

Numerical Modeling of the Mixing Process of Concentrated Brine Outfall in Shallow Water

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Abstract: *This study investigates the mixing and dispersion of concentrated brine discharged from a small seawater reverse osmosis plant along the Jeddah coast of the Red Sea, Saudi Arabia. MIKE 21 Spectral Wave and MIKE 3 Flow Model FM were applied to simulate wave conditions, hydrodynamic circulation, and salinity and temperature transport. The calibrated wave model achieved a correlation coefficient of 0.85, an RMSE of 0.28 m, and a bias of -0.009 m, while the hydrodynamic model achieved a current-speed correlation coefficient of 0.74, an RMSE of 0.089 m/s, and a bias of -0.03 m/s. Outfall depths of 7 m and 10 m were examined under calm, most frequent, and stronger wind conditions. For the 7 m outfall, the saline plume extended approximately 345 m under calm conditions, 298 m under the most frequent conditions, and 170 m under stronger forcing. Plume transport was predominantly southward under prevailing northerly and northwesterly winds. The 10 m outfall reduced nearshore salinity accumulation and achieved approximately 35.4% higher dilution at the outfall location compared with 7m configuration. The results demonstrate the value of three-dimensional modelling for evaluating brine dispersion and comparing outfall depths in shallow Red Sea coastal waters.*

Keywords: Brine dispersion; Numerical modeling; Shallow coastal waters; MIKE 21/MIKE 3; Red Sea

1. Introduction

One of the most important environmental and development issues facing arid and semi-arid regions today is freshwater scarcity. To overcome the future water challenges, desalination has emerged as one of the few options capable of meeting rapidly increasing demand, particularly in the Middle East and North Africa, where natural freshwater availability is limited and evaporation rates are high (1). The concentration of desalination capacity in the Gulf Cooperation Council (GCC) states highlights the need for effective management of the brine generated by the desalination process (2).

As desalination capacity expands, the management of brine disposal is becoming an increasingly important environmental issue. The continuous release of concentrated reject water requires careful planning to avoid long-term impacts on coastal water quality, seabed conditions and sensitive marine habitats. The six Arabian Gulf countries are operating 3,401 plants with a total seawater desalination capacity of approximately 22.67 million m³/day. In addition, these states account for more than a third of the global water desalination production capacity (2). In Saudi Arabia, desalination is a fundamental component of national water security; the Saudi Water Authority reports that the Kingdom produces the world's largest amount of desalinated water at 11.1 million m³/d (3).

In seawater reverse osmosis (SWRO), seawater is pumped at high pressure through semi-permeable membranes, producing freshwater while retaining salt and other dissolved constituents in a concentrated reject stream. The resulting reject brine is typically denser and more saline than ambient seawater and may also contain residual anti-scalants, chlorine-derived species, corrosion products, and trace metals (4).

The disposal of brine remains one of the main environmental challenges associated with desalination. The discharge of brine into the sea is expected to alter the physical and chemical characteristics of the seawater through increased salinity, density and possibly temperature. The environmental impact associated with SWRO brine discharge is complex and influenced by several factors, including discharge rate, brine concentration, temperature, effluent density, outfall configuration, bathymetry, currents, tides, and wind (4,5). Because SWRO brine is negatively buoyant, it tends to sink and spread along the seabed after discharge (6).

Despite the increasing number of studies on desalination brine dispersion, there remains a need for detailed site-specific modelling of small- to medium-scale SWRO discharges along the Saudi Red Sea coast. Jeddah, KSA is one of the most important urban, commercial and tourism centers on the Red Sea, and its shallow nearshore waters support ecological, recreational and economic activities. The proximity of desalination facilities to sensitive coastal waters makes the evaluation of brine mixing and transport essential for

environmental management. This is particularly important where brine is released into shallow water, where dilution may be limited by low water depth, nearshore bathymetry and local circulation patterns.

Accordingly, this study investigates the mixing and dispersion of concentrated brine discharged from an SWRO plant located along the Jeddah coast. The study applies numerical hydrodynamic and dispersion modelling supported by field and operational data to evaluate brine plume behavior under local coastal conditions. By examining interactions among discharge characteristics, shallow-water hydrodynamics, and salinity transport, this study provides a scientific basis for sustainable reject-brine management and assesses the suitability of the selected outfall configuration for the local shallow-water coastal setting.

The principal contribution of this study is the incorporation of calibrated wave-induced currents into a site-specific three-dimensional assessment of brine-plume dispersion in the shallow coastal waters of the Red Sea.

This was achieved by using the MIKE 21 Spectral Wave model to simulate the propagation and transformation of offshore waves across the study domain and to calculate the corresponding radiation stresses. The calibrated radiation-stress outputs were transferred to MIKE 3 Flow Model FM to account for wave-induced currents in the hydrodynamic simulations. This coupling was considered relevant because the brine outfall is located in shallow coastal water, where wave shoaling, refraction, bottom friction and depth-induced breaking can alter the nearshore current field and mixing conditions. Consequently, wave-induced circulation may affect the transport direction, spatial extent and dilution of the saline plume. The wave model therefore served as a forcing component of the hydrodynamic and transport framework rather than as an independent assessment of the regional wave climate.

The study provides a practical decision-support framework for the assessment and preliminary optimization of small-scale SWRO brine outfalls located in shallow urban coastal waters of the central Red Sea. The proposed framework could also serve as a supporting technical reference for the National Center for Environmental Compliance (NCEC) when reviewing and evaluating comparable reverse osmosis desalination facilities and brine-discharge systems operating under similar environmental and hydrodynamic conditions in the same coastal area.

2. Literature Review

Prior research has shown that the method of disposal strongly influences the dilution efficiency and spatial extent of the affected area. The risk of salinity buildup in coastal areas may be increased by surface and shoreline discharges, which usually have little initial dilution. However, submerged outfalls and diffuser systems can achieve high dilution by using the jet momentum as well as ambient turbulence to develop highly mixed plumes (4,5). Al-Ghamdi (7) used the CORMIX hydrodynamic model to simulate the plume behavior for Jeddah multipoint outfall. Alameddine and El-Fadel (4) applied the CORMIX hydrodynamic mixing model

to investigate and compare the performance of various configurations for surface channels, single and multi-port outfalls, and a multi-port diffuser for a proposed desalination and power generation plant in the Gulf region. The results indicated that surface channel configurations generally have limited mixing and large potential impacts, while a multi-port diffuser configuration has improved dilution and reduced potential impacts (4). Bleninger and Jirka (5) reached similar conclusions for contemporary large-capacity desalination plants that need submerged negatively buoyant jet discharges to achieve high dilution and reduce environmental impacts. They also emphasized the significance of diffuser angle, offshore transport, and boundary interaction.

The mixing and dispersion of brine discharged through a marine outfall occur over two physically distinct regions: the near field and the far field. The near field is located immediately around the discharge outlet and is dominated by the momentum and buoyancy fluxes of the effluent. In this region, jet trajectory, initial dilution, maximum rise or fall, and seabed impingement are controlled primarily by discharge velocity, port diameter, port orientation, diffuser configuration, effluent density and the local ambient current. Integral and semi-empirical tools such as CORMIX, CORJET and UM3 are commonly applied to this region because they can efficiently evaluate the initial behavior of negatively buoyant jets and assess alternative diffuser configurations (4,8).

The far-field region begins after the discharge momentum and jet-generated turbulence have substantially decayed. The brine then behaves as a saline plume or gravity current whose transport and dilution are governed mainly by ambient advection, turbulent diffusion, density-driven spreading, bathymetry, tides, wind-driven circulation, wave-induced currents and vertical stratification. The initial conditions produced in the near field influence the subsequent far-field plume (5,6).

The negatively buoyant plume can produce vertical salinity and density gradients and may descend and spread close to the seabed; therefore, a depth-averaged model would not adequately represent its vertical behavior. MIKE 3 permits the simulation of spatially and temporally varying currents, vertical mixing, salinity, temperature and density effects using sigma layers while also incorporating realistic bathymetry, tides, wind forcing and wave-induced currents generated by MIKE 21 SW.

In the Red Sea region, numerical modelling has become a valuable tool for assessing the dispersion of desalination discharges under site-specific hydrodynamic conditions. Fallatah et al. (9) combined observations and hydrodynamic modelling to assess environmental impacts near the Yanbu and Rabigh desalination plants on the central Red Sea coast, including hydrographic variables, trace metals and plume behavior. Aljohani et al. (10) used a calibrated three-dimensional Delft-3D model to investigate thermal and brine dispersion from the Yanbu desalination plant, which is located on the eastern coast of the Red Sea. Their results indicated that local circulation, wind and seasonal eddy circulation had significant effects on the far-field dispersion of the desalination plant effluent plume. Well-mixed

environmental conditions greatly enhanced the plume dilution. These studies indicate that the Red Sea coastal environment requires local-scale assessment because plume behavior is strongly controlled by site-specific currents, bathymetry and discharge characteristics.

The study area is located along the eastern coast of the central Red Sea near Jeddah, where coastal circulation is controlled by the combined effects of tides, atmospheric forcing, waves and complex nearshore bathymetry. The Jeddah coastal zone is characterized by shallow nearshore waters followed by a relatively rapid increase in depth offshore. This configuration affects wave transformation, current circulation, vertical mixing and the transport of dense effluents. Tides near Jeddah follow a mixed regime containing both diurnal and semi-diurnal components and should therefore not be considered purely semidiurnal (11,12). Madah et al. (12) demonstrated the spatial variability of the Red Sea tidal regime and the importance of using appropriately resolved tidal forcing in regional and local hydrodynamic models.

Wave conditions in the central Red Sea consist of both locally generated wind seas and remotely generated swell, which may occur simultaneously. Shanas et al. (13) documented the superposition of multidirectional wave systems in the central Red Sea, while Albarakati and Aboobacker (14) showed that waves undergo transformation across the shallow nearshore waters of Jeddah. These transformations, including shoaling, refraction, bottom interaction and depth-induced breaking, can generate or modify nearshore currents and consequently influence plume transport and dilution.

Predominant northerly and northwesterly winds, along with a noticeable diurnal land-sea-breeze circulation, dominate atmospheric forcing along the Jeddah coast (15). These wind systems affect surface mixing, wave generation, and the magnitude and direction of nearshore currents.

Due to high evaporation and little freshwater input, the central Red Sea is characterized hydrographically by warm, extremely saline water. Strong spatial and temporal variability in coastal water quality has been reported in earlier studies along the Jeddah and central Saudi Red Sea coasts. These studies have also shown that the dispersion of coastal discharges is influenced by local currents, wind conditions, bathymetry, and seasonal circulation (9,10,16).

3. Materials and Methods

Study Area

The study area is located along the eastern coast of the Red Sea in Jeddah, Saudi Arabia (Figure 1), within a shallow coastal environment influenced by tidal forcing, wind-driven circulation, and wave-induced processes. The region is characterized by a narrow continental shelf followed by a relatively steep offshore bathymetric gradient, which plays a significant role in controlling the transport and dispersion of dense brine discharges.

