

TOWARDS A SUSTAINABLE SEAWATER DESALINATION IN MARINE PROTECTED AREAS: MODELLING AND MONITORING ACTIVITY

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Abstract

This study presents numerical simulations on the downstream discharge of a desalination plant planned within a protected marina, in an area facing increasing demand for freshwater. The simulations assess potential impacts on the coastal marine ecosystem, supporting the design of environmentally sustainable solutions. The proposed plant adopts innovative techniques and a strategy aimed at minimizing ecological impact, ensuring a balance between local water needs and environmental protection. The numerical approach enables the analysis of different dispersion and mitigation scenarios, promoting the sustainable integration of the plant into the coastal setting. The results show that, although the response of biological communities is difficult to predict, the mixing of brines with existing freshwater discharge is expected to cause minimal salinity variations, lower than in the current situation, thus potentially limiting salinity-related effects on the marine ecosystem. Therefore, the project highlights the importance of green desalination solutions, based on renewable energy and efficient technologies, as a concrete response to water scarcity. This approach represents a sustainable management model that combines water security with marine ecosystem conservation.

Keywords

Green desalination, brackish water, sustainable water management, Mediterranean Sea

1. 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 (Musie et al., 2023; Amparo-Salcedo et al., 2025).

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 freshwater sources are insufficient or overexploited, as well as in areas where freshwater provision is needed due to aridity or lack of natural sources. 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 — primarily seawater desalination — have been recognized as critical for achieving the United Nations Sustainable Development Goal 6 (UN SDG 6): “Ensure availability and sustainable management of water and sanitation for all” (Ayaz et al., 2022).

Moneer et al. (2024) have examined the latest developments in desalination technologies. The emergence of new solutions provides numerous opportunities to expand the sector, which has historically relied on thermal desalination (phase change) and membrane-based desalination (non-phase change). Recent innovations in membrane technology (Ali et al., 2018), energy recovery devices (Ghazi et al., 2022) and hybrid systems (Hoyer et al., 2016) have improved efficiency and reduced costs, while methods like membrane distillation (MD) and forward osmosis (FO) allow integration with renewable energy sources.

Advanced storage solutions such as batteries, hydrogen, and thermal storage help ensure continuous operation despite the intermittency of renewables. Falling renewable energy costs, combined with supportive policies and international collaboration, make large-scale implementation increasingly feasible, particularly in coastal and island regions.

However, in the past few decades, the global capacity of desalination 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 feasibility studies that assess hydrodynamics, wave conditions, water quality, and biological communities. Mathematical modeling is often employed to predict brine dispersion, optimize outfall configurations, and minimize environmental harm (Palomar & Losada, 2011). Appropriate planning and advanced design methodologies are therefore essential to reduce ecological risks while ensuring a sustainable water supply. Thus, 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 UN SDG 6.

Consequently, the advancement of desalination technologies will hinge upon the synergistic integration of technological innovation, renewable energy utilization, and global cooperation, ensuring its role as a reliable and environmentally sustainable freshwater source.

The present study investigates the case of the Tremiti Islands Marine Protected Area (MPA), which is affected by chronic potable water scarcity. 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 (Di Lecce & Di Natale, 1985).

For years, a direct connection to the mainland has been under discussion: an underwater pipeline approximately 22–25 km long, capable of supplying up to 2,000–3,000 m³ per day, but the costs of realization and maintenance coupled with potential impact on the benthic communities and risks related to damages by anchoring practice and illegal fishing, have hindered any project so far.

Thus, the current freshwater provision of Tremiti Islands is based entirely on a tank vessel providing non-potable water, and periodic crises occur among the islands due to submarine pipeline linking. During such events, some islands still experience periods from days to weeks without freshwater, highlighting the critical need to develop local, self-sustaining, and climate-resilient freshwater production systems.

Other Mediterranean 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).

The best solution for the Tremiti Islands seems to be a modular reverse osmosis desalination plant, one of which has been currently designed for San Nicola Island and is going to be realized. 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.

The present work aims at assessing 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 conservation of marine and coastal ecosystems.

2. Materials and Methods

2.1 Study area

The focus of this study is the Tremiti Islands, 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.

The archipelago consists of three main islands (San Nicola, San Domino, Capraia), the Cretaccio islet, and the uninhabited Island of Pianosa, 11 nautical miles NE from the main archipelago. The islands are aligned along a northeast-southwest (NE-SW) axis and are separated from each other by only a few hundred meters.

