

École polytechnique de Louvain

A 3D hydrodynamic model to assess the environmental impact of urban and industrial discharges in Qatar

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Abstract

Qatar's rapid coastal development and industrialization have raised growing concerns about the environmental impact of pollutant discharge in the marine ecosystems. In particular, desalination plants, power generation facilities, and stormwater runoff represent major sources of pollution. This thesis aims to assess the environmental impact of these discharges along the coast of Qatar. First, a 3D hydrodynamic model (SLIM3D) is used to simulate current circulation, salinity, and temperature in the Gulf. An Eulerian transport model is then applied to analyze the behavior of various pollutants, including brine, thermal discharge, fecal coliforms (FC), and total suspended solids (TSS). Results show that pollutant dispersion is strongly influenced by the outfall location, with local bathymetry and exposure to current circulation being the most critical factors. Deeper waters and stronger currents enhance dispersion, while shallow and enclosed areas lead to localized accumulation. The density and size of pollutants also play a key role in settling dynamics, which in turn affects the extent of the impacted area. In Doha Bay, an environmental risk assessment reveals that the stormwater discharge primarily affects the vicinity of the outfalls, with negligible risk observed across the rest of the bay. Overall, this study can provide valuable insights into the environmental risks associated with coastal discharge and highlights the importance of outfall location to reduce the ecological impact of the discharge.

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Disclaimer

Some content in this document was produced with the assistance of generative AI tools. These tools were used only to support grammar and style correction. The ideas and concepts presented in this work are entirely the author's own and have not been influenced by AI.

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Chapter 1

Introduction

1.1 Context

The Persian/Arabian Gulf, hereafter referred to as the Gulf, is a semi-enclosed, highly saline, and shallow sea. Most of its depth does not exceed 30 meters, with a maximum depth of around 60 meters. The Arabian shore more specifically has a gentle incline and a relatively flat seabed (Sheppard et al., [2010](#)). The Gulf lies in a low-latitude, subtropical region, resulting in warm temperatures and significant seasonal variations in insolation.

Due to high temperatures and winds originating from the Anatolian and Iranian highlands (the Shamal), the region experiences intense evaporation. The evaporation along the Arabian coast is particularly pronounced due to the shallow shoreline, raising salinity levels over 39 practical salinity units (PSU) in much of the Gulf and even up to 70 PSU in low flushing zones (Burt, [2014](#); Sheppard et al., [2010](#)). These high salinity levels create density gradients, which in turn generate circulation patterns. In the deepest parts of the Gulf, denser saline water exits through the Strait of Hormuz, while at the surface, less saline water from the Indian Ocean enters via the Sea of Oman (Paparella et al., [2022](#)). In the shallower regions, sea dynamics are governed more by tides and by wind, primarily the Shamal from the north and to a lesser extent the Nashi from the east, rather than by density differences (Hanert et al., [2023](#)). Coastal circulation is also influenced by natural features such as sabkhas, mudflats, mangrove swamps, seagrass meadows, and coral reefs (Burt, [2014](#)). In recent years, however, numerous artificial structures have increasingly affected the region's hydrodynamics.

During the past few decades, the coastline of the Gulf has been heavily modified. The development of coastal cities is closely linked with the shoreline geometry of

the Gulf and most of the urbanization of the coast is taking place on reclaimed land, therefore modifying the shoreline and damaging the natural asset of the peninsula. An other consequence is the modification of the circulation pattern and an increase of the residence time (Hanert et al., 2023).

The modifications occurring in the Gulf affect not only water circulation but also pose a significant threat to the environment and biodiversity. Urbanization in shallow waters is particularly concerning because most of the Gulf's photic zone¹ extends only to depths between 6 and 15 meters (Sheppard et al., 2010). The consequences of the construction and inadequate planning include increased sedimentation, odor, turbidity, and fluctuations in pH, all of which negatively impact marine life (Lecart et al., 2024). Furthermore, new infrastructure can contribute to coastal erosion and raise sea temperatures due to the discharge of heated water (Sheppard et al., 2010).

For most Gulf countries, seawater desalination is the primary source of fresh water. According to Paparella et al. (2022), desalination accounts for approximately 2% of the Gulf's net annual evaporation. This proportion could increase to 8% by 2050 and potentially reach 10% in the second half of the century, a magnitude comparable to the inter-annual variability of net evaporation. The brine discharged from desalination plants into the open sea can have salinity levels up to twice that of natural seawater. It is also warmer and may contain pollutants, leading to increases in temperature and salinity (Sheppard et al., 2010). To improve efficiency, desalination facilities are often coupled with power plants, further increasing the stress on the marine ecosystem through thermal discharges. While it is generally assumed that discharged effluents disperses rapidly, this may not be accurate in some of the Gulf's poorly flushed coastal areas. The elevated salinity poses a serious environmental threat, and the temperature difference between the discharged effluents and ambient seawater can adversely affect local flora and fauna. Increased temperature can reduce dissolved oxygen levels, thereby inhibiting marine organism growth. Additionally, high salinity and temperature influence stratification, mixing, and advection-dispersion processes at discharge sites (Aljohani et al., 2022). The Gulf's already elevated salinity levels are further increased by this additional stress, impacting biodiversity through reductions in corals and sea-grass, as well as decreases in fish size and maturity. Elevated salinity also impacts the economic viability of desalination plants, as higher salinity increases operational costs (Paparella et al., 2022). The locations of desalination plants in the Gulf are shown in Figure 1.1. Altogether, the Gulf contains more than 55 plants producing

¹Region of the ocean through which light penetrates and where photosynthetic marine organisms live (European Environment Agency, 2025)

approximately 11 million cubic meters of fresh water daily (Lattemann & Höpner, 2008; Paparella et al., 2022).