Desalination Plant and Discharge Characteristics

The desalination facility considered in this study is a private sector seawater reverse osmosis (SWRO) system with a total production capacity of 3000 m³/day. The corresponding reject brine discharge is approximately 6000 m³/day, equivalent to 0.0694 m³/s. The discharged brine is characterized by a salinity of 60 PSU and a temperature of 32.5 °C. These values were obtained from the field survey.

Due to its higher density compared to ambient seawater, the effluent behaves as a negatively buoyant plume. In the near field, the discharge is governed by jet momentum and buoyancy effects, while in the far field, the plume spreads along the seabed as a density current under the influence of ambient hydrodynamic conditions.

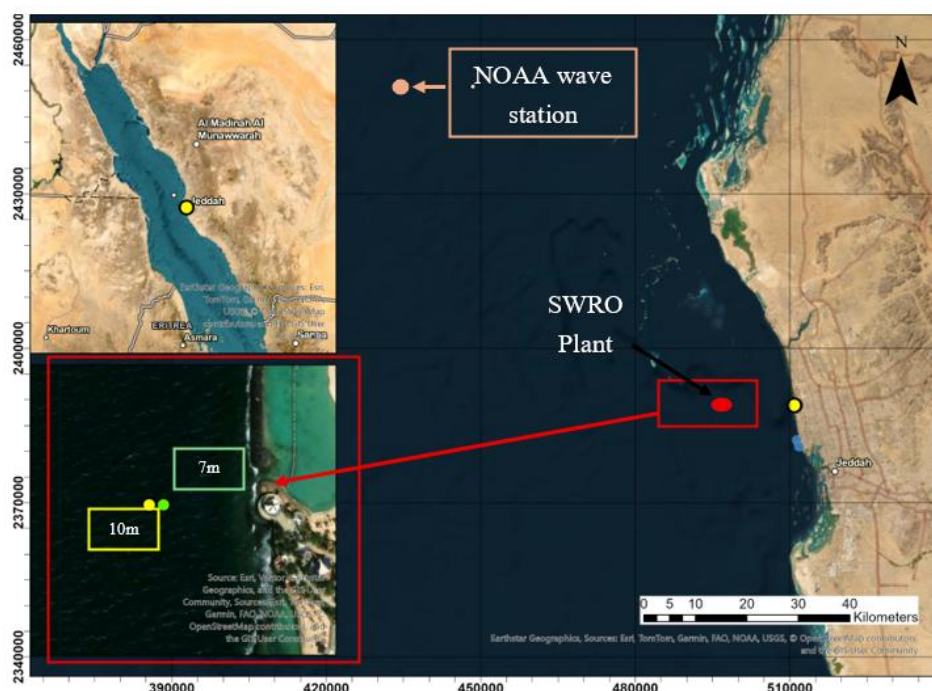


Figure 1: The location of the study area and the desalination plant showing the site of NOAA wave measurement point, location of Scenario A – 7m water depth outfall (green point) and Scenario B – 10m water depth outfall (yellow point).

4. Data Sources

Bathymetry

Bathymetric data were obtained from the General Bathymetric Chart of the Oceans (GEBCO) (17) at a horizontal resolution of 450 m and were supplemented with nearshore field measurements provided by a local bathymetric survey in the study area at a resolution of 50 m. The dataset was processed and imported into the modelling system as scatter data to generate the seabed surface.

The bathymetric data show that the nearshore zone is relatively shallow (less than 30 m depth), while offshore depths increase rapidly to reach – 840 m depth. These steep bathymetric gradients influence the wave and current regimes and thereby affect saline-plume dispersion.

Meteorological, Oceanographic and field Data

Two main categories of datasets are implemented in this study: calibration and simulation dataset. Wave buoy observations from National Data Buoy Center of NOAA (18) during the year 2010 were used for the calibration of the wave numerical model. Also, Acoustic Doppler Current Profiler (ADCP) data were used for calibrating the hydrodynamic model for current speeds and directions, which was deployed near the outfall location at approximately -17 m water depth, and it was the only available data in this area. The ADCP was installed from (10 Jun 2021 – 26 Jun 2021), recording data at 10-minute intervals across multiple vertical layers (17 bins).

Simulation data included wind and wave forcing derived from the ERA5 (19) reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

Hourly significant wave heights, mean wave periods and directions, wind speed and direction were extracted for the years 2010, 2021 and 2024. and applied as surface forcing in the hydrodynamic model. Figure 2 shows the wind speeds and direction during the whole year of 2024. The figure shows that winds predominantly approached from the north and northwest, with a maximum speed of approximately 13 m/s.

Tidal boundary conditions were generated using the MIKE toolbox (20) that uses the Global Tidal Model data (GTM) represents the major diurnal (K1, O1, P1 and Q1) and semidiurnal tidal constituents (M2, S2, N2 and K2) to represent tidal regime of the study area. These tidal waves and wind forcings constitute a portion of the circulation drivers within the study area. The extracted tidal variations for the year 2024 are illustrated in figure 3. The tidal range near the desalination plant reaches around 0.3 m.

Analysis of the predicted hourly tidal elevations for 2024 confirmed that the study area is characterized by a mixed, mainly semidiurnal tidal regime. A harmonic least-squares analysis of the principal constituents produced a tidal form factor, $F = (K_1 + O_1)/(M_2 + S_2)$, of approximately 0.71. This value indicates that the semidiurnal constituents are dominant, while the diurnal constituents remain sufficiently important to produce inequality between successive high and low waters. This classification is consistent with Ahmad and Sultan (11), who reported a form factor of 0.60 and classified the tide at Jeddah as mixed, mainly semidiurnal with diurnal inequality. It also agrees with the regional assessment of Madah et al. (12), which identified a mixed tidal regime dominated by semidiurnal constituents along the eastern coast of the central Red Sea.

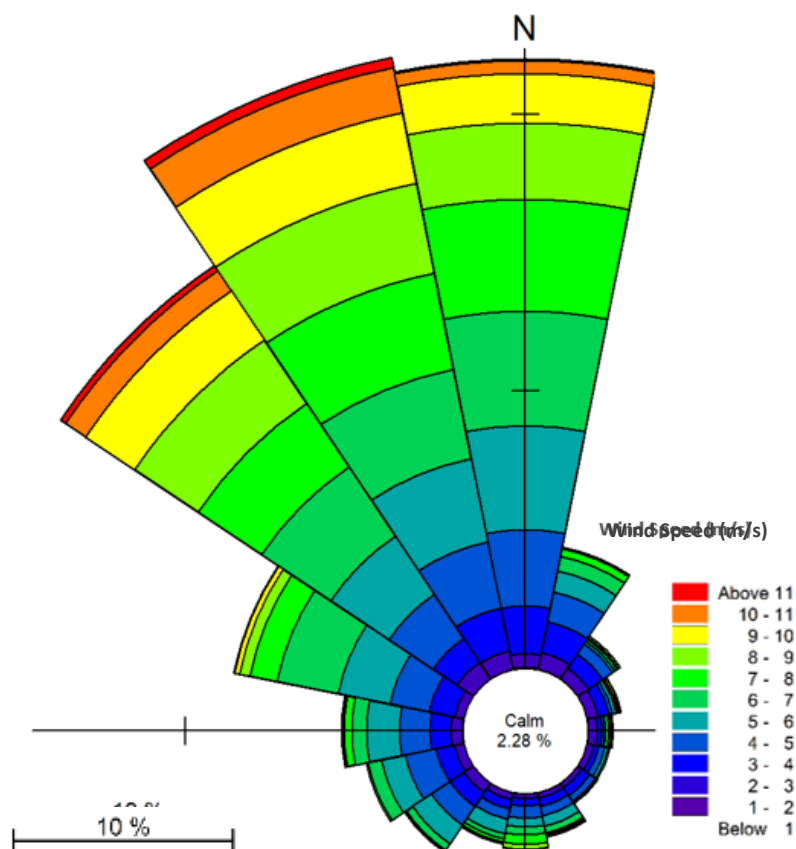


Figure 2: The wind rose showing directions and speeds for 2024.

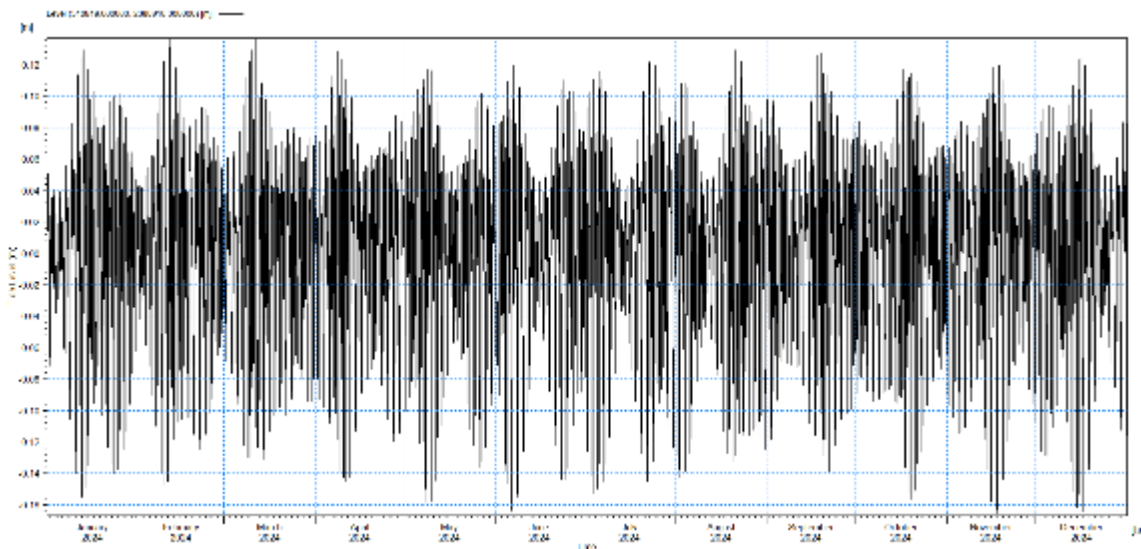


Figure 3: The tidal levels fluctuate near the desalination plant (year 2024).

Numerical Modelling Framework

Spectral Wave Model (MIKE 21 SW)

Wave conditions were simulated using the MIKE 21 Spectral Wave (SW) model. MIKE 21 SW is a third-generation time-dependent spectral wind-wave model based on unstructured meshes (21). It simulates the growth, propagation, decay and transformation of wind generated waves and swells in offshore and coastal areas. The model includes for wave growth due to wind force, interactions between waves of differing frequencies, and energy dissipation caused by whitecapping. Additionally, the model includes shallow water effects such as refraction and shoaling influenced by changing depth, as well as energy dissipation resulting from depth-limited wave breaking and friction with the seabed.

The SW model was used to compute wave fields across the study area, and the resulting radiation stresses were transferred to the hydrodynamic model. This coupling enables representation of wave-current interactions, which significantly influence nearshore circulation and plume dispersion. The key equation for the SW model is the wave-action conservation equation by Komen et al. (22) and Young (23):

$$\frac{\partial N}{\partial t} + \nabla \cdot (\vec{v}N) = \frac{S}{\sigma} \quad (1)$$

where $N(\vec{x}, \sigma, \theta, t)$ is the action density, t is the time, $\vec{x} = (x, y)$ is the Cartesian coordinates. ∇ is the four-dimensional differential operator in the $\vec{x}, \sigma, \theta$ -space. $\vec{v} = (c_x, c_y, c_\sigma, c_\theta)$ is the propagation velocity of a wave group in the four-dimensional phase space $\vec{x}, \sigma$ and θ , and S is the source term for the energy balance equation. The directional discretization applied in the SW model was 360 degrees rose with 18 directions, while the frequency discretization was logarithmic with number of frequencies 25 and minimum frequency 0.055 Hz.

