastewater. For the winter condition (T2A), the mixed effluent was characterized by a salinity of 66.92 PSU and a flow rate of 50.00 m³/h; for the summer condition (T2B), the salinity was 55.68 PSU with a flow rate of 150.00 m³/h.

Results and discussions

Biological characterization of the seabed

The video surveys revealed a variety of seabed types and benthic assemblages along the investigated transects, ranging from sandy-muddy bottoms to well-developed coralligenous habitats. For the sake of brevity, only selected survey results are presented. For instance, along transect M4, starting at a depth of -50 m, typical platform coralligenous bioconstructions were observed, richly colonized by the yellow gorgonian Eunicella cavolinii and the red gorgonian Paramuricea clavata, forming extensive facies comparable to true underwater gardens (Fig. 6).

Figure 6: Forests of yellow gorgonians Eunicella cavolinii and red gorgonians Paramuricea clavata.

Hydrodynamics

The simulated average winter surface circulation (at 1 m depth) shows a northward flow that branches into two main currents: one feeding a relatively strong upwelling between the islands of San Nicola and Caprara, and another directed southward between San Nicola and Cretaccio. The latter current intensifies south of Cretaccio, channeling between

San Domino and San Nicola, where the highest flow velocities are reached.

An intense downwelling flow is also observed along the northwestern coasts of San Domino Island, which, before veering southward, contributes to the formation of a counterclockwise eddy in the southwestern area of the island.

The bottom circulation pattern closely mirrors the surface flow structure, though with generally lower current magnitudes (Fig. 7).

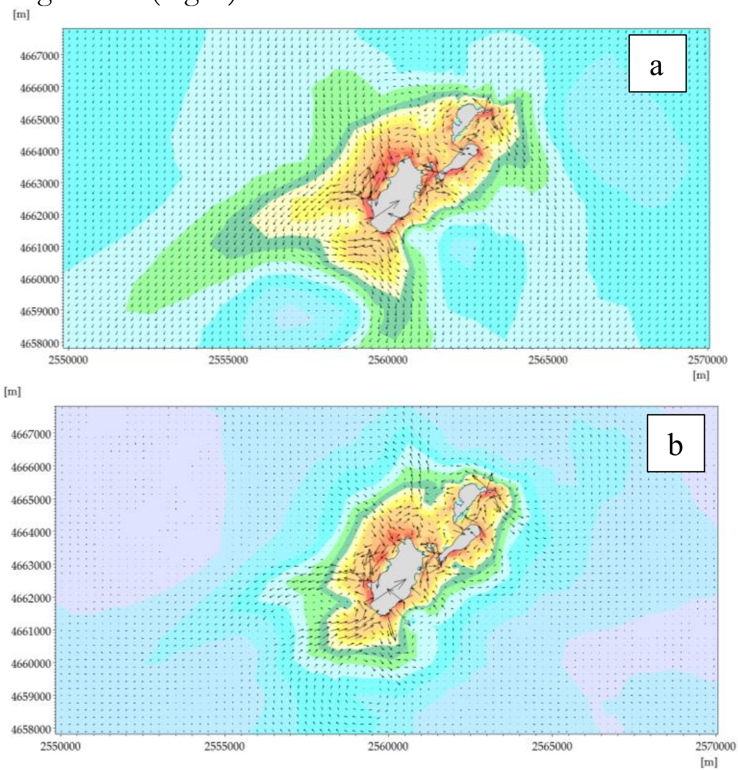


Figure 7 - Average winter current: surface(a) and bottom (b).

The summer circulation pattern is similar to that observed during the winter period; however, the currents generally exhibit lower intensity.

In particular, the average summer surface circulation (at 1 m depth) shows a branching of the northward flow, feeding a relatively strong upwelling between the islands of San Nicola and Caprara, and a weaker southward current between San Nicola and Cretaccio. As in the winter scenario, the coastal downwelling current along San Domino Island contributes to the formation of a large counterclockwise eddy, extending along the western and southern coasts of the island before gradually flowing southward.