The archipelago is characterized by a high ecological and aesthetic value (Chimienti et al., 2017), with the presence of relevant marine ecosystems including seagrass meadows (Tursi et al., 2022), rhodolith beds (Chimienti et al. 2020b), marine animal forests (Chimienti et al., 2020a) and unique corallith beds (Chimienti et al., 2025), representing a climate-change hotspot in the Adriatic Sea (Chimienti et al., 2021; De Padova et al., 2024) and a strategic area for conservation.

Since 1989, the Tremiti Islands have been designated as a MPA, within which three management zones have been established (Fig. 1): Zone A (no take, no entry zone), Zone B (general reserve) and Zone C (buffer zone).

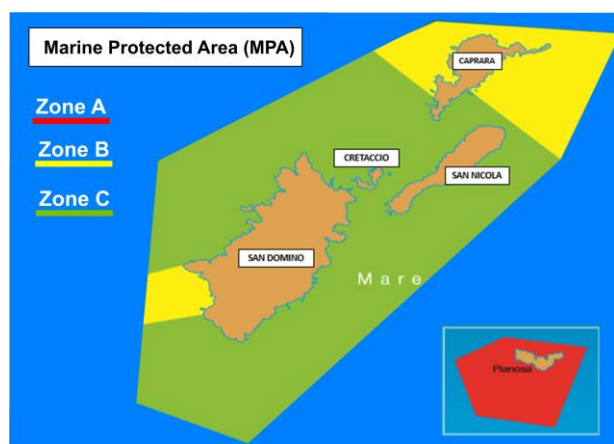


Fig. 1: Study area, Tremiti Islands Marine Protected Area

2.2 Seabed characterization

The study of the seabed characteristics and benthic communities potentially affected by the discharge from the desalination plant was carried out in the area of the existing wastewater treatment plant outfall. Six video transects were carried out perpendicularly to the coast using the Remotely Operated Vehicle (ROV) Ageotec Perseo (Fig. 2).

Two transects (C1, C2) were aligned with the wastewater discharge pipe, one offshore and one onshore, while the remaining four were performed on adjacent areas, two north (M1, M2) and two south (M3, M4) to the outfall (Fig. 3).



Fig. 2: Tools and instruments used

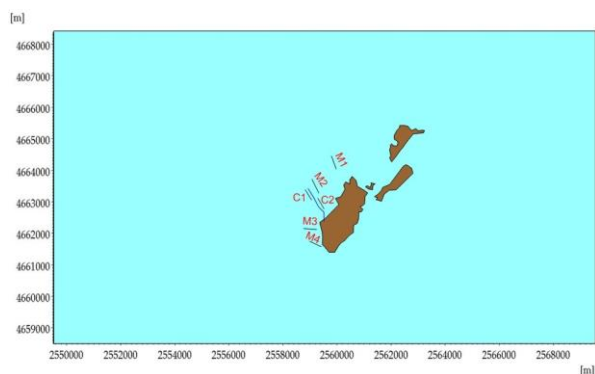


Fig. 3: Transects carried out for the study of the seabed (C1, C2, M1, M2, M3, M4) and the benthic communities that will be affected by the discharge from the desalination plant.

2.3 Numerical model and implemented runs

The aim of the modeling activity carried out in this study was to analyze, the wave and current regime, as well as the dispersion process of the waters discharged from the desalination plant's submarine outfall using the 3D numerical model MIKE 3 Flow Model (FM) provided by the Danish Hydraulic Institute (DHI, 2016).

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 circulations, 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).

Simulations were performed by adopting a Smagorinsky coefficient (C_s), a seabed roughness and a wind drag coefficient (C_d) equal to 0.6, 0.1 m and 0.002 respectively, according to recent sensitivity analysis, and a wind drag coefficient C_d

equal to 0.002, based on earlier studies (Armenio et al., 2016, 2017a, 2017b, 2018a, 2018b; 2019; De Padova et al., 2020, 2023).