Hydrodynamic Model (MIKE 3 Flow)

Hydrodynamic and transport processes governing brine dispersion were simulated using the three-dimensional (3D) MIKE 3 Flow Model FM. The model solves the three-dimensional incompressible Reynolds-averaged Navier-Stokes equations under the Boussinesq approximation,

allowing simulation of density-driven flows, stratification, and plume dynamics (24). The governing system consists of the continuity equation, momentum equations, and scalar transport equations for salinity and temperature

The conservation of mass for an incompressible fluid is expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

where u , v , and w are the velocity components in the x , y , and z directions, respectively.

The three-dimensional momentum equations describing the flow dynamics are given by:

$$\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial wu}{\partial z} = fv - \frac{1}{\rho_0} \frac{\partial q}{\partial x} - g \frac{\partial \eta}{\partial x} - \frac{1}{\rho_0} \frac{\partial p_A}{\partial x} - \frac{g}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial x} dz + F_u - F_{vx} + \frac{\partial}{\partial z} \left(\nu_t^v \frac{\partial u}{\partial z} \right) \quad (3)$$

$$\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial wv}{\partial z} = -fu - \frac{1}{\rho_0} \frac{\partial q}{\partial y} - g \frac{\partial \eta}{\partial y} - \frac{1}{\rho_0} \frac{\partial p_A}{\partial y} - \frac{g}{\rho_0} \int_z^\eta \frac{\partial \rho}{\partial y} dz + F_v - F_{vy} + \frac{\partial}{\partial z} \left(\nu_t^v \frac{\partial v}{\partial z} \right) \quad (4)$$

$$\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial vw}{\partial y} + \frac{\partial w^2}{\partial z} = -\frac{1}{\rho_0} \frac{\partial q}{\partial z} + F_w - F_{vz} + \frac{\partial}{\partial z} \left(\nu_t^v \frac{\partial w}{\partial z} \right) \quad (5)$$

Here, t denotes time; x , y , and z are the Cartesian coordinates; η represents the surface elevation; and u , v , and w are the velocity components in the x -, y -, and z -directions, respectively. The variable q denotes the non-hydrostatic pressure, while $f = 2\Omega \sin \phi$ is the Coriolis parameter, where Ω is the angular velocity of the earth and ϕ is the geographic latitude. In addition, ν_t^v represents the vertical eddy viscosity, g is the gravitational acceleration, p_A is the atmospheric pressure at the free surface, ρ is the density of water, and ρ_0 is the reference density of water. Finally, $F_v = (F_{vx}, F_{vy}, F_{vz})$ denotes the drag force due to vegetation.

While the salinity and temperature transport are governed by the advection-diffusion equations written as (24):

Salinity Transport

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = F_s + \frac{\partial}{\partial z} \left(D_{ts}^v \frac{\partial S}{\partial z} \right) \quad (6)$$

Temperature Transport

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = F_t + \frac{\partial}{\partial z} \left(D_{ts}^v \frac{\partial T}{\partial z} \right) + \hat{H} \quad (7)$$

where S and T represent salinity and temperature, respectively, and D_{ts}^v is the vertical turbulent diffusion coefficient. The term $\hat{H}$ represents heat exchange processes at the surface.

Model Setup

The numerical framework used two unstructured triangular meshes with different spatial extents. The regional mesh covered approximately $33 \text{ km} \times 19.5 \text{ km}$, corresponding to an area of approximately 644 km^2 , and was used for wave and hydrodynamic calibration and for calculating wave-radiation stresses. It consisted of 46055 elements and 23860 nodes (Figure 4). The horizontal resolution varied from approximately 10 m near the outfall, shoreline and ADCP measurement location to approximately 480 m near the offshore boundaries. A smaller local mesh was subsequently developed for the final brine-dispersion simulations. It consisted of 2137 elements and 1174 nodes, with a minimum characteristic element size of approximately 10 m around the discharge source and a maximum size of approximately 200 m away from the plume-analysis area (Figure 5). The element size increased gradually between the refined and offshore regions to limit numerical errors associated with abrupt spatial transitions. The vertical domain was divided into 17 layers to correspond with the 17 ADCP measurement bins and facilitate comparison between the modelled and observed current profiles. A sigma vertical mesh was implemented to preserve vertical resolution across the shallow and bathymetrically variable study area and to improve representation of the near-bed brine plume. The offshore and nearshore bathymetric datasets were interpolated onto the computational mesh using natural neighbour interpolation method.

The regional domain was selected to include the shallow coastal zone and the offshore bathymetric gradient, to provide sufficient distance for offshore wave transformation, and locate the open boundaries sufficiently far from the outfall and field-measurement locations. The smaller local mesh was used to resolve the site of the plume while maintaining a manageable computational cost.

Mesh quality was examined before model execution through internal angles and element size transitions. The minimum internal angle was 26° . Because the horizontal discretization consisted of unstructured triangular elements, element-angle was used as the principal mesh-quality indicator.

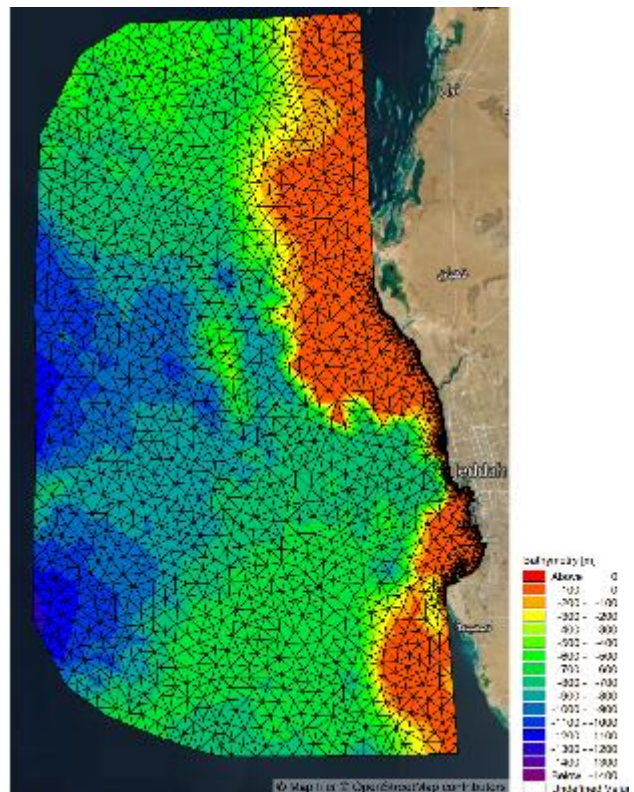


Figure 4: The computation mesh showing the bathymetric variations and fine mesh resolution at the study location

This mesh was implemented in the SW and flow model for calibration purposes. However, a smaller local mesh with greater spatial resolution was used for the final simulations to better resolve saline-plume dispersion while reducing computational cost. This mesh size transformation process was carried out through extraction of wave radiation stress from the calibrated model to cover only the new small mesh.

The brine discharge with a port diameter of 315 mm, was represented in the model as a simple continuous point source located on the seabed at two different depths. In Scenario A, the source was located at coordinates 510919 m Easting and 2388918 m Northing at a depth of -7 m , while in Scenario B, it was located at 510906 m Easting and 2388918 m Northing at a depth of -10 m . The flow rate was constant with $0.0694 \text{ m}^3/\text{s}$, a salinity of 60 PSU, and a temperature of 32.5°C .

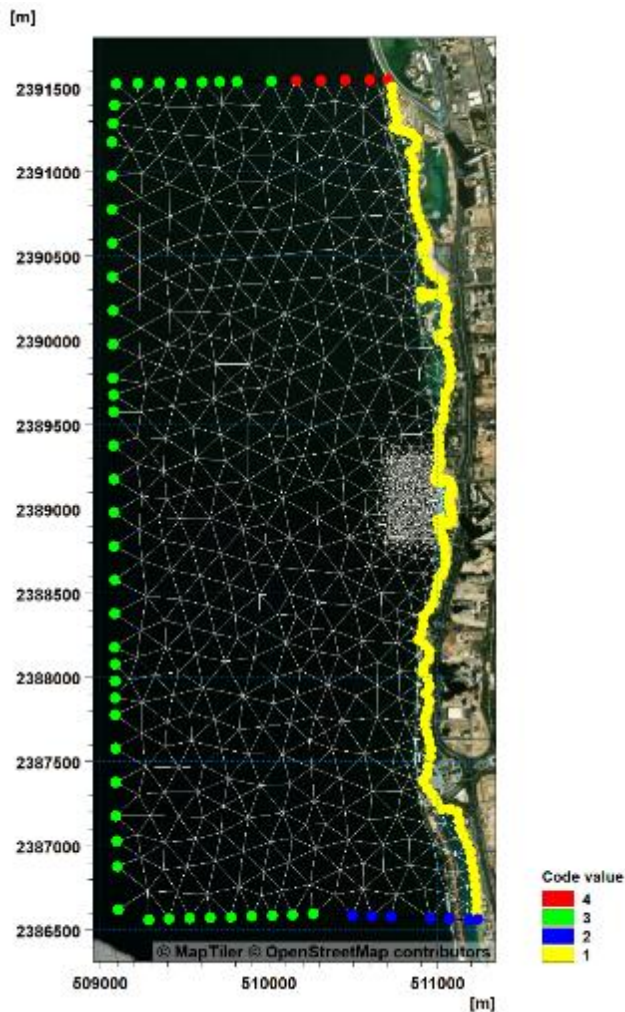


Figure 5: The smaller local mesh with the four boundaries

The computational domain contained three open-water boundaries located along its northern, eastern and southern

limits (Code value 2, 3, 4), while the coastline was treated as a closed land boundary (Code value 1). A zero-normal-flow condition was imposed along the closed shoreline boundary. The open boundaries were forced using time-varying tidal elevations generated through the MIKE tidal prediction toolbox based on the DHI Global Tidal Model. The tidal water-level series were prescribed continuously along the open-boundary segments throughout the simulation period. Adaptive time stepping was applied. The hydrodynamic time step ranged from 0.052 to 0.105 s, while the transport time step ranged from 1.93 to 30 s. The maximum value of 30 s was selected, and smaller steps were automatically applied to maintain numerical stability. Hourly forcing data were interpolated internally at each computational time step. The step interval for the model was selected as one hour following the input data intervals (wave, wind and tide).

The main numerical settings adopted for the coupled MIKE 21 SW–MIKE 3 FM modelling framework are summarized in Table 1. The table consolidates spatial and vertical discretization, forcing conditions, numerical parameters, boundary conditions, and brine-source characteristics used in the simulations.