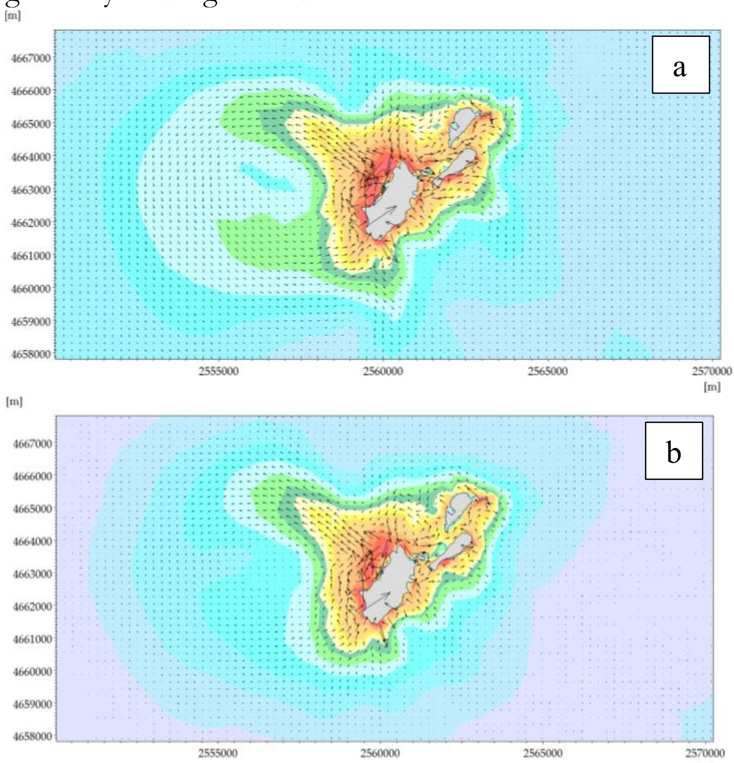


Figure 8: Average summer current: surface(a) and bottom(b)

The bottom circulation field displays a similar structure to that of the surface layer, though with generally lower current magnitudes (Fig. 8).

Plume spreading

T1: Configuration 1: T1A and T1B

The results obtained are presented below as follows:

- Map of minimum surface (Figure 9a) and bottom (Figure 9b) salinity values reached during the average winter condition at each point in the domain, along with the vertical salinity profile (Figure 9c) taken along the transect perpendicular to the flow for the same condition (T1A).
- Map of minimum surface (Figure 10a) and bottom (Figure 10b) salinity values reached during the average summer condition at each point in the domain, along with the vertical salinity profile (Figure 10c) taken along the transect perpendicular to the flow for the same condition (T1B).

It should be emphasized that in the visualization of the figures presented below, color scales have been used to make the transport and diffusion of the tracer visible, and therefore areas of plumes with salinity values close to 38 PSU, which is the salinity of seawater, are also visible.

For both winter and summer conditions, the analysis of the figures suggests that, both at the surface and at the bottom, the S plume moves away from the discharge point and is predictably transported by the current—towards the NW during winter conditions and towards the SW during summer conditions—spreading around the southwestern coast of San Domino Island; however, the mixing effect is limited, and the vertical profiles indicate that the plume remains confined to the area closest to the seabed, with a maximum reduction in S $\leq 0.001\%$.