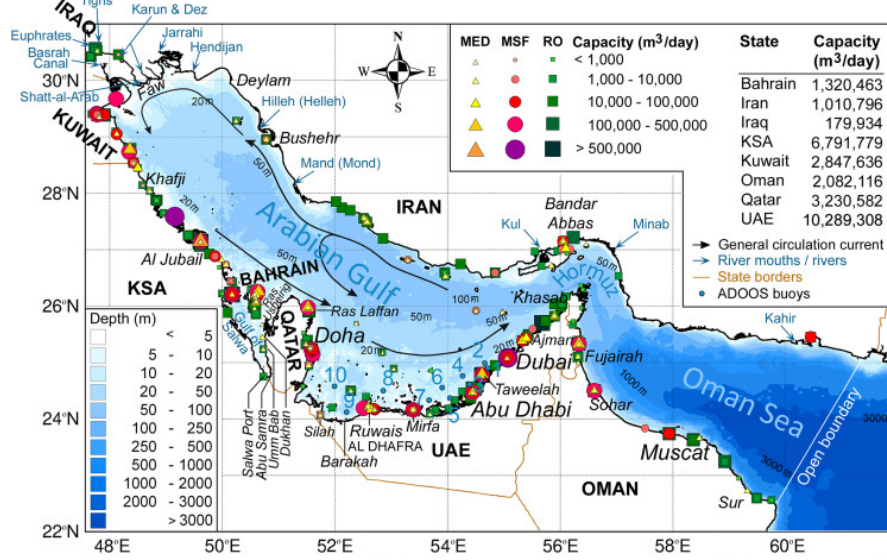


Figure 1.1: Locations of desalination plants displayed on the bathymetry of the Gulf (Nesterov, 2025).

Another source of pollution originates from stormwater outfalls, which discharge effluents that often contains pollutants from urban runoff (Al Mamoon et al., 2016). It is estimated that the Gulf receives around 7300 million cubic meters of stormwater per year. The water discharged from the outfalls contains various harmful pollutants such as nitrogen, fecal coliforms, suspended solids, and petroleum hydrocarbons. This pollution negatively impacts the ecosystem and deteriorates bathing water quality, posing health risks for populations living near the outfalls (Al Mamoon et al., 2020). Unlike desalination plants, stormwater outfalls tend to decrease salinity due to the input of freshwater. This effect is increased by the low circulation in some areas, which limits mixing with seawater (Al Mamoon et al., 2020).

To assess the pollution level of a body of water, it is common to refer to the residence time within a predefined region. A shorter residence time means that pollutants exit the region more quickly and are diluted into a larger water body, reducing their impact. In contrast, a longer residence time can lead to the accumulation of pollutants, negatively affecting water quality (Lecart et al., 2024). As previously mentioned, although the Gulf is relatively large, it is a shallow, semi-enclosed sea with a high evaporation rate and poor flushing characteristics. As a result, residence times in the Gulf can be relatively long, and dilution occurs more

slowly and is more limited than in other marine systems (de Mora et al., 2004). Due to seasonal weather variations, residence times in the Gulf also vary, with slightly higher values in winter than in summer. Combined with the discharge from desalination and power plants, as well as stormwater outfalls, the high residence time increases the environmental risk in the Gulf.

In the particular case of Qatar, the natural shape of the country plays a significant role. As a peninsula, most of Qatar's borders consist of shoreline, totaling around 600 kilometers of coast. This massive amount of land projects far into the Gulf and can influence regional water circulation, potentially generating eddies between Qatar's western coast and the coast of Saudi Arabia (Hanert et al., 2023). Beyond the natural features, major construction projects must also be considered. Over the past four decades, Doha Bay has undergone substantial modification, leading to a reduction in water exchange with the Gulf (Lecart et al., 2024). Key artificial developments include the Pearl Project, Lusail City, the port of Doha, the industrial port of Mesaieed, the LNG terminal at Ras Laffan, and the port of Al Ruwais. These structures contribute to increased spatial variability in coastal circulation by locally intensifying flow in some areas while reducing it in adjacent zones (Hanert et al., 2023).

Moreover, as in most other Gulf countries, Qatar's primary source of fresh water is seawater desalination (de Mora et al., 2004). Qatar's coastline currently hosts three major desalination plants: one in Ras Laffan, another in Ras Abu Fontas, and a third one in Um Al Houl, each combined with power plants. Together, the desalination plants have a capacity of more than 3 million cubic meters per day and the power plants have a capacity exceeding 8000 MW. In addition to these facilities, several stormwater outfalls discharge into coastal waters. Four of these are located in Doha Bay: Souq Waqif, Al-Rumailah, Tennis Court, and Diplomatic Area (Figure 1.2). Among them, the Souq Waqif outfall poses the highest risk of eutrophication² due to its drainage of a significantly larger urban area. Nevertheless, the other outfalls also present environmental risks, particularly in the direct vicinity of the discharge points (Al Mamoon et al., 2020).

The waterfronts and coastal areas in Qatar are some of the most valuable assets of the country in term of biodiversity. Like most of the other countries of the Gulf,

²Overabundance of nutrients in a body of water that results in harmful algal blooms, fish kills, and in some cases ecosystem collapse. It is a process driven by enrichment of water by nutrients, particularly compounds of nitrogen and/or phosphorus, leading to increased growth, primary production and biomass of algae; changes in the balance of nutrients causing changes to the balance of organisms; and water quality degradation (United Nations Office for Disaster Risk Reduction, 2024)

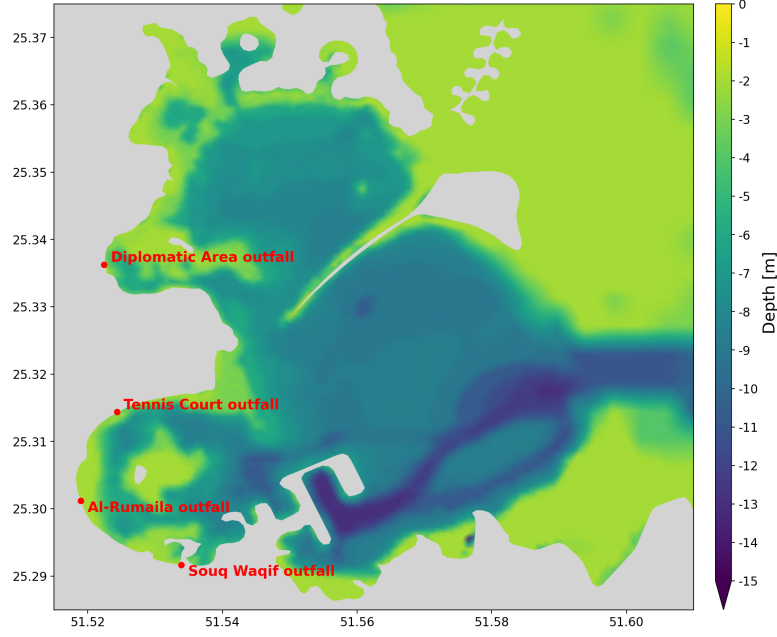


Figure 1.2: Location of the four primary stormwater outfalls in Doha Bay displayed on the bathymetry.

the urbanization is threatening the natural resources such as mangrove trees, coral reefs, seagrass meadows. These ecosystems provide important ecological services, including provision of food and soil formation, as well as being highly productive carbon sink. They also serve as coastal protection to the erosion and to the storms. Qatar also relies heavily on the sea for multiple socioeconomic reasons. Even though the country main sources of revenue are oil and gas (O&G), the seafood is still very valuable for export revenues as well as for local consumption (Burt, 2014). With the increase of population and the recent growing interest of Qatar in hosting major international event such as the FIFA 2022 World Cup, it is therefore important to properly manage the coastal areas to protect them and ensure their longevity.