Table 1: Summary of numerical model configuration and settings

Model component	Parameter / setting	Adopted value / configuration
MIKE 21 SW	Model type	Spectral Wave FM
	Horizontal mesh	Unstructured triangular mesh
	Regional domain	Approx. 33 km × 19.5 km (~644 km ²)
	Regional mesh	46,055 elements; 23,860 nodes
	Horizontal resolution	Approx. 10 m near outfall/shoreline/ADCP to 480 m offshore
	Directional discretization	18 directions over 360°
	Frequency discretization	25 logarithmically spaced frequencies
	Minimum frequency	0.055 Hz
	Main forcing	ERA5 wind and wave data
	Output transferred to MIKE 3	Wave radiation stresses
MIKE 3 Flow FM	Model dimensionality	Three-dimensional
	Local mesh	2,137 elements; 1,174 nodes
	Local horizontal resolution	Approx. 10 m near source to 200 m away from plume-analysis area
	Vertical coordinate	Sigma
	Number of vertical layers	17
	Open boundaries	Northern, eastern and southern boundaries
	Land boundary	Closed shoreline; zero-normal-flow condition
	Tidal forcing	MIKE Global Tidal Model
	Wind forcing	ERA5 hourly wind speed and direction
	Wave forcing	Radiation stresses from calibrated MIKE 21 SW
	Horizontal eddy viscosity	Smagorinsky formulation, coefficient = 0.28
	Vertical eddy viscosity	Log-law; minimum = 1×10^{-6} m ² /s; maximum = 0.4 m ² /s
	Bed resistance	Constant roughness height = 0.05 m
	Wind friction coefficient	0.001255 at 7 m/s; 0.002425 at 25 m/s
	Hydrodynamic time step	Adaptive, 0.052–0.105 s

Brine transport	Transport time step	Adaptive, 1.93–30 s
	External forcing interval	1 h; internally interpolated during computation
	Source representation	Continuous seabed point source
	Source coordinates	510919 m E, 2388918 m N in -7 m scenario, 510906 m E, 2388918 m N in -10 m scenario.
	Discharge rate	0.0694 m ³ /s (~6,000 m ³ /day)
	Brine salinity	60 PSU
	Brine temperature	32.5 °C
	Ambient salinity	39.07 PSU
	Ambient temperature	30.8 °C
	Port diameter	315 mm
	Scenario A	Outfall at 7 m water depth
	Scenario B	Outfall at 10 m water depth

Model Calibration and Validation

Calibration of each numerical model with real observed data is crucial before reaching the simulation runs to ensure the reliability and validity of the model results.

Wave Model Calibration

The spectral wave model was calibrated to minimize the deviations in comparison with the NOAA NDBC buoy station 23020, located in deep water wave buoy data during the same period of measurement. This was undertaken by fine tuning the depth-induced wave breaking parameters, through iterative approach. This validation ensured accurate representation of offshore wave conditions before coupling with the hydrodynamic model.

Hydrodynamic Calibration

The radiation stresses output from the calibrated spectral wave (SW) model were inserted into the hydrodynamic (HD) model to drive the wave-induced currents within the study area. The HD model was subsequently calibrated against the ADCP measurements, including both current speed and direction. Key calibration parameters included bed resistance, wind friction, and horizontal eddy viscosity. Model performance was quantitatively assessed using statistical indicators, namely the correlation coefficient (CC), root mean square error (RMSE), and bias.

The correlation coefficient (CC) is calculated by using the formula below:

$$r = \frac{\sum_{i=1}^n (M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (M_i - \bar{M})^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (8)$$

The correlation coefficient measures the strength and direction between two variables and can be either positive or negative depending on the directionality of the estimate, and it has a range from -1 to 1. A value of 0 indicates no linear relationship between modeled (M) and observed (O) values, whereas a value of 1 indicates perfect positive linear agreement. Negative values indicate an inverse linear relationship.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (M_i - O_i)^2} \quad (9)$$

The root mean square error (RMSE) serves as a broader version of standard deviation that assesses the difference

between a model and its observations in a least-squares approach. By squaring the deviations, both negative and positive contributions are included, while taking the square root returns the units back to those of the original variable. One advantage of RMSE is that it imposes a greater penalty on larger errors. Lower RMSE values indicate a strong correlation between the model and the observations.

$$BIAS = \sum_{i=1}^n \frac{1}{n_i} (M_i - O_i) \quad (10)$$

Model bias is a straightforward statistic that quantifies the average difference between model predictions (M) and observed data (O). It can take on positive or negative values, indicating whether the model overestimates or underestimates the observations, respectively. Similar to RMSE, lower absolute bias values indicate a stronger agreement between the values predicted by the model and the actual observed data.

5. Results

Calibration results

Wave model calibration

Wave-model calibration used NOAA buoy observations from 2010. The process implemented the same period of the measurement to minimize the deviations between the input ERA5 data and the observed data. Several trials were conducted through an iterative approach identifying the best-performing parameter combination through testing different values for wave breaking alpha, gamma and wave steepness gamma. The optimum values were 3 for alpha, 0.85 for gamma, 4 for wave steepness gamma and 3 for whitecapping dissipation coefficient (C_{dis}). These values resulted in a correlation coefficient between significant wave heights of the modeled and observed datasets around 0.85, while the root mean square error (RMSE) and bias reached 0.28 m and -0.009 m, respectively. These results indicate that the model provides an acceptable representation of the general wave conditions for use as forcing in the coupled hydrodynamic simulations. However, the model underestimated some higher-wave events, which may be associated with the relatively low ERA5 wind speeds reported as a limitation in previous studies (25,26,27). Figure 6 shows the distribution of significant wave heights of the modeled (orange) and observed (blue) data.

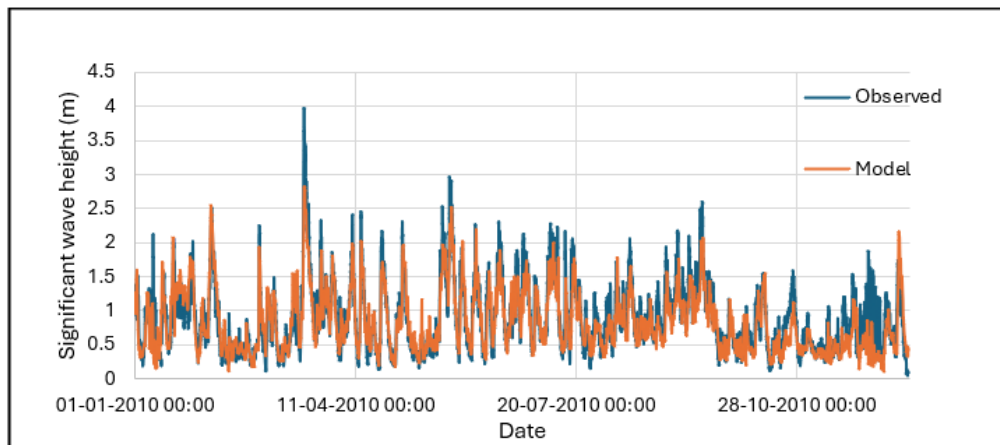


Figure 6: The results of the wave calibration process showing the relation between the modeled (orange) and observed (blue) wave data

Hydrodynamic Calibration results

The results of the hydrodynamic model calibration are concerned with the current speed and direction in the study area. This was undertaken through adjusting the parameters that minimize the variations between the modeled data and the only available ADCP data that was installed near the study area. The calibration parameters that were applied include horizontal viscosity Smagorinsky formulation with value of 0.28 and vertical viscosity log law formulation with minimum value of $1 \times 10^{-6} \text{ m}^2/\text{s}$ and maximum value of $0.4 \text{ m}^2/\text{s}$, wind friction coefficient linear variation with value of 0.001255 at wind speed 7 m/s and 0.002425 at wind speed 25 m/s. Bed resistance was represented using a constant roughness-height formulation. Sensitivity tests showed that variations in

roughness height affected bottom friction and simulated current speeds, particularly in shallow waters. Several values were tested, and a final value of 0.05 m was adopted and applied uniformly because spatially distributed seabed roughness data were unavailable. The results of the calibration process are shown in figure 7. The correlation coefficient for the current speed reached around 74% and RMSE and bias around 0.089 and -0.03 respectively. The current directions of the model and observed data are shown in figure 8.

A summary of the final calibrated parameter values and corresponding model-performance statistics is provided in Table 2.

Table 2: Summary of the calibrated model parameters and quantitative model-performance statistics.

Model	Calibration variable	Calibration data	Main calibrated parameters	Final adopted values	CC	RMSE	Bias
MIKE 21 SW	Significant wave height, H_s	NOAA NDBC buoy observations, 2010	Wave-breaking α ; breaking γ ; wave-steepness γ ; whitecapping C_{dis}	$\alpha = 3.0$; $\gamma = 0.85$; wave-steepness $\gamma = 4.0$; $C_{dis} = 3.0$	0.85	0.28 m	-0.009 m
MIKE 3 FM	Current speed	ADCP measurements	Horizontal eddy viscosity; vertical eddy viscosity; wind friction; bed roughness	Smagorinsky = 0.28; vertical viscosity = 1×10^{-6} – $0.4 \text{ m}^2/\text{s}$; roughness = 0.05 m; wind friction = 0.001255–0.002425	0.74	0.089 m/s	-0.03 m/s
MIKE 3 FM	Current direction	ADCP measurements	Same calibrated HD parameters	Same as above	—	—	—

However, the agreement between the modelled and observed current directions was weaker than that obtained for current speed. The model captured the dominant directional tendency and some of the main directional changes but did not reproduce all short-term fluctuations recorded by the ADCP. Current-direction measurements were available from only one ADCP location and for a limited monitoring period,

which restricts the spatial and temporal assessment of model performance. Furthermore, the ADCP records fluctuations in a single point, whereas the numerical results represent velocities averaged over a computational element and vertical layer. Therefore, the directional calibration demonstrates the model's ability to reproduce the general circulation pattern, but not every instantaneous change in current direction.