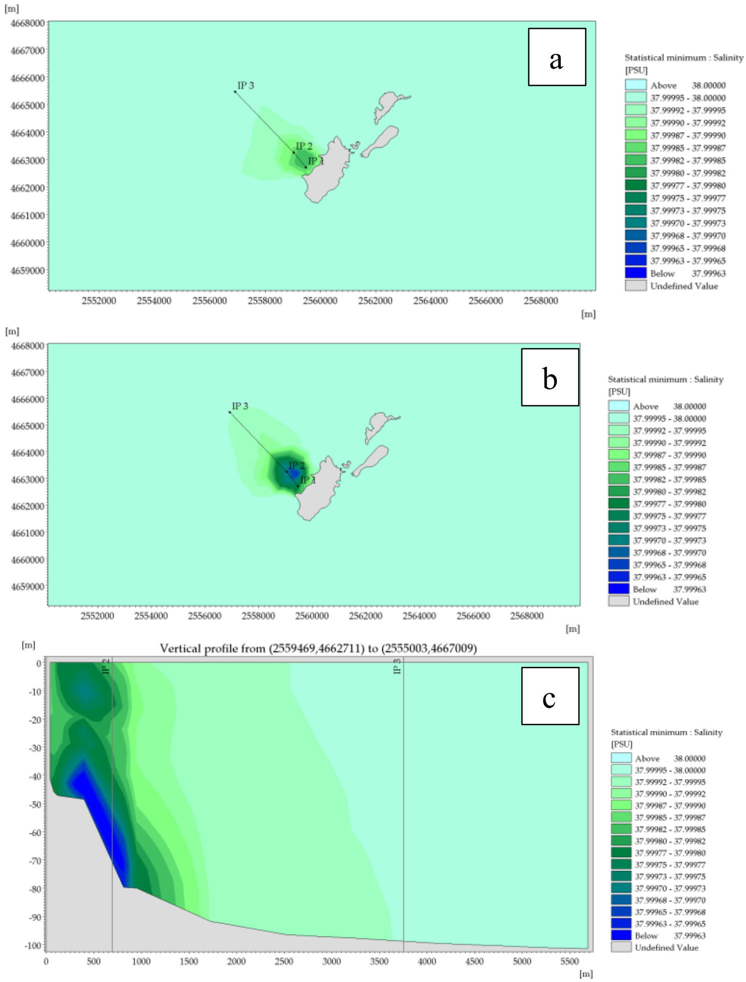


Figure 9 - Average Winter Condition: Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of S along the transect perpendicular to the coastline.