In Qatar, over the past 20 years, the residence time has increased on average by 40% in winter and 79% in summer, with the most significant rise observed in the southern area of the Pearl Project, where residence time increased up to 90% in winter and 250% in summer (Lecart et al., 2024). The weakening of circulation in the bay and the increase in residence time were primarily influenced by developments occurring after 2000, most of which took place in the northern part of the peninsula. Among these, the Pearl Project is particularly impacting, as it acts as a barrier preventing the southward flow from reaching Doha Bay (Lecart et al., 2024).

1.2 Scope of the thesis

The motivation for this thesis is the growing concern over environmental deterioration in the coastal areas of the Gulf, and more specifically, the coastal areas of Qatar, which serve as the focus of our study. The two main sources of pollution are (1) the hot brine discharged from desalination and power plants, inducing an increase in temperature and salinity, and (2) the stormwater discharged through sea outfalls. While stormwater contains various pollutants, our study focuses on fecal coliforms (FC) and total suspended solids (TSS). The impact of these pollutants is further increased by recent extensive urbanization along the shoreline, particularly large construction projects such as the Pearl Project, Lusail City, the port of Doha, the industrial port of Mesaieed, and the LNG terminal of Ras Laffan. These developments pose major threats to the shallow-water ecosystem due to the destruction of marine life and the increased residence time, which increases the negative effects of pollution.

While other studies have already investigated the residence time inside the Gulf and the influence of urbanization (Hanert et al., 2023; Lecart et al., 2024), they consider only a two-dimensional approach by assuming that the shallow waters on the Arabian side of the Gulf can be approximated by a 2D barotropic model. The advantage of the 2D approach is that it allows more resources to be focused on the spatial resolution of the model while still providing a good representation of the overall dynamics. However, the simulated hydrodynamics represent only the average behavior of the entire water column, assuming uniform density throughout the domain and a variation of the pressure only depending on the water depth, without being affected by salinity or temperature gradients.

In our study we investigate the water quality in five key areas: Ras Laffan, Ras Abu Fontas, and Um Al Houl, which host major desalination and power plants; Mesaieed, containing a significant power plant; and Doha Bay with four stormwater outfalls (Diplomatic Area, Tennis Court, Al-Rumailah, and Souq Waqif). A 3D baroclinic model is employed, implemented using the Second-generation Louvain-la-Neuve Ice-ocean Model (SLIM, www.slim-ocean.be), to simulate hydrodynamics and pollutant dispersion patterns. The analysis focuses specifically on thermal discharge and brine effluent from industrial facilities, along with FC and TSS from urban runoff. The goal of the research is to evaluate the environmental impacts of these discharges and assess their potential long-term effects on marine ecosystems.

Chapter 2

Materials and methods

2.1 General approach

In order to assess the impact of the urbanization and industrialization of the coastal area of Qatar, we analyze the impact of the desalination plants, the power generation facilities, and the stormwater outfalls. The modeling is divided in three steps, with the goal of evaluating the environmental impact of the thermal discharge from power plants, the brine effluents from desalination plants, and the pollutants discharged into Doha Bay at the sea outfall.

The first step is the modeling of the hydrodynamics of the Gulf using the multi-scale Second-generation Louvain-la-Neuve Ice-Ocean Model (SLIM). SLIM is a multi-scale hydrodynamic model that uses an unstructured mesh to simulate ocean circulation flows. It achieves remarkable accuracy by using the Discontinuous Galerkin finite element method to solve the governing equations. One of the advantages of SLIM is that it contains multiple modules, including SLIM1D, SLIM2D, SLIM3D, and an ensemble of Lagrangian and Eulerian transport models, allowing it to be used in a range of different environments. In this work we primarily use the SLIM3D module, which can model complex barotropic and baroclinic flows by accounting for the vertical dimension, as well as the Eulerian transport model to simulate the dynamics of tracers such as pollutants and sediments. The model has been developed at UCLouvain for over a decade and has already been successfully applied to multiple areas of interest, including Lake Tanganyika (Delandmeter et al., 2018; Sterckx et al., 2023), the Congo River (Vallaey et al., 2021), Florida’s coastal water (Alaerts et al., 2022), Lake Titicaca (Duquesne et al., 2021), and the Columbia River (Vallaey et al., 2018).

In the second step, the currents obtained from SLIM3D are used to simulate pollutant dispersion via the Eulerian transport model. This allows for the study of pollutant transport and dispersion based on currents, while incorporating sedimentation velocity and decay rate to accurately represent the behavior of the studied substances. The pollutants of focus are the FC and the TSS present in the stormwater discharged into Doha Bay.

Lastly, the impact of desalination and power plants is assessed by analyzing increases in salinity and temperature in the affected area. In Doha Bay, an environmental risk assessment is conducted using a methodology similar to that of Al Mamoon et al. (2020) to evaluate the impact of FC concentrations on bathing water quality and the effects of hazardous contaminants adhered to suspended solids. This approach considers pollutant impact, exposure duration, spatial extent of contamination, and the probability of occurrence of pollutant discharge.

2.2 Study area

This study focuses on the eastern coast of Qatar, extending from the shoreline up to approximately 50 kilometers offshore into the Gulf. This region was selected due to its concentration of key urban and industrial facilities which can cause significant environmental concerns, particularly with regard to water quality degradation.

One of the most critical hotspots is the capital city, Doha, where most of the population of the country is located. Urban expansion projects such as The Pearl and Lusail City in the north and the Hamad International Airport on the south have significantly altered the coastal landscape. These developments have reduced water circulation within Doha Bay, making the area particularly susceptible to the accumulation of pollutants (Hasna et al., 2024). This study focuses on the four major marine outfalls that discharge into Doha bay: one located in the Diplomatic Area (north embayment), and three in the south embayment, located in Tennis Court, Al-Rumailah, and Souq Waqif.