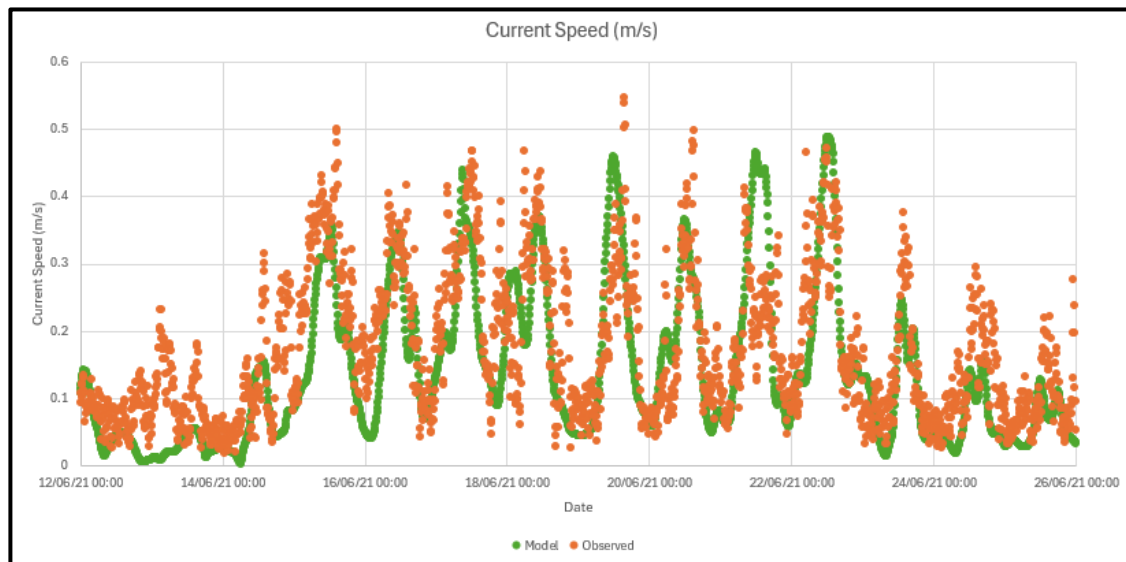


Figure 7: The relation between the modeled (green) and observed (orange) current speeds

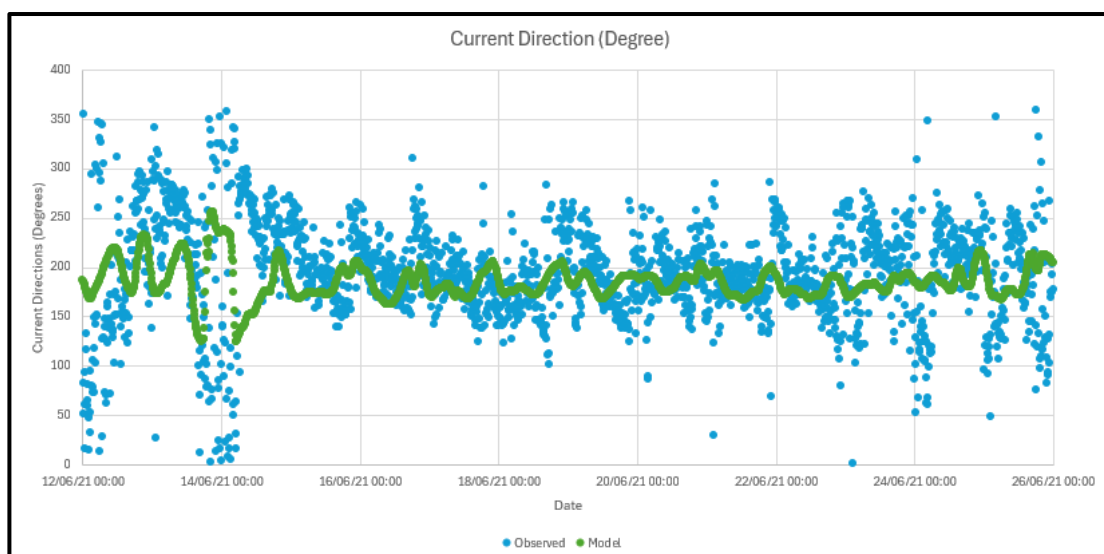


Figure 8: The relation between the modeled (green) and observed (blue) current directions

Simulation results

The results of the numerical model simulations were represented in three classes. These classes were categorized according to the available wind speeds during the year 2024. The three classes are calm conditions (where wind speeds range from 0 to 4 m/s), most frequent conditions (speeds range from 4 to 8 m/s) and heavy conditions (wind speeds ranging from 8 to 12 m/s). These conditions represent around 34%, 55% and 11% duration through the year 2024 for the

calm, most frequent and heavy conditions, respectively. The current speeds and directions under the three conditions are shown in figure 9 to 11. These snapshots represent time steps that were chosen taking into consideration the conditions of the previous time steps to ensure the plume is not under the impact of a different previous condition. This classification was used to evaluate the effects of wind intensity on the dispersion behavior of the brine plume.

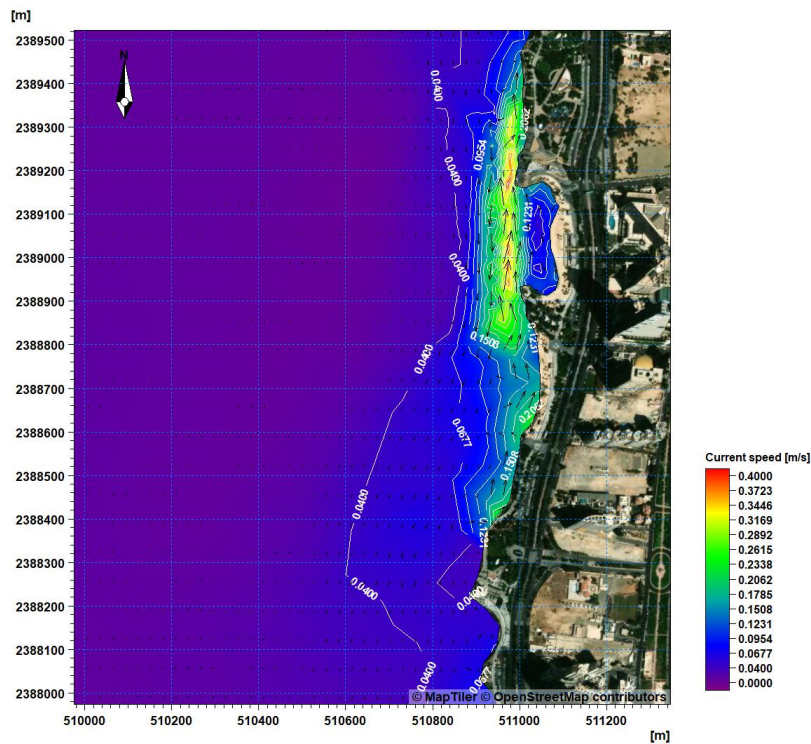


Figure 9: Current speeds and directions in calm conditions (Max. speed: 0.4 m/s, Min. speed: 0.0028 m/s) – Spring tide period

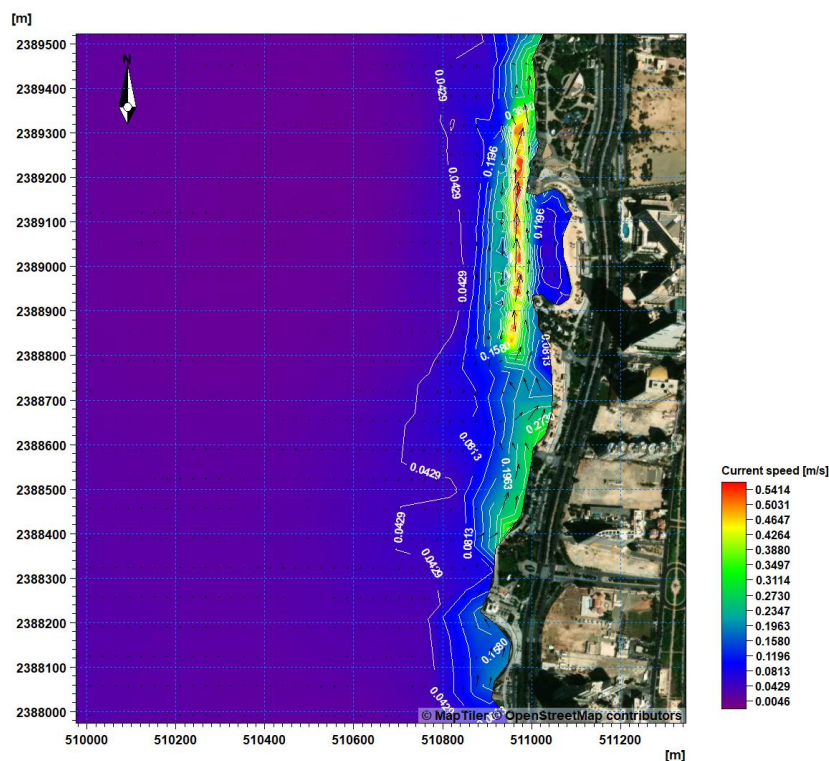


Figure 10: Current speeds and directions in most frequent conditions (Max. speed: 0.535 m/s, Min. speed: 0.03 m/s) – neap tide period

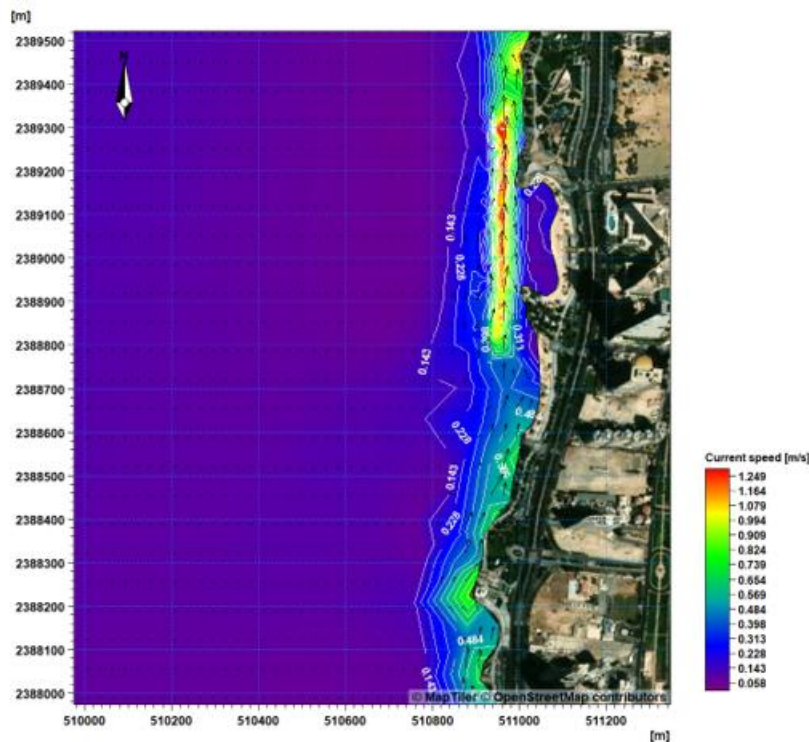


Figure 11: Current speeds and directions in heavy conditions (Max. speed: 1.32 m/s, Min. speed: 0.09 m/s) – neap tide period

This study has conducted two scenarios for the outfall location of the desalination plant. Scenario A the outfall has been placed at a water depth of - 7 m, while Scenario B involved the location of the outfall at - 10 m water depth. The simulations examined saline and thermal plume dispersion under calm, most frequent, and strong wind conditions. The affected distance was identified as the distance from the outfall location at each scenario and the maximum distance that implies an excess salinity above the ambient conditions.

6. Analysis of Results

Scenario A shows that, under calm conditions, the saline plume accumulated more strongly around the outfall area,

indicating limited dispersion and weaker mixing with the surrounding seawater, with the plume influence extending approximately 345 m from the discharge point (Figure 12). Under the most frequent meteorological conditions, the plume extension decreased to about 298 m (Figure 13). However, under heavy meteorological conditions, stronger hydrodynamic mixing enhanced the dilution process, resulting in lower salinity levels near the outfall and reducing the affected distance to approximately 170 m (Figure 14). A similar pattern was observed for thermal dispersion, where calm conditions produced a more localized thermal footprint (Figure 15), while the thermal impact became less pronounced under the most frequent (Figure 16), and heavy conditions due to stronger mixing and dilution (Figure 17).