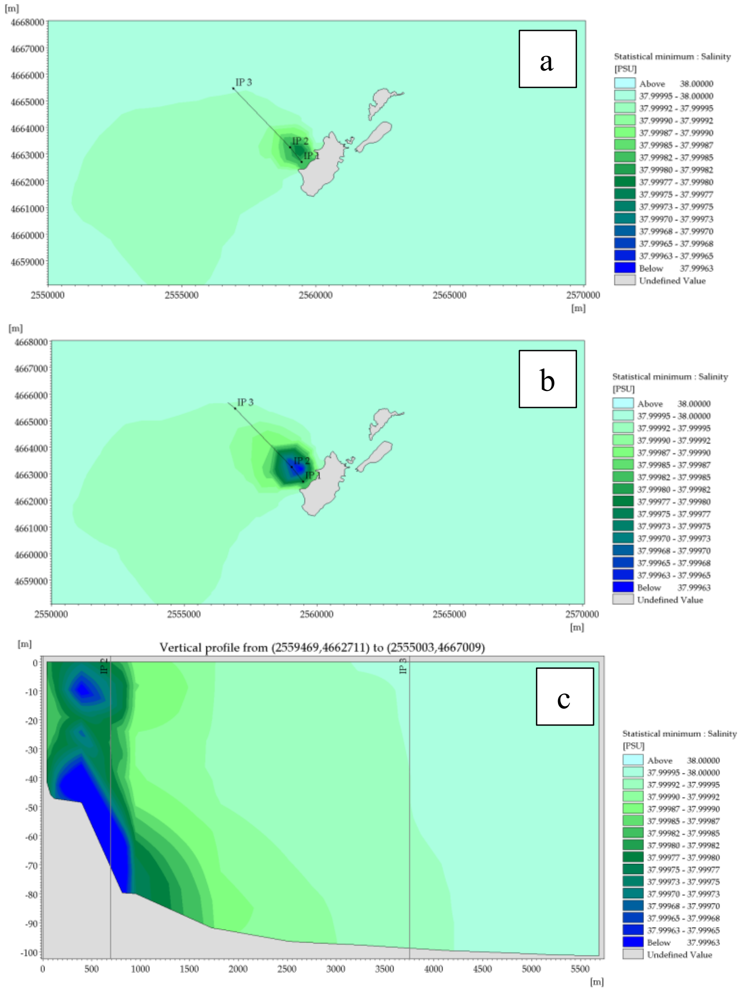


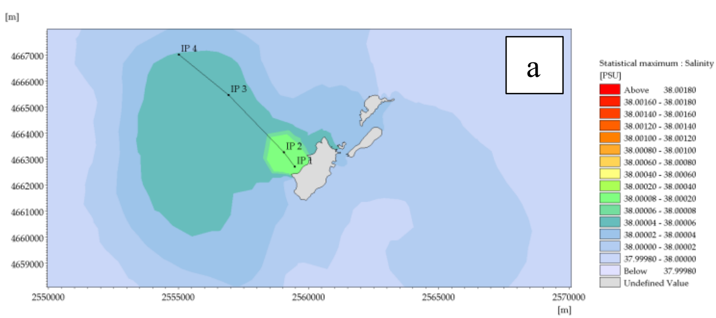
Figure 10- Average summer Condition: Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of *S* along the transect perpendicular to the coastline.

Configuration 2: T2A and T2B

Also, for the second configuration, the results are organized as follows:

- Map of minimum surface (Figure 11a) and bottom (Figure 11b) salinity values reached during the average winter condition at each point in the domain, along with the vertical salinity profile (Figure 11c) taken along the transect perpendicular to the flow for the same condition (T2A).
- Map of minimum surface (Figure 12a) and bottom (Figure 12b) salinity values reached during the average summer condition at each point in the domain, along with the vertical salinity profile (Figure 12c) taken along the transect perpendicular to the flow for the same condition (T2B).

For both winter and summer conditions, the analysis of the figures suggests that the salinity plume spreads north-northwest at both the surface and bottom, then is carried by the current towards the southwest, affecting the western coast of San Domino Island. The mixing effect is limited in both cases, and the vertical profiles indicate that the plume remains confined near the seabed, with a maximum salinity increase of 0.001% in winter and 0.002% in summer.



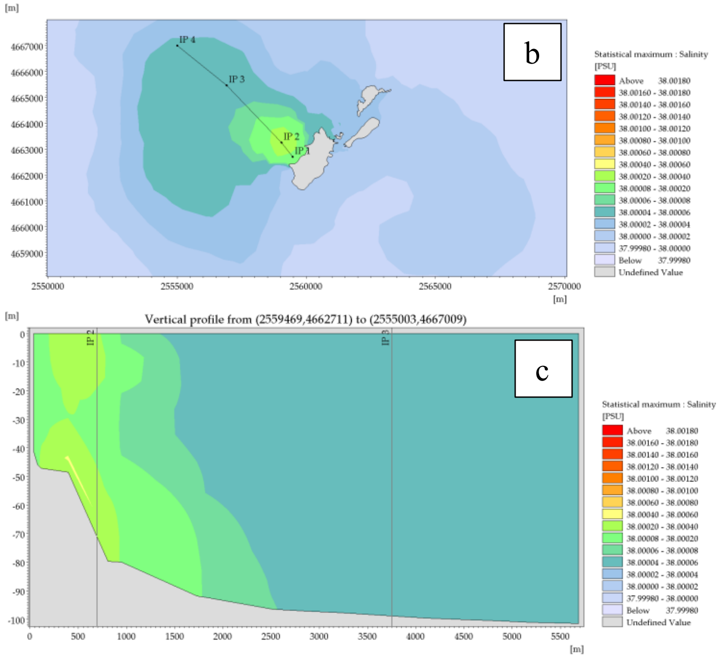
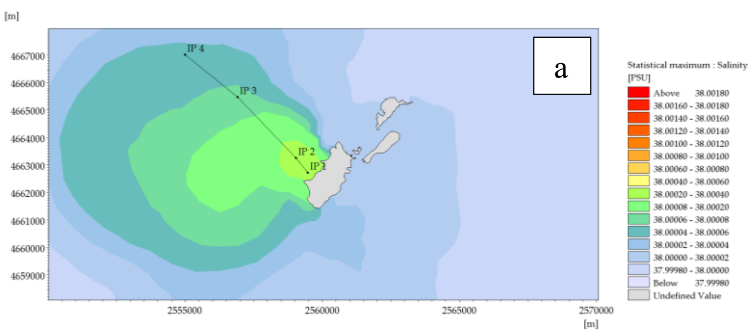