The second focus of this study concerns the desalination and power plants, which contribute to environmental stress through thermal discharges and the release of hypersaline brine. These discharges can adversely affect marine ecosystems by altering temperature and salinity profiles (Lattemann & Höpner, 2008; Roberts et al., 2010). The study highlights four major facilities located in Ras Laffan, Ras Abu Fontas, Um Al Houl, and Mesaieed.

2.3 Hydrodynamics

This section is based on the work of Scherpereel (2022), Vallaes et al. (2018), and Van Eetvelt (2024), informations from the SLIM Wiki¹, and with the additional help of C. Scherpereel (personal communication, April 25, 2025).

2.3.1 Mathematical model

Domain

The domain on which SLIM3D solves the three-dimensional hydrostatic Boussinesq equation is denoted Ω , and can be represented as in Figure 2.1. The position vector is defined in the cartesian coordinate system as $\mathbf{x} = (x, y, z)$ with x and y the horizontal coordinates and z the vertical coordinate. The domain is defined by a moving surface boundary Γ_s , and two fixed surfaces, the bottom boundary Γ_b and the lateral boundary Γ_l . Depending on the location of the lateral boundaries, they can either be closed if they correspond to the coastline or open if they correspond to the rest of the Gulf. The bottom boundary correspond to the seafloor and is located in $z = -h(x, y)$ with $h(x, y)$ the bathymetry. The top boundary Γ_s is defined in reference to a fixed surface layer $\Gamma_{s,0}$ ($\eta = 0$) which correspond to the sea surface at rest. As the sea surface is time dependent, Γ_s correspond to the moving surface located at $z = \eta(t, x, y)$. The total water depth is thus $H(t, x, y) = h(x, y) + \eta(t, x, y)$.

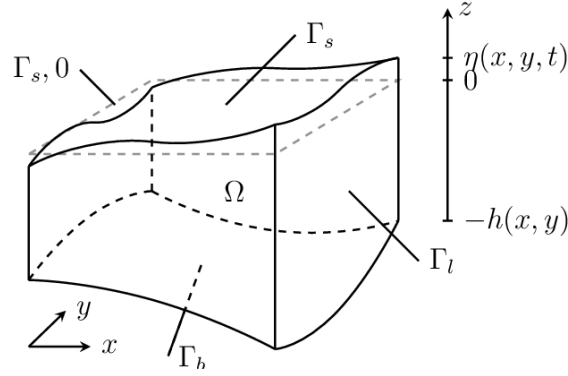


Figure 2.1: Representation of the domain Ω defined by the two fixed boundray Γ_b and Γ_l , and the moving boundary Γ_s located in $\eta(t, x, y)$. Source Delandmeter (2017).

¹<https://forge.uclouvain.be/slim-enge/scripts>

Model Assumptions

The equation used by SLIM3D are derived from the Navier Stokes equations and are solved under the hydrostatic hypothesis and the Boussinesq approximation. The first assumption states that the pressure gradient balances the weight of the water column. The Navier Stokes vertical momentum equation can thus be reduced to :

$$\frac{\partial p}{\partial z} = -\rho g , \quad (2.1)$$

where $p(t, x, y, z)$ is the hydrostatic pressure [N.m^{-2}], g is the gravitational acceleration [m.s^{-2}], and $\rho(t, x, y, z)$ is the density [kg.m^{-3}]. When integrating from z to η , it yields:

$$p = p_a + \int_z^\eta \rho g dz, \quad (2.2)$$

$$= p_a + g\rho_0(\eta - z) + g \int_z^\eta (\rho - \rho_0) dz, \quad (2.3)$$

where $p_a(t, x, y)$ is the atmospheric pressure [N.m^{-2}], $\rho_0 = 1027$ [kg.m^{-3}] is the constant reference seawater density and $\rho - \rho_0$ is the density deviation.

The Boussinesq approximation assumes that density variations are much smaller than the reference density ($\rho - \rho_0 \ll \rho_0$). Consequently, these variations can be neglected in all terms of the momentum equation, except for the gravitational term. The exception for the gravity field is due to the fact that gravity is considered to have a sufficiently large magnitude to make the fluid's specific weight significant.

Equations

There are five governing equations that need to be solve by SLIM3D and a supplementary equations for the computation of the density. The output of these equations is a temporal sequence of six hydrodynamic variables which are presented in Table 2.1.

Variable	Description	Units
$\mathbf{u}(t, \mathbf{x})$	Horizontal velocity field	[m.s^{-1}]
$w(t, \mathbf{x})$	Vertical velocity component	[m.s^{-1}]
$\eta(t, x, y)$	Sea surface elevation	[m]
$S(t, \mathbf{x})$	Salinity	[PSU]
$T(t, \mathbf{x})$	Temperature	[°C]
$p(t, \mathbf{x})$	Hydrostatic pressure	[N.m^{-2}]

Table 2.1: List of variables used in the model

Momentum equation This equation is derived from the principle of momentum conservation, which states that the change of momentum within a domain is proportional to the sum of the forces acting on the system. It can be written as follows:

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla_h \cdot (\mathbf{u}\mathbf{u}) + \frac{\partial(w\mathbf{u})}{\partial z} = \nabla_h \cdot (\nu_h(\nabla_h \mathbf{u}) + \frac{\partial}{\partial z} \left(\nu \frac{\partial \mathbf{u}}{\partial z} \right) - f \mathbf{e}_z \wedge \mathbf{u} - \frac{1}{\rho_0} \nabla_h p \quad (2.4)$$

where ∇_h is the horizontal gradient operator and f the Coriolis force [s^{-1}] defined as:

$$\nabla_h = \frac{\partial}{\partial x} \mathbf{e}_x + \frac{\partial}{\partial y} \mathbf{e}_y, \quad (2.5)$$

$$f = 2 \Omega \sin \phi \quad (2.6)$$

with $\Omega = 7.29 \times 10^{-5}$ the rotation of the Earth [rad.s^{-1}] and ϕ the latitude. ν and ν_h are respectively the vertical and horizontal eddy viscosity [$\text{m}^2.\text{s}^{-1}$]. The later one is defined following the Smagorinsky (1963) closure scheme:

$$\nu_h = \alpha \Delta^2 \sqrt{2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2} \quad (2.7)$$

where α is a non-dimensional constant and Δ^2 is the surface of the horizontal section of the 3D mesh element.