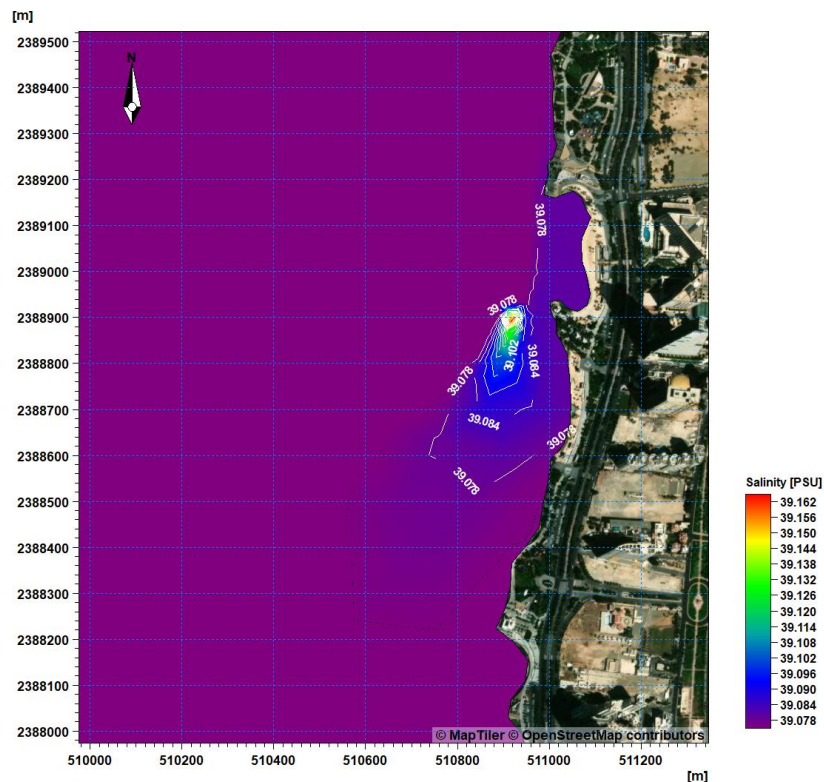


Figure 12: The Saline dispersion under scenario A - calm conditions

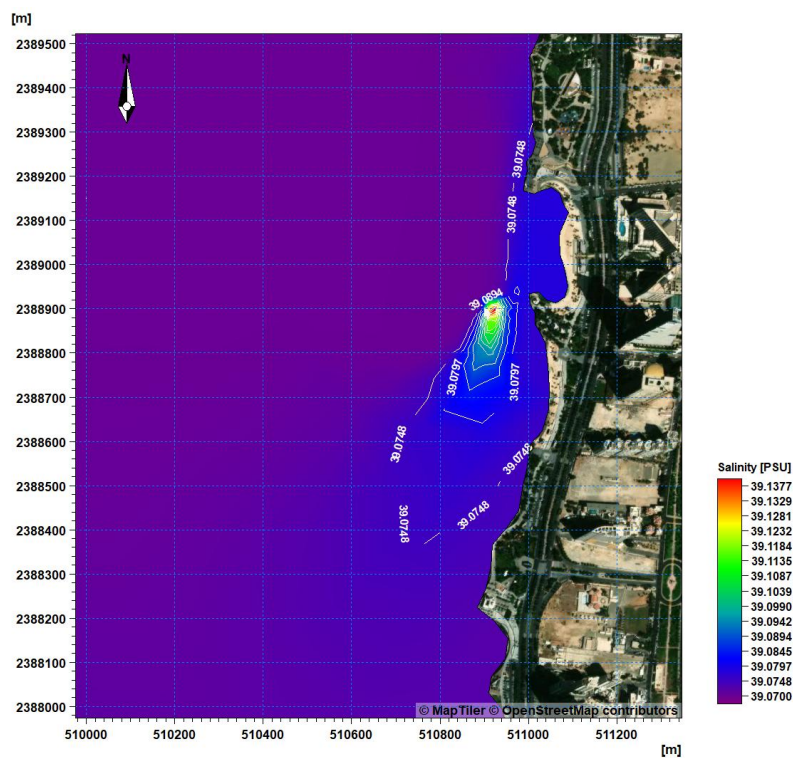


Figure 13: The Saline dispersion under scenario A – most frequent conditions

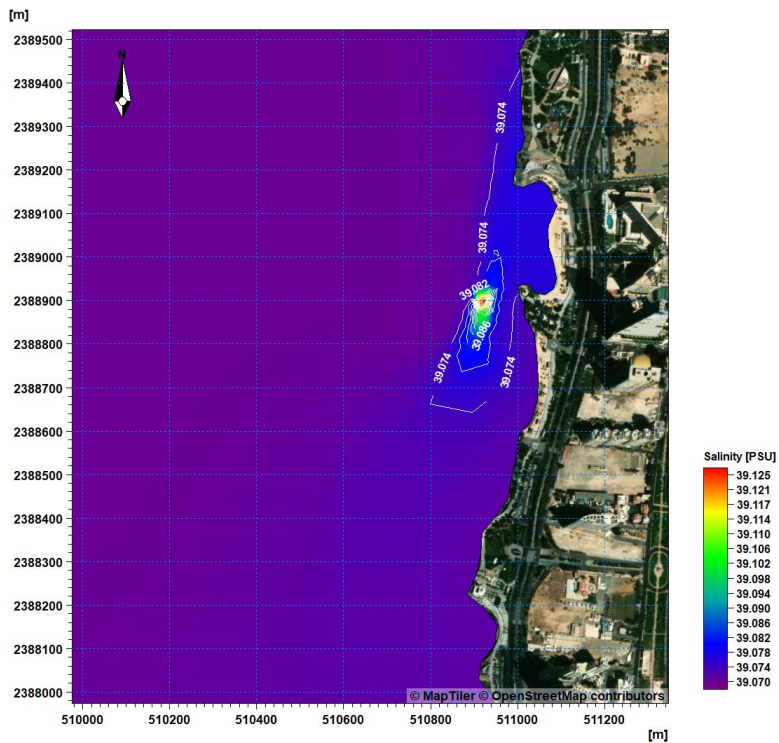


Figure 14: The Saline dispersion under scenario A - heavy conditions

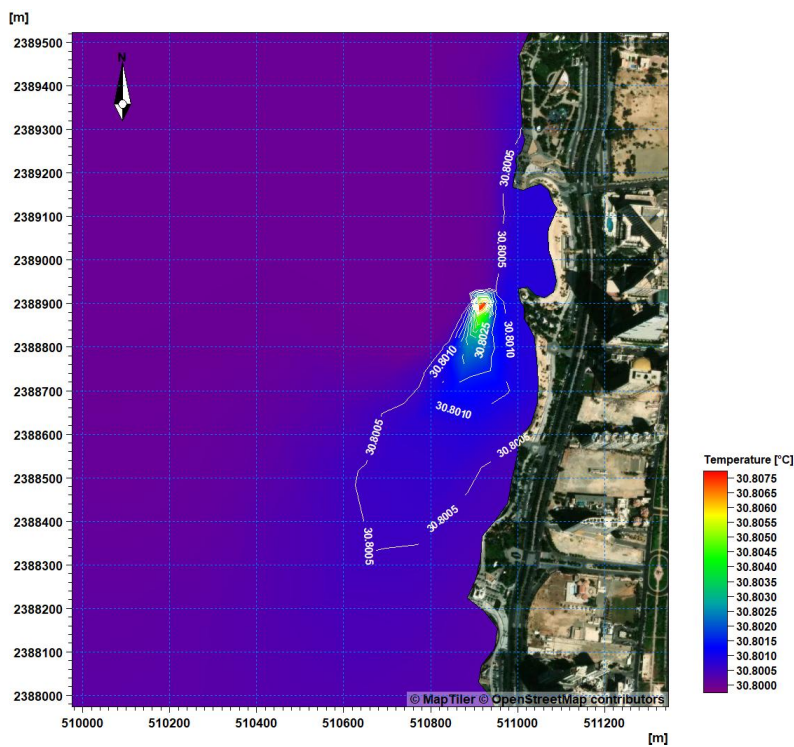


Figure 15: Thermal dispersion under scenario A - calm conditions

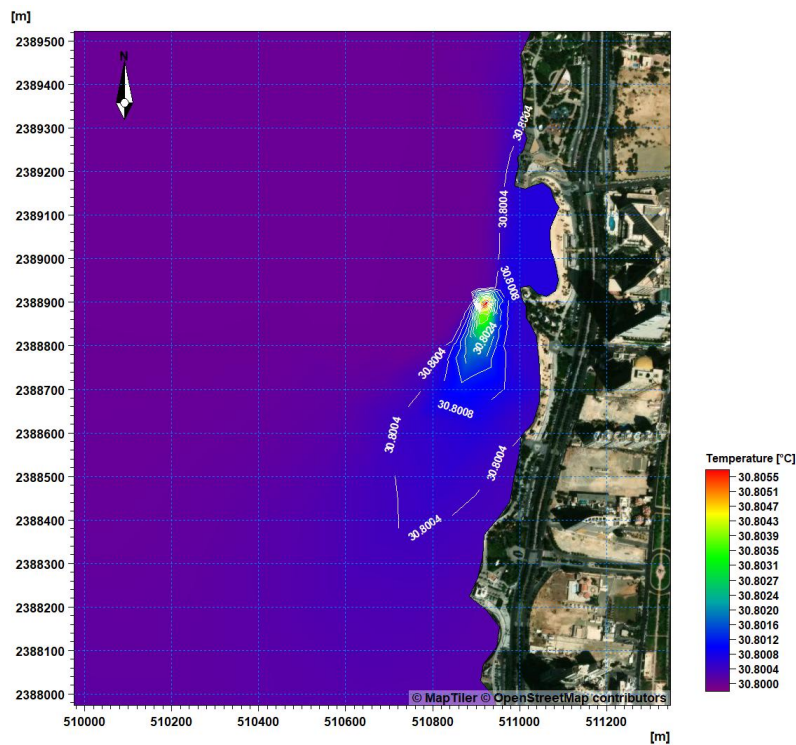


Figure 16: Thermal dispersion under scenario A – most frequent conditions

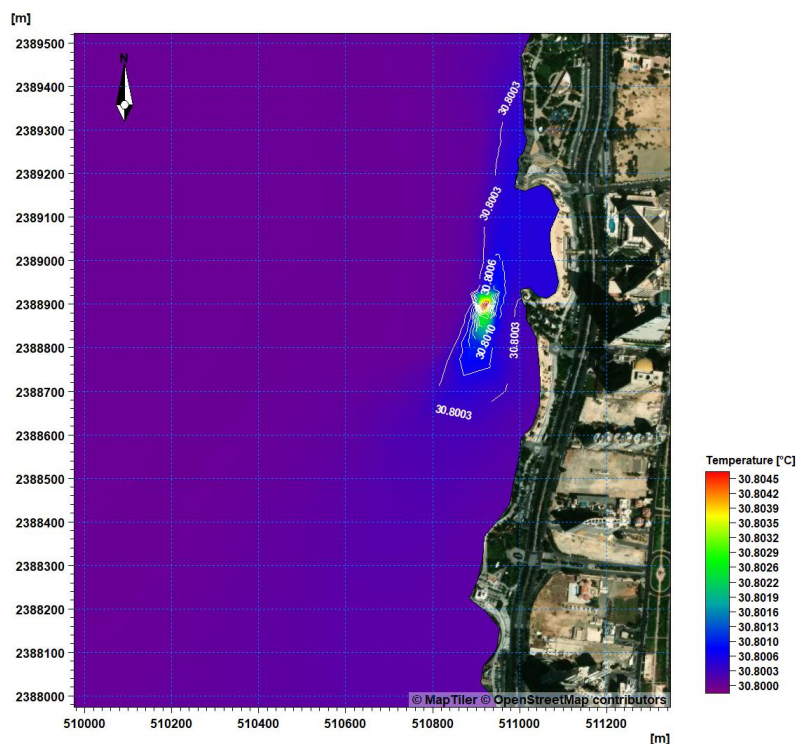


Figure 17: Thermal dispersion under scenario A – heavy conditions

Scenario B showed higher dilution compared with scenario A. The saline plume extension reached approximately 263 m, 200 m, and 143 m under calm, most frequent, and heavy meteorological conditions, respectively. These results

indicate improved mixing and lower salinity accumulation near the discharge location for the deeper outfall configuration. The corresponding plume salinity and thermal distributions for scenario B are presented in figures 18 to 23.