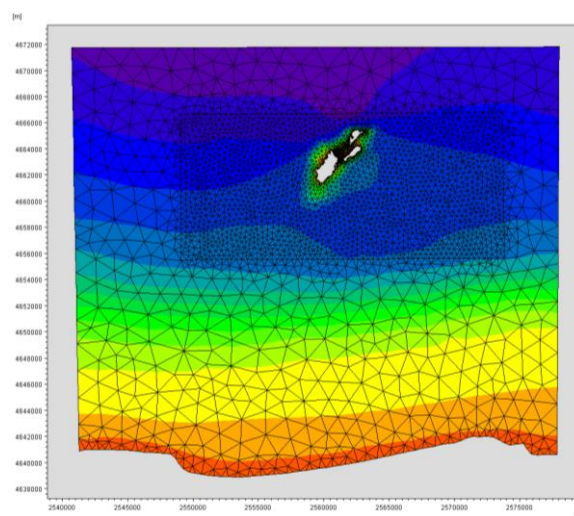


Fig. 4: Computation domain used for numerical simulations

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 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 (DHI). Specifically, the representative wave motion for the winter condition, as reported in the Regional Coastal Plan for Apulia, is characterized

by a direction of 336° NW, $H_s = 2.1$ m and $T_p = 6.43$ s.

The representative wave motion for the summer condition, as reported in the Regional Coastal Plan for Apulia, is characterized by a direction of 333° NW, $H_s = 1.34$ m and $T_p = 5.12$ s.

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).

In the first configuration (T1) only the treated wastewater discharge was considered, characterized by a salinity of approximately 0.05 PSU and a flow rate of $500 \text{ m}^3/\text{h}$, for both the average winter (T1A) and summer (T1B) conditions.

In the second configuration (T2), the discharge consisted of a mixture of brine and treated wastewater resulting in a high salinity. For the winter condition (T2A), the mixed effluent was characterized by a salinity of 66.92 PSU and a flow rate of $50.00 \text{ m}^3/\text{h}$; for the summer condition (T2B), the salinity was 55.68 PSU with a flow rate of $150.00 \text{ m}^3/\text{h}$.

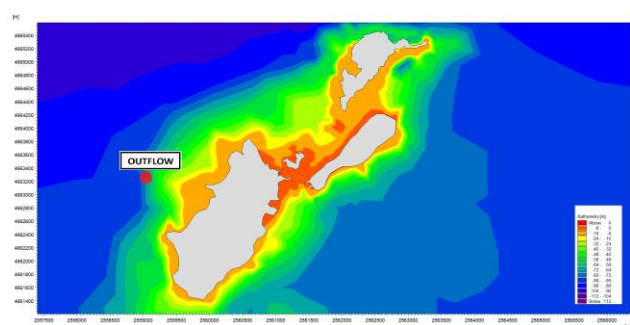


Fig. 5: Location of the outflow

3. Results and discussions

3.1 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. In detail, the coastal area where the existing

wastewater discharge pipe is present (transect C2) was characterized by mosaics of sandy and rocky bottoms colonized by photophilous algae. Then, from 34 to 48 m depth, patches of rhodolith beds (*sensu* Chimienti et al., 2020b) were present, interspersed with coralligenous formations locally dominated by bryozoans, polychaetes and occasionally sponges in the genus *Axinella* up to 60 m depth (transect C1). Proceeding deeper, the seabed slightly shifted to more sandy/muddy bottom up to the end of the pipe (70 m depth) and below.

Similarly, NE to the pipe area (transects M2 and M1), the seabed was characterized by patches of coralligenous and rhodolith beds and, below 80 m depth, muddy bottoms colonized by the sea pens *Pennatula rubra* and *Veretillum cynomorium*.

Ca. 1300 m SW of the pipe (transect M3), the seabed was characterized by coralligenous bioconstructions generally colonized by algae, bryozoans and sponges, with patches of rhodoliths at 50-55 m, areas dominated by the ascidian *Diazona violacea* (*sensu* Mastrototaro et al. 2020) at 50-60 m depth, as well as the presence of the black coral *Antipathella subpinnata* at 60-70 m. Similarly, transect M4 (ca. 1800 m SW the pipe) was characterized by coralligenous formations that, however, were abundantly colonized by the octocorals *Eunicella cavolini* and *Paramuricea clavata* (Fig. 6) forming dense coral forests between 35 and 50 m depth. Mesophotic coralligenous formations dominated by *D. violacea* were also present between 50 and 60 m depth. Below 70 m depth, both M3 and M4 were characterized by a muddy bottom with the sea pens *P. rubra* and *Pteroeides griseum*.



Fig. 6: Forest of *Paramuricea clavata* at transect M4.

3.2 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 (Fig. 7). 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).