Continuity equation The continuity equation is based on the principle of mass conservation, which states that the change in mass within the domain Ω is equal to the net mass flow across its boundary. It reads:

$$\nabla_h \cdot \mathbf{u} + \frac{\partial w}{\partial z} = 0 \quad (2.8)$$

Pressure equation Using the hydrostatic hypothesis (Equation (2.3)), it is possible to derive an expression for the horizontal pressure gradient which depends on the atmospheric pressure p_a , the height of the water column, and the density of the fluid ρ . By applying the horizontal gradient operator ∇_h and dividing by ρ_0 , one obtains:

$$\frac{1}{\rho_0} \nabla_h p = \frac{1}{\rho_0} \nabla_h p_a + g \nabla_h \eta + \frac{g}{\rho_0} \nabla_h \int_z^\eta (\hat{\rho}(S, T) - \rho_0) dz \quad (2.9)$$

where $\hat{\rho}(S, T)$ is the density calculated with the state equations from Jackett et al. (2006).

Temperature equation The equations for the temperature is found by using the advection-diffusion equation:

$$\frac{\partial T}{\partial t} + \underbrace{\nabla_h \cdot (\mathbf{u}T)}_{Advection} + \frac{\partial(wT)}{\partial z} = \underbrace{\nabla_h \cdot (\kappa_h \nabla_h T)}_{Diffusion} + \frac{\partial}{\partial z} \left(\kappa \frac{\partial T}{\partial z} \right) \quad (2.10)$$

where κ_h and κ are the horizontal and vertical diffusivity respectively [$\text{m}^2.\text{s}^{-1}$]. The vertical diffusivity κ and the vertical eddy viscosity ν from the momentum equation (Equation (2.4)) can be determined from the $\kappa - \epsilon$ turbulence closure model (Kärnä et al., 2012) with Canuto A stability functions (Canuto et al., 2001). For the horizontal diffusivity κ_h , it is the parametrization of Okubo (1971) that is used:

$$\kappa_h = c\Delta^{1.15} \quad (2.11)$$

with c the Okubo coefficient and Δ the mesh size.

The temperature surface boundary equation can than be written as:

$$\kappa \frac{\partial T}{\partial z} = -(Q_{nudg} + Q_{surf} + Q_{pen}) \quad (2.12)$$

where Q_{nudg} is an additional heat flux that is imposed at the surface to nudge the value of the temperature to the observed values. It is computed as:

$$Q_{nudg} = \frac{\Delta z_s (SST_{obs} - T)}{\tau_s} \quad (2.13)$$

with SST_{obs} the Sea Surface Temperature which is retrieved from Copernicus' OSTIA product, τ_s the relaxation period and Δz_s the the depth over which the relaxation is applied. The second term of Equation (2.12) is Q_{surf} . It is the surface heat flux which is made of a combination of 4 other components: the heat transfer through turbulent air motion for sensible and latent fluxes, Q_{sens} and Q_{lat} respectively, and the heat transfer through radiative forcing for thermal (longwave) and solar (shortwave) radiation, respectively Q_{LW} and Q_{SW} . Theses fluxes are retrieved from the ECMWF's ERA5 global reanalysis and the surface heat flux is computed as follows:

$$Q_{surf} = \frac{-(Q_{sens} + Q_{lat} + Q_{LW} + 0.77 Q_{SW})}{\rho c_p} \quad (2.14)$$

The last term of Equation (2.12) is Q_{pen} which is the heat flux that effectively penetrates the water surface due to the short wave radiation (Q_{SW}). It is defined as:

$$Q_{pen} = \frac{-(0.23 Q_{SW})e^{-\frac{(\eta-z)}{d}}}{\rho c_p} \quad (2.15)$$

with $d = 19.1$ [m] the penetrating distance (or less if the bathymetry is shallower), and C_p the specific heat capacity of seawater [$\text{J.kg}^{-1}.\text{K}^{-1}$].

Salinity equation The salinity equation is defined similarly to the temperature equation:

$$\frac{\partial S}{\partial t} + \underbrace{\nabla_h \cdot (\mathbf{u}S) + \frac{\partial(wS)}{\partial z}}_{\text{Advection}} = \underbrace{\nabla_h \cdot (\kappa_h \nabla_h S) + \frac{\partial}{\partial z} \left(\kappa \frac{\partial S}{\partial z} \right)}_{\text{Diffusion}} \quad (2.16)$$

The variables of the equation are the same as for the temperature equation but the salinity surface boundary equation reads differently:

$$\kappa \frac{\partial S}{\partial z} = S(P - E) - Q_{nudg} \quad (2.17)$$

with P the precipitation which is retrieved from ECMWF's ERA5 reanalysis, and E the evaporation which is computed from the latent heat flux and the latent heat of vaporization L_e .

$$E = \frac{-Q_{lat}}{\rho L_e} \quad (2.18)$$

Finely the surface nudging defined as:

$$Q_{nudg} = \frac{\Delta z_s (SSS - S)}{\tau_s} \quad (2.19)$$

where SSS is the Sea Surface Salinity that is retrieved from the Nucleus for European Modelling of the Ocean (NEMO).

External mode The external 2D mode is used to compute the surface elevation $\eta(t, \mathbf{x})$. It relies on the depth average velocity $\bar{\mathbf{u}}(t, \mathbf{x})$ given by the shallow water equation:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (H \bar{\mathbf{u}}) = P - E, \quad (2.20)$$

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + (\bar{\mathbf{u}} \cdot \nabla_h) \bar{\mathbf{u}} + f \mathbf{e}_z \wedge \bar{\mathbf{u}} = -g \nabla_h \eta + \frac{\nu}{H} \nabla_h \cdot (H \nabla_h \bar{\mathbf{u}}) + \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho_0 H} + P - E \quad (2.21)$$

where τ_s and τ_b are respectively the surface and bottom stresses, and $\bar{\mathbf{u}}$ is defined as:

$$\bar{\mathbf{u}} = \frac{1}{H} \int_{-h}^{\eta} \mathbf{u} dz \quad (2.22)$$

Boundary condition The boundary conditions are different depending on which boundaries they are applied on. The closed lateral boundaries (coast) as well as the bottom boundary are impermeable:

$$\mathbf{u} \cdot \mathbf{n}_h = 0 \quad \mathbf{x} \in \Gamma_l , \quad (2.23)$$

$$w + \mathbf{u} \cdot \nabla_h h = 0 \quad \mathbf{x} \in \Gamma_b , \quad (2.24)$$

where $\mathbf{n}_h(x, y) = (n_x, n_y)$ is the horizontal unit vector normal to Γ_l .