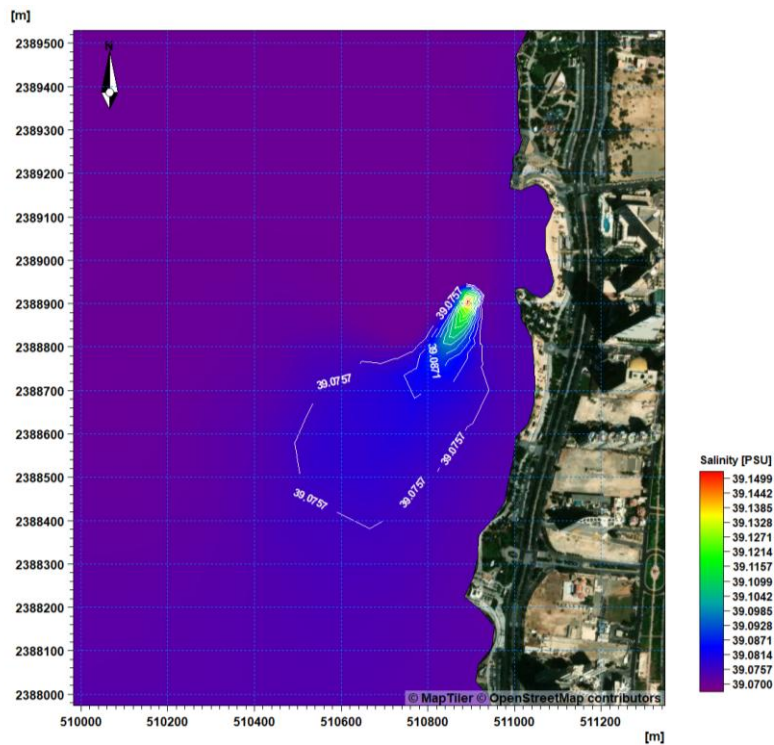


Figure 18: The Saline dispersion under scenario B - calm conditions

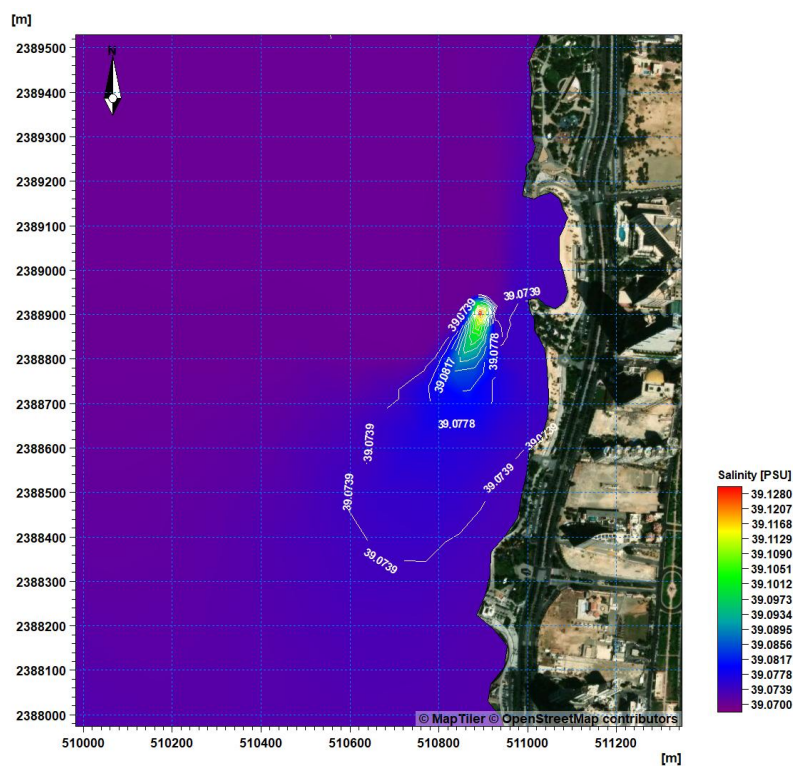


Figure 19: The Saline dispersion under scenario B – most frequent conditions

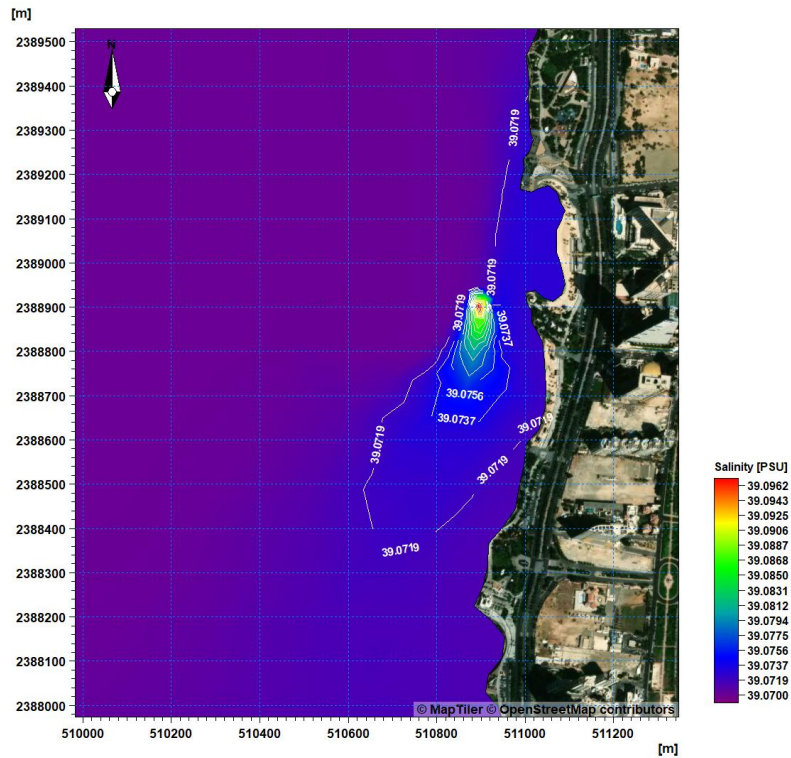


Figure 20: The Saline dispersion under scenario B – heavy conditions

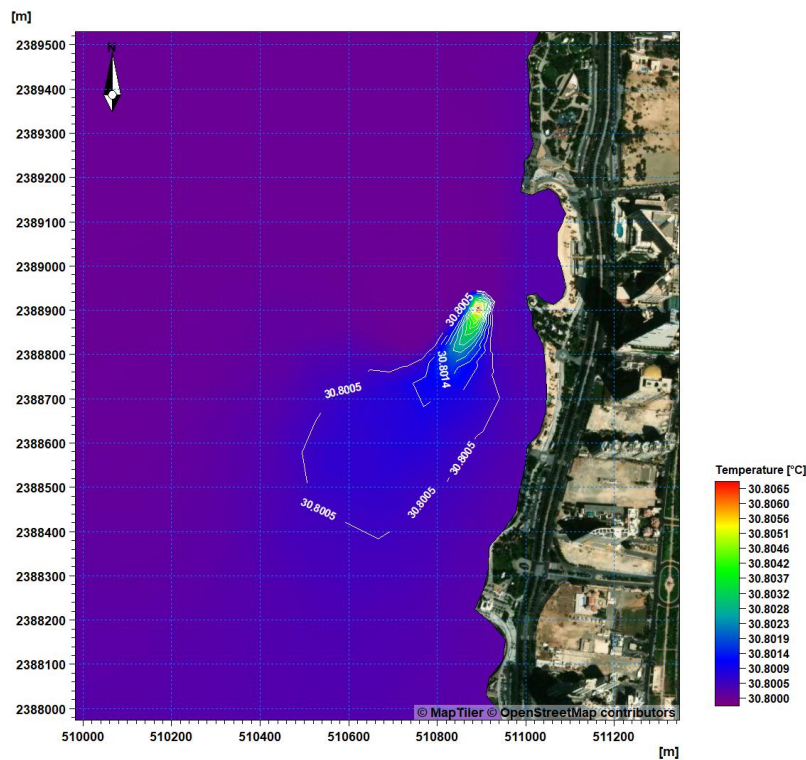


Figure 21: Thermal dispersion under scenario B – calm conditions

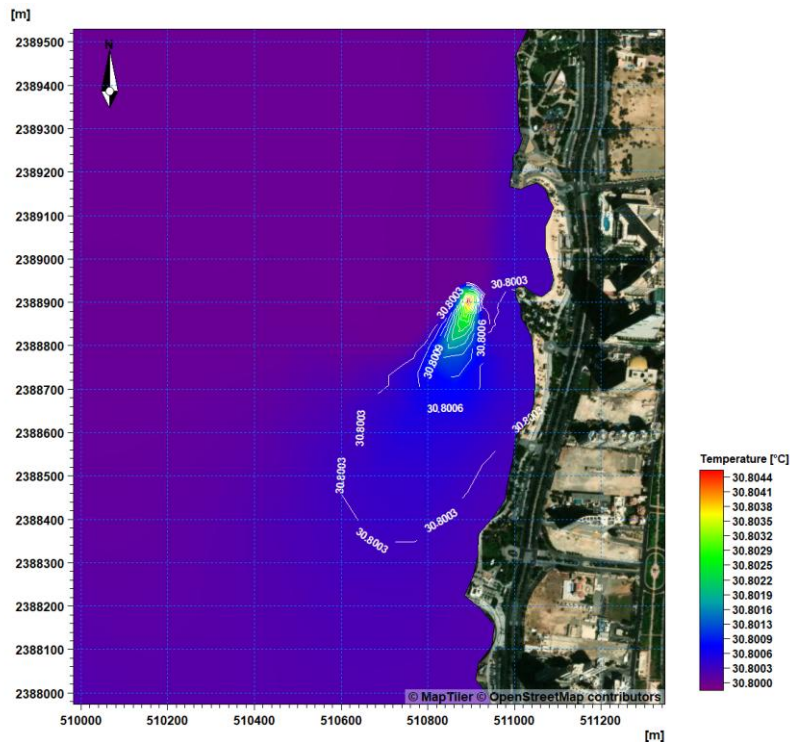


Figure 22: Thermal dispersion under scenario B – most frequent conditions

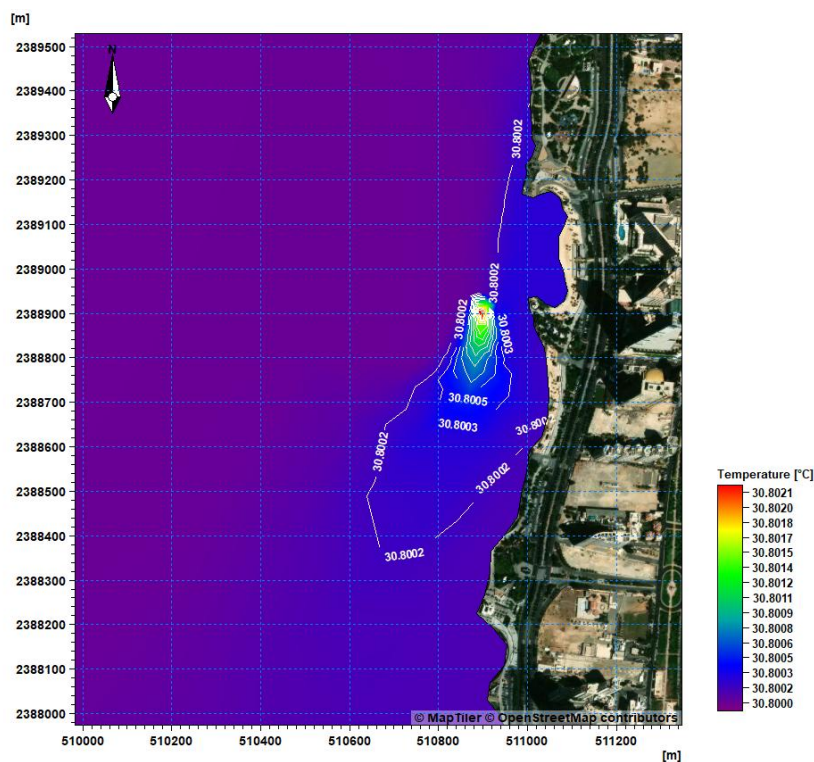


Figure 23: Thermal dispersion under scenario B – heavy conditions

A salinity time series at the outfall point was analyzed for both Scenarios A and B throughout the full year of 2024, as presented in figure 24. The maximum values of the salinity

for the scenarios A and B were 39.5367 and 39.3716, respectively. While the minimum values were 39.1476 and 39.1078, respectively.

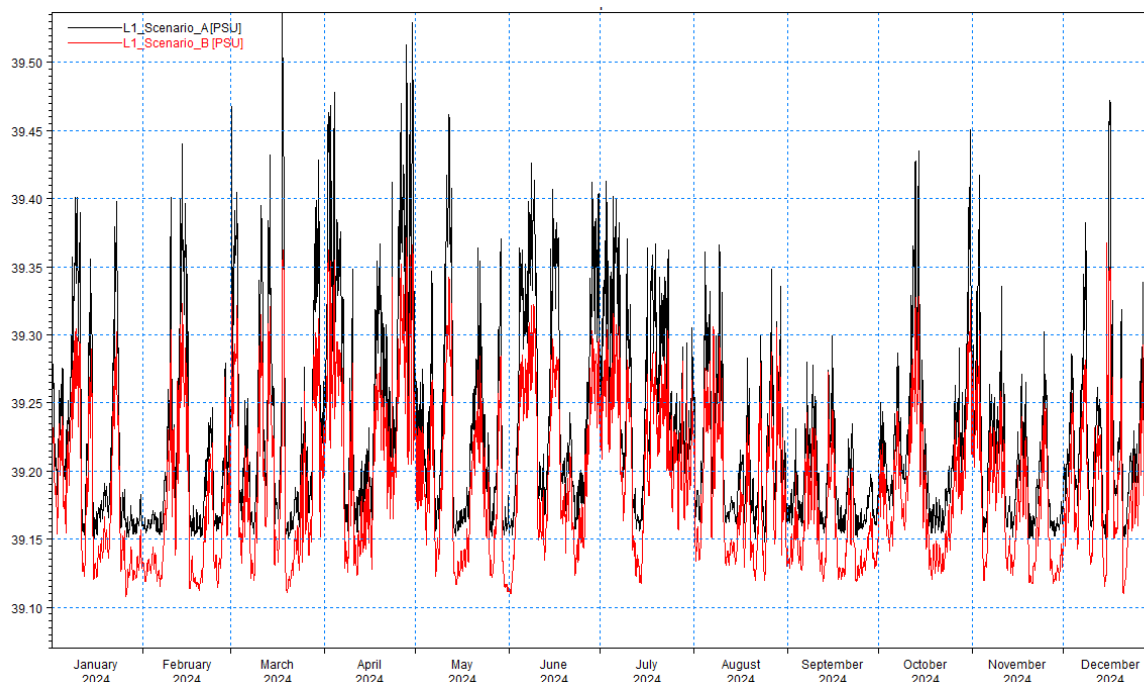


Figure 24: Salinity time series at the outfall point – scenario A (black) and scenario B (red)

The results showed that Scenario B achieved approximately 35.4% higher dilution compared with Scenario A at -7 m depth. This indicates that the deeper outfall configuration provides more effective dilution and reduces salinity accumulation in the immediate vicinity of the discharge point.

7. Discussion

Due to the predominant wind conditions and the corresponding current directions coming from the north and northwest, both scenarios show that the plume dispersion was primarily directed toward the south. The primary factors influencing current speed are wind speed and wave radiation stresses, both of which help to create wave-induced currents. The saline and thermal plume's transport route away from the discharge point was governed by these hydrodynamic conditions.

The calibration results provide reasonable confidence in the ability of the numerical framework to reproduce the principal hydrodynamic conditions controlling plume transport. The wave model achieved a correlation coefficient of 0.85, with an RMSE of 0.28 m and a bias of -0.009 m, indicating good reproduction of the general variation in significant wave height. The hydrodynamic model achieved a current-speed correlation coefficient of 0.74, with an RMSE of 0.089 m/s and a bias of -0.03 m/s. These statistics indicate that the model reproduced the main temporal variation and general magnitude of the observed currents, although the current agreement remained moderate and should not be interpreted as an exact point-by-point reproduction of the measurements.

The hydrodynamic performance is comparable to values reported in other complex coastal modelling applications. For example, Rezaee Mazyak et al. (28) reported a current-speed correlation coefficient of 0.79 and an RMSE of 0.19 m/s for a hydrodynamic model in the Persian Gulf. Such comparisons demonstrate that discrepancies between simulated and measured currents are common in coastal modelling because

the circulation is affected by uncertainties in bathymetry, atmospheric forcing, turbulence parameterization, boundary conditions, and small-scale processes that may not be fully resolved by the computational grid. Therefore, the present calibration is considered suitable for assessing the dominant plume-transport pathways and the relative performance of the two outfall-depth scenarios, rather than for reproducing every short-term fluctuation in the measured current

The reduction in the affected plume distance under stronger wind conditions does not indicate weaker plume transport, but rather stronger mixing and faster dilution. Under calm conditions, the lower current activity allowed the saline and thermal plume to remain concentrated near the discharge point, producing a larger detectable footprint. In contrast, under most frequent and stronger wind conditions, wind-driven and wave-induced currents increased turbulent mixing and reduced the salinity and temperature excess around the outfall. As a result, the plume became less concentrated and the measurable affected distance decreased.

Overall, the results show that both scenarios produced limited nearshore influence under the simulated conditions. However, Scenario B is recommended, as the outfall location at 10 m water depth showed better dilution of salinity and temperature near the beach area. This indicates that placing the outfall in slightly deeper water may improve mixing efficiency, minimize the accumulation of the plume close to the shoreline, and reduce the impact of the desalination plant outfall on the nearshore environment.