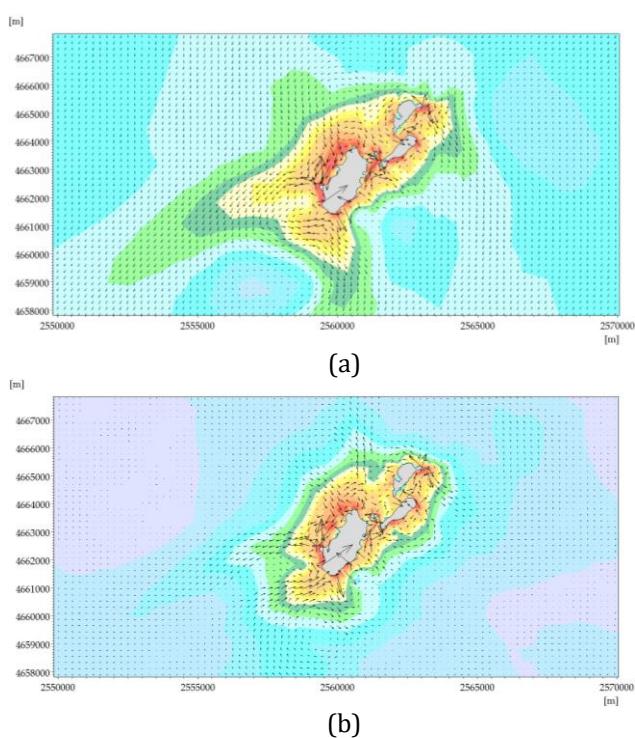


Fig. 7: Average winter current: surface (a) and bottom (b).

The summer circulation pattern is similar to that observed during the winter period, but with currents exhibiting an overall 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. The bottom circulation field displays a similar structure to that of the surface layer, though with generally lower current magnitudes (Fig. 8).

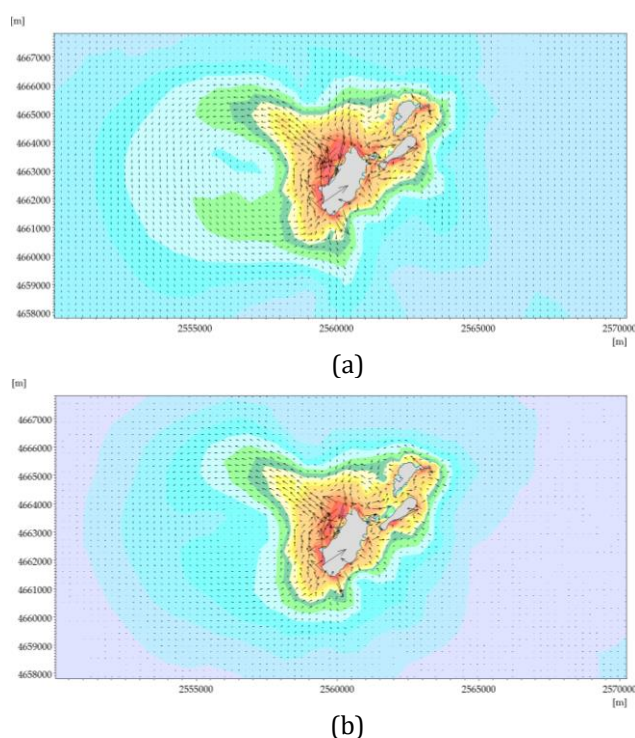


Fig. 8: Average summer current: surface (a) and bottom (b).

3.3 Plume spreading

3.3.1 Configuration T1: treated wastewater

The simulation results are reported in figures 9 and 10 for winter and summer conditions, respectively. 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 minimum seawater salinity in the study area, are also visible. For both winter and summer conditions, the simulations show that, both at the surface and at the bottom, the salinity plume moves away from the discharge point and is predictably transported by the current — towards NW during winter and SW during summer — 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 salinity $\leq 0.001\%$.