The surface boundary is subject to precipitations and evaporation and the boundary condition writes as follow:

$$w - \frac{\partial \eta}{\partial t} - \mathbf{u} \cdot \nabla_h \eta + P - E = 0 \quad \mathbf{x} \in \Gamma_s , \quad (2.25)$$

Additional boundary conditions need to be applied on the top surface to account for the wind stress $\boldsymbol{\tau}_s$, and to the bottom surface to account for the friction $\boldsymbol{\tau}_b$. These can be expressed as follow:

$$\nu \frac{\partial \mathbf{u}}{\partial z} = \frac{\boldsymbol{\tau}_b}{\rho_0} \quad \mathbf{x} \in \Gamma_b , \quad (2.26)$$

$$\nu \frac{\partial \mathbf{u}}{\partial z} = \frac{\boldsymbol{\tau}_s}{\rho_0} \quad \mathbf{x} \in \Gamma_s . \quad (2.27)$$

The bottom friction is computed using the law of the wall and a logarithmic profile velocity. The bottom roughness is set to $z_{0b} = 10^{-4}$ [m] for sandy bottom and to $z_{0h} = 5 \times 10^{-1}$ [m] for rough surface such as areas with seagrasses, coral reefs, and mangroves.

2.3.2 Numerical model

To solve the hydrodynamic equations presented previously, SLIM3D uses the Discontinuous Galerkin (DG) finite element method applied on an unstructured 3D mesh. Unlike the Continuous Galerkin (CG) methods, the DG doesn't require the continuity of the solution between neighboring elements. Each element is considered as a separate entity on which the solution can take different values. This will, however, increase the number of degrees of freedom per element, which results in a higher computational cost than CG methods. To optimize the use of resources, the unstructured mesh allows to refine the resolution near the areas of interest while maintaining a coarser resolution in other parts of the domain. This adaptive meshing strategy helps balance precision and computational workload. A well-designed unstructured mesh has multiple advantages: it allows describing the topography more accurately, capturing small-scale flow features, and it also

reduces the computational cost of the simulation.

In SLIM3D, each internal 3D mode is coupled with an external 2D mode. Several 2D time steps are required to compute the variables used at each 3D time step. The number of 2D time steps mainly depends on the mesh elements size and the number of vertical layers. Consequently, high-resolution simulations become significantly more expensive in terms of computational cost. Maintaining a coarser resolution in less critical areas helps reduce this cost.

The combination of DG with unstructured meshing also enables the use of parallel programming and high-performance computing (HPC). By dividing the 3D domain into multiple local subsets that can be handled in parallel, simulation time is significantly reduced. To take full advantage of these capabilities, this work uses the latest version of SLIM3D, which runs on GPUs. To optimize performance on GPUs, numerical time integration is performed using explicit methods. These methods are easier to implement than implicit ones but are less stable and require smaller time steps to ensure convergence.

The first step to create the mesh is to define the 2D unstructured mesh, which will then be extruded vertically to form the 3D mesh. The generation of the mesh is made using the *seamsh* Python library which uses GMSH², a 3D finite element mesh generator with built-in CAD engine and post-processor. GMSH allows building meshes whose resolution can depend on multiple criteria. The first criteria is the distance from the coastline. As a coastal ocean model, SLIM is usually used to capture small-scale ocean circulation in topologically complex coastal areas. The mesh resolution is thus refined near the coast and kept coarser in deeper areas. The second criteria is the presence of particular features such as coral reefs, seagrass meadows, and coastal infrastructure. The mesh can also be refined based on other criteria such as bathymetry or bathymetry gradients.

When extruding the 2D mesh to create the 3D mesh, one must first choose the number of vertical layers to use and an appropriate stretching function. The 3D mesh is extruded along the Z -axis so that all nodes and triangles are superimposed in a way that ensures alignment in the vertical direction. Just like the size of the triangles, the spacing between 2D surfaces (or the layer thickness) depends on the level of refinement needed. SLIM3D has three stretching functions available: the base function, the Song and Haidvogel (1994) (SH) stretching, and the Siddorn and Furner (2013) (SF) stretching. An illustration of the three stretching is given on Figure 2.2. The base function is the simplest and relies only on a parameter

²<https://gmsh.info>

$\alpha \geq 1$ to define the stretching. The larger the value of α or the greater the number of layers, the closer the surface layers will be to each other. For $\alpha = 1$, there is no stretching, and all layers are equally spaced. The SH and SF stretching methods are more complex and allow for the division of the domain into two parts depending on water depth, applying different stretching functions in each. The SH function can control the stretching near the surface with a parameter $\theta_s \in]0; 20]$. the larger its value, the closer together the layers will be above the critical depth h_c . The second parameter is $\theta_b \in [0; 1[$. A small value will increase resolution near the surface, whereas a higher value shares the resolution between the surface and the bottom. The SF stretching uses a critical depth h_c as well but has three other parameters. The first parameter $\alpha \geq 1$ (not to be confused with the parameter of the base function) controls the dispatch of the stretching. The higher its value, the more stretching is applied to the surface and the lower its value, the more stretching is applied to the bottom. The two other parameters are ΔZ_s and ΔZ_b which specifies the value of the surface and bottom layer. The SF method is slightly more complex than SH but provides greater flexibility in specifying layer thickness at the top and bottom of the domain, making it preferable for our study. Since the Gulf has a shallow bathymetry, the number of layers was set to 10 to achieve a good compromise between having enough layers in the deepest regions and avoiding excessive layers in the shallower parts.

Depending on the type of application, different types of layers can be used, each having advantages and drawbacks. SLIM supports three types of layers represented on Figure 2.3: z -layers, which traverse the domain at fixed depths (staircase-like); σ -layers, which follow the bathymetry; and hybrid layers, which combine the two. Z -layers are the most computationally stable and can capture sharp bathymetry gradients but, due to their "staircase" nature, do not represent bathymetry smoothly. On the other hand, σ -layers give a better representation of the bathymetry but they are less stable than z -layers, especially in areas with strong bathymetry gradients. The hybrid system combines σ -layers for shallow bathymetry and z -layers for deeper areas. Depending on the type of bathymetry, different layers will be used. σ -layers are used in shallow depth to give a good representation of the hydrodynamics while Z -layers will be used in deeper bathymetry to avoid instability and sometimes reduce the number of layers at high depths.