The present findings are consistent with Aljohani et al. (10), who used a numerical model to simulate salinity and temperature dispersion from a desalination plant at Yanbu on the eastern coast of the Red Sea. They reported that excess salinity remained below 2 PSU at the discharge location and was lower near the coast under the simulated hydrodynamic conditions. Moreover, the thermal dispersion reported in the study showed negligible excess-temperature values near the

coast, indicating limited thermal impact under the simulated conditions. In a global context, the study of Patel et al. (29), that dealt with the saline dispersion of a desalination plant (using Mike 21 FM numerical model) on the Eastern Coast of India, also reported that the excess salinity level does not exceed 1 PPT during calm and strong hydrodynamic conditions with different outfall distance scenarios.

8. Conclusion

This study assessed the dispersion of concentrated brine discharged from a coastal SWRO desalination plant along the Jeddah coast using a site-specific numerical modelling approach. The combined use of MIKE 21 SW and MIKE 3 Flow FM allowed the main wave, current, salinity, and temperature processes to be represented under the local shallow-water conditions of the eastern Red Sea. The SW model simulated the transformation of offshore waves into the near-shore zone, including wave-breaking processes that generate wave-induced currents and influence saline-plume transport.

The calibration results indicate that the numerical model reproduced the principal hydrodynamic conditions of the study area with acceptable reliability. The simulation results showed that the dispersion pattern was mainly governed by wind-driven circulation and wave-induced currents. Calm conditions produced the largest and most concentrated salinity and temperature plume, while stronger wind and wave activity increased mixing and dilution. In all tested scenarios, plume transport was mainly southward, consistent with the dominant local wind and current patterns. Under the most frequent wind conditions, the affected distance decreased compared with calm conditions.

Both outfall configurations showed limited nearshore impact, but the 10 m outfall depth performed better than the 7 m depth by reducing salinity and temperature accumulation near the beach. This makes the 10 m option the more environmentally suitable configuration under the simulated conditions.

The study's overall findings highlight the significance of site-specific hydrodynamic and dispersion modeling for brine-outfall design, especially in shallow coastal environments where plume dispersion is significantly influenced by winds, waves, currents, and bathymetry.

Further work is recommended using longer field measurements, seasonal simulations, and seabed ecological surveys to better understand the long-term response of the receiving coastal environment.

Collectively, these findings provide a practical basis for the preliminary assessment of small-scale SWRO brine outfalls in shallow urban coastal waters of the central Red Sea and may support NCEC screening of comparable facilities requiring further modeling, field monitoring, or environmental assessment.

9. Future Scope

Future research should extend the present numerical framework through longer field-measurement campaigns,

seasonal simulations, and seabed ecological surveys to improve understanding of the long-term response of the receiving coastal environment. Model validation could also be strengthened by using ADCP measurements from multiple locations and over longer monitoring periods, since the present hydrodynamic calibration relied on observations from a single location and for a limited duration. Further improvement may include the use of spatially varying seabed roughness, rather than the uniform value adopted in the present study due to the absence of detailed seabed-roughness data. Additional observational data may also reduce uncertainty associated with atmospheric forcing, particularly for higher-wave conditions that were underestimated in the present wave-model calibration. Future studies may further examine additional outfall depths, discharge configurations, seasonal conditions, and longer simulation periods to evaluate plume behavior over a wider range of environmental and operational conditions.

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