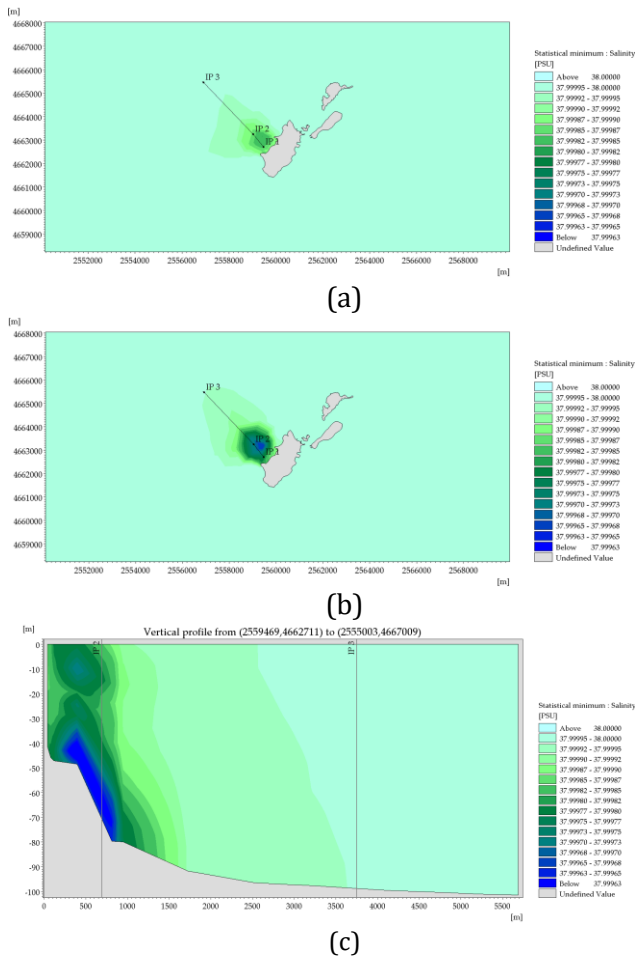


Fig. 9: Average Winter Condition for the scenario T1A: treated wastewater. Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of the salinity plume perpendicular to the coastline.

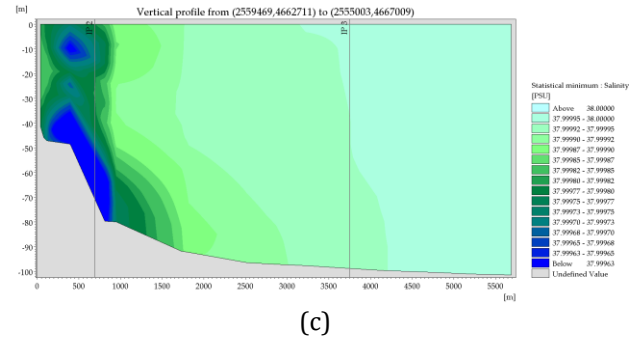
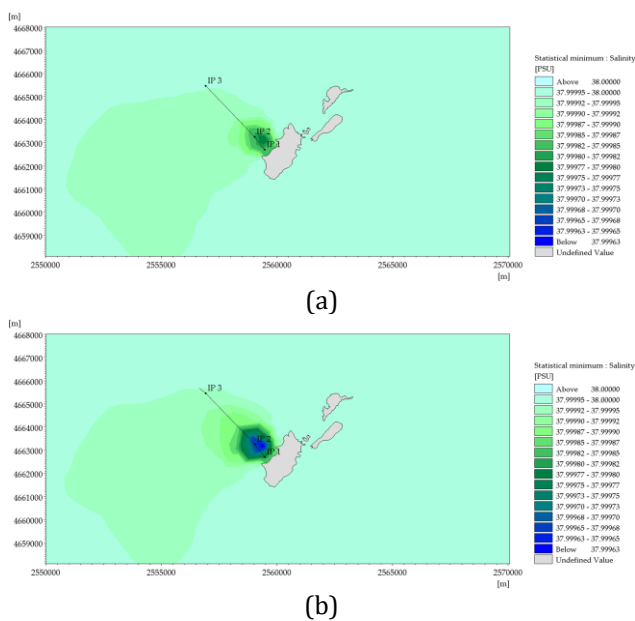
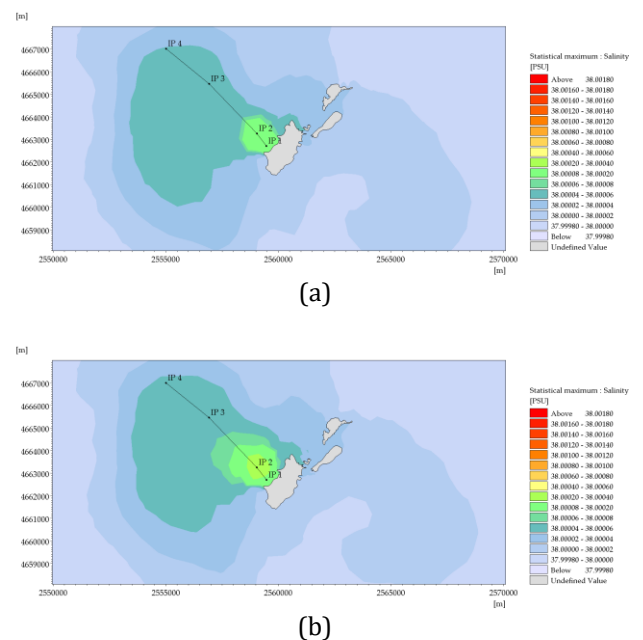


Fig. 10: Average summer Condition for the scenario T1B: treated wastewater. Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of the salinity plume perpendicular to the coastline.