In the case of the Gulf, the bathymetry is quite shallow and has mostly a gentle slope, which allows for the use of σ -layers. However, as mentioned earlier, σ -layers can be unstable. Since the layers follow the bathymetry, the elements top and bottom surfaces won't be horizontal, specially in regions with highly variable bathymetry. To avoid any issues, the mesh must be constructed such that every

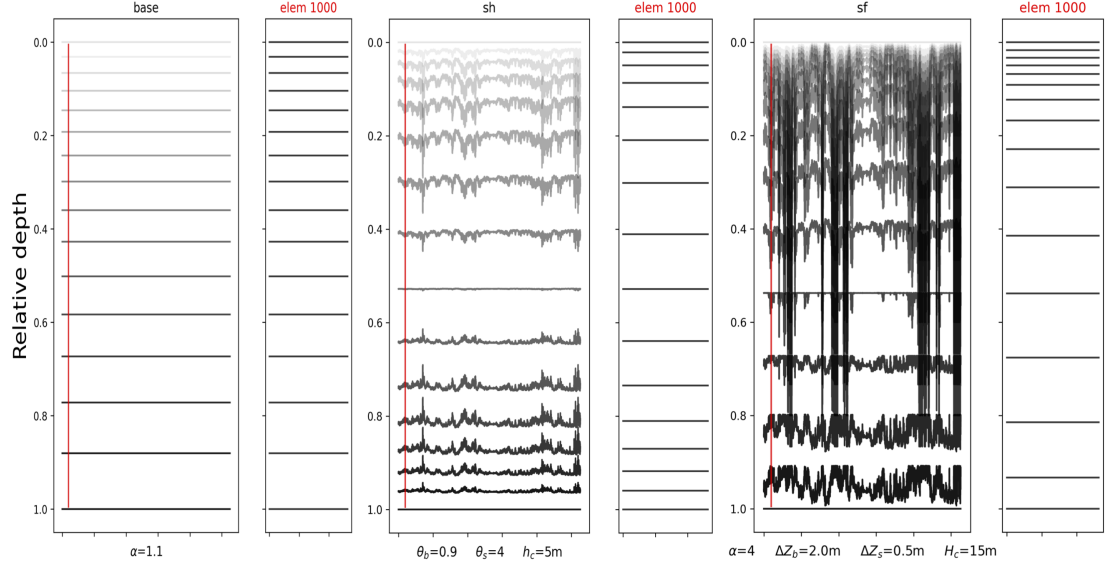


Figure 2.2: Illustration of the 3 types of stretching. The number of layers is set here to $n_z = 15$. The layers for the base function are all horizontal because the thickness of each given layer is the same everywhere in the domain. For visualization purpose the smaller plot shows the stretching for the element 1000 which is highlighted in red on the on the bigger plots. The parameters of each stretching function are shown at the bottom of the plot.

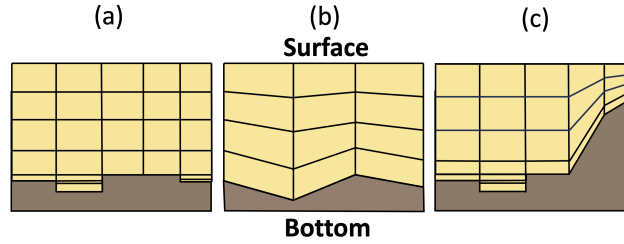


Figure 2.3: (a) Z -layers, (b) σ -layers, and (c) hybrid $Z - \sigma$ layers

node of every surface is positioned lower than its neighboring node on the upper surface and higher than its neighboring node on the lower surface. This can be expressed by respecting the Haney (1991) criterion:

$$\left| \frac{\sigma}{h} \frac{\delta h}{\delta x} \right| \Delta x < \Delta \sigma \quad (2.28)$$

with $\sigma = -z/h$ the vertical coordinate in the σ -layer system, z the vertical coordinate measured from the sea surface reference level, h the local bathymetry, δh the horizontal change of bathymetry between two neighboring nodes, and Δx the horizontal grid interval. The previous equation is equivalent to:

$$\frac{\Delta h}{h} < \frac{\Delta \sigma}{\sigma} \quad (2.29)$$

Figure 2.4 represent the different parameters of the mesh and how the vertical and horizontal resolution can be adapted to comply with the Haney criterion. Essentially, when the bathymetry gradient becomes too steep, the mesh must be refined horizontally or coarsened vertically.

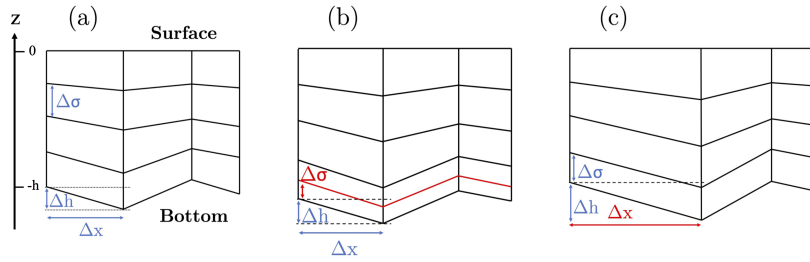


Figure 2.4: (a) The Haney criterion is respected. (b) The vertical resolution is too high which leads to $\Delta \sigma$ being too small. (c) The horizontal resolution is too coarse which leads to Δx being too big.

While the Haney criterion ensures numerical stability, it is not strictly required, meaning it is a sufficient condition but not a necessary one and it can be too restrictive in some situations. A less restrictive alternative is the Haidvogel criterion (Beckmann & Haidvogel, 1993), which introduces a slope parameter (r) defined as the ratio between the slope of the computational layer and the average local depth $\bar{h}$:

$$r = \frac{|\delta h|}{2\bar{h}} \quad \text{with} \quad 0 < r < 1 \quad (2.30)$$

The slope parameter is such that the simulation will get more stable as r tends to 0.