Figure 11 - Average Winter Condition: Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of S along the transect perpendicular to the coastline.



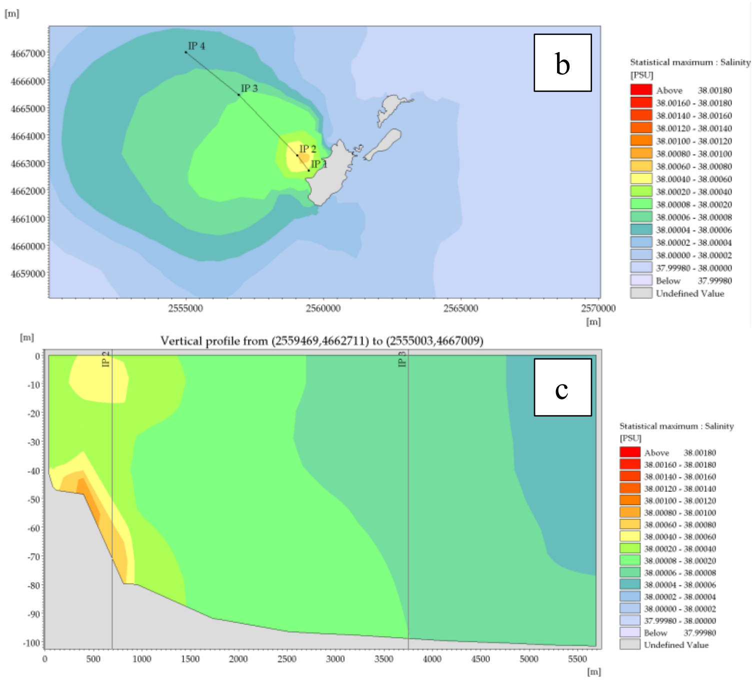


Figure 12 - Average summer Condition: Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of S along the transect perpendicular to the coastline.

Conclusions

In this study, we analyzed the potential discharge configuration of an innovative desalination plant that plans to release its brine through the existing treated wastewater outfall pipeline, to limit possible alterations caused by increased water salinity.

The examination of the salinity dispersion maps for the design condition, both at the surface and near the bottom, under average winter and summer scenarios, showed that the salinity plume (S) spread toward the N–NW and was generally transported southwest by the prevailing current, reaching the southwestern coast of San Domino Island. The plume remained largely confined near the seabed, with a maximum salinity increase of S ≤ 0.002%, indicating limited mixing.

The salinity increase was therefore restricted to the immediate vicinity of the planned brine diffuser, and its impact on benthic communities—as assessed through seabed video surveys—was regarded negligible. Importantly, the valuable coralligenous bioconstructions located northeast (transect M1) and southwest (transects M3 and M4) of the outfall remained entirely unaffected by the minor salinity changes associated with the desalination system.

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