3.3.2 Configuration T2: treated wastewater and brine

The simulation results are reported in figures 11 and 12 for winter and summer conditions, respectively. For both winter and summer conditions, the model shows that the salinity plume spreads NNW at both the surface and the 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.



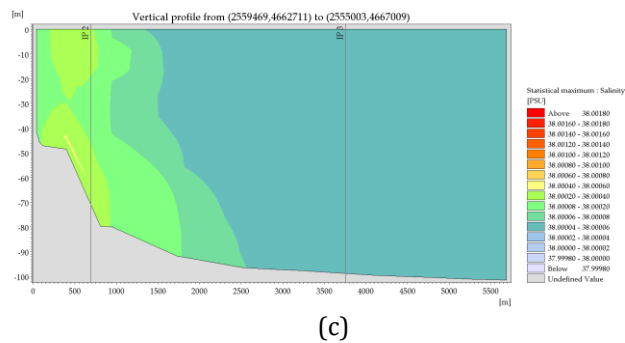


Fig. 11: Average Winter Condition for the scenario T2A: treated wastewater and brine. Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of the salinity plume perpendicular to the coastline.

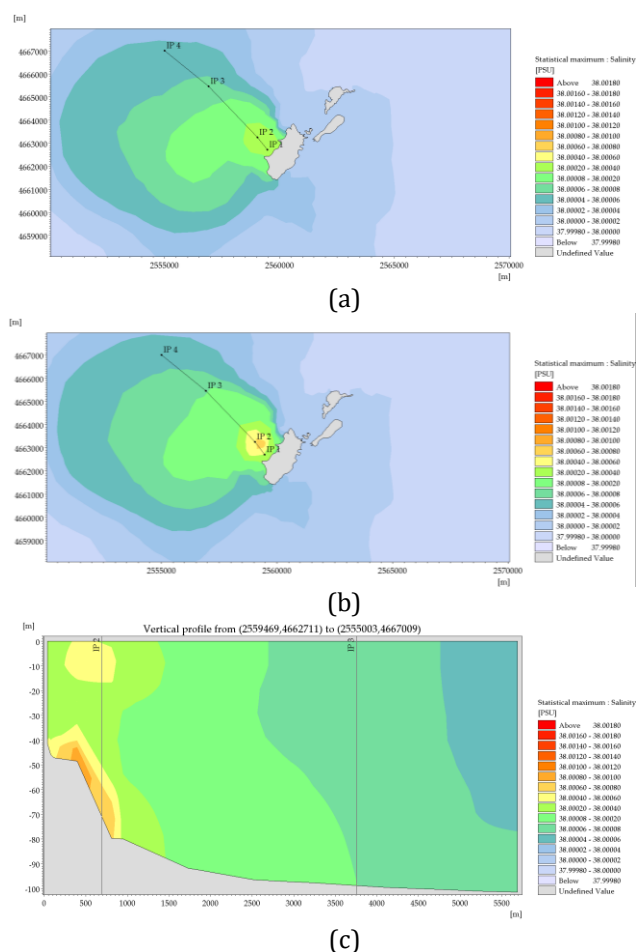


Fig. 12: Average summer Condition for the scenario T2B: treated wastewater and brine. Salinity Minimum Map (a) at the surface; (b) at the bottom; (c) vertical profile of the salinity plume perpendicular to the coastline.

4. 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 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 lower than 0.002%, indicating limited mixing.

The increase in salinity was therefore restricted to the immediate vicinity of the planned brine diffuser, and its impact on benthic communities is potentially negligible. Although it is difficult to predict the response of the biological communities to anthropogenic changes, the mixing of the brines with the existing freshwater discharged is expected to cause a minimal salinity variation, lower compared to the current situation – where only freshwater is discharged by the pipeline – possibly limiting the effects of discharge in terms of salinity variation.

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