Depending on the type of stretching used when extruding the 2D mesh, the criterion to use will be different. The Haney criterion is only use with the base stretching, and the Haidvogel criterion is used for the SH and SF stretching. In this work it is therefore the Haidvogel criterion that is used. In order to satisfy this criterion, a preliminary bathymetry smoothing step is applied during the extrusion of the 2D mesh. Since the mesh cannot be modified once it has been created, the only available solution is to smooth the bathymetry to ensure the criterion is met throughout the domain. However, this approach comes with a drawback: reducing bathymetry gradients also diminishes the accuracy of the simulated hydrodynamics. In this study, the smoothing is controlled by a maximum slope value $r_{\max}$, such that the bathymetry is adjusted until the condition $r < r_{\max}$ is satisfied everywhere on the domain.

The final mesh is represented on Figure 2.5 and is made of a 2D mesh made of 50,323 nodes and 96,710 triangles, and extruded on 10 σ -layers which means that the 3D mesh has 967,100 prism. For the 2D mesh used in this work, the general rule is to have a default resolution of 800 meters along the coast, decreasing to 5 kilometers offshore. The mesh is further refined to a resolution of about 100 meters around the areas of interest which are: Ras Laffan, Doha Bay, Ras Abu Fontas, Um Al Houl, and Mesaieed. It is also refined to a resolution of about 100 meters near the Pearl Project and Lusail City due their proximity of Doha Bay and their complex topography. A final adjustment is made around the coral reefs, seagrass meadows, and mangroves, refining the mesh to 800 meters to capture potential perturbations in the Gulf's flow. As mentioned previously, the stretching used the SF functions. The parameters for these functions are $\alpha = 3$, $\Delta Z_b = 2$, $\Delta Z_s = 1$, and $h_c = 10$. The bathymetry smoothing parameter is $r_{\max} = 0.2$.

2.3.3 Forcing data

External forcings play a important role in driving ocean circulation and must thus be taken into account to produce realistic simulations. The model requires both initial conditions and time-varying boundary conditions to accurately represent the physical environment. The time dependent forcings encompass wind stress, tidal forces, large-scale oceanic currents, and density gradients, each influenced by multiple ocean variables. The forcings are derived from external numerical models and observational datasets which are detailed hereafter.

The bathymetry has a significant influence on the model, making it crucial to obtain the most accurate data possible. In this work, most of the bathymetry data is extracted from the GEBCO (General Bathymetry Chart of the Oceans) model, which has a 15-arc-second (450 meters) resolution. Even though GEBCO is

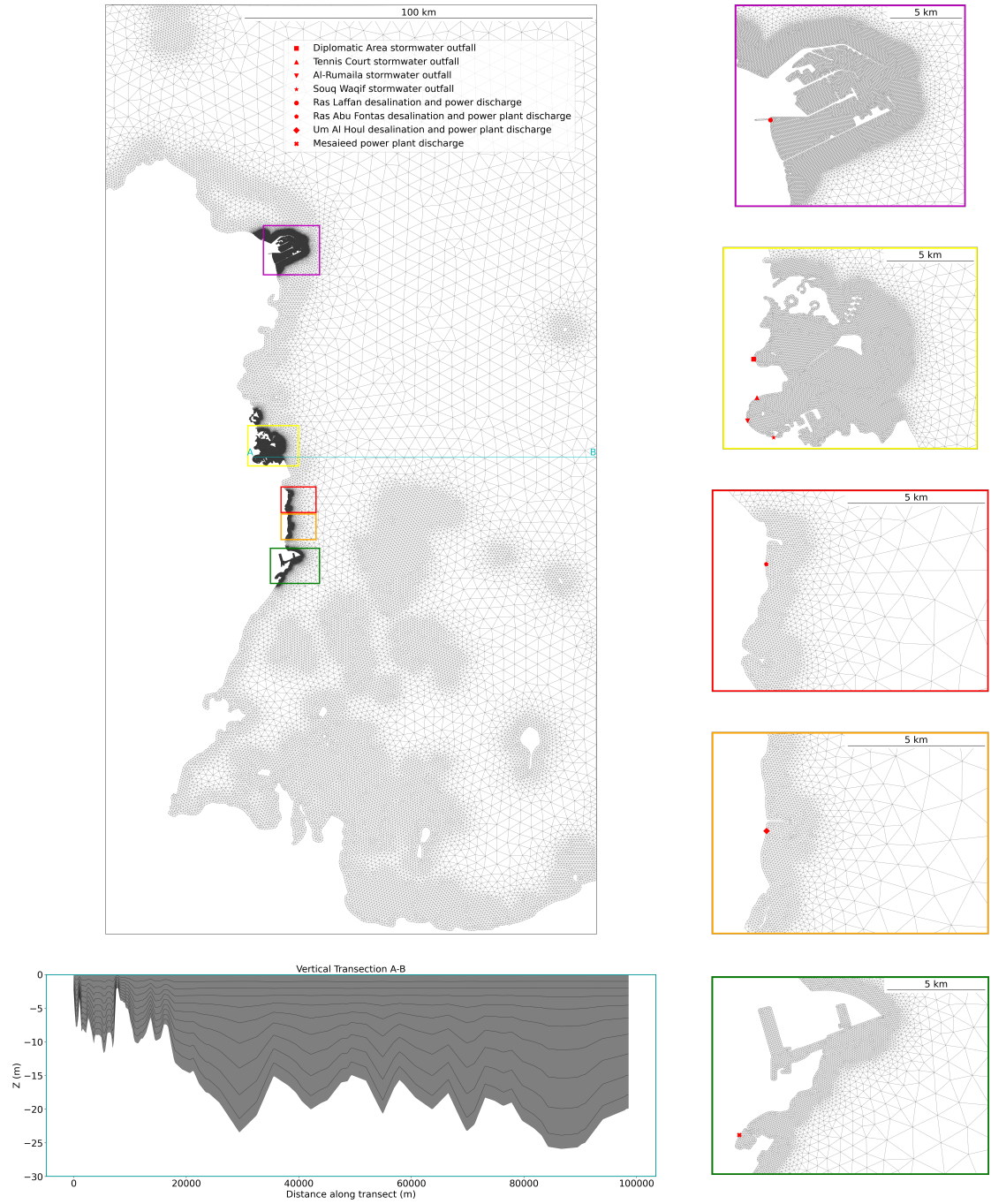


Figure 2.5: Representation of the mesh with a zoom on the areas of interest and a vertical cross-section showing the 10 σ -layers.

an accurate open-source bathymetry dataset, the presence of numerous artificial structures in the coastal areas of Qatar may introduce some bias into the data. Land reclamation may have induced modifications in the bathymetry by increasing sedimentation and erosion around these structures. To improve the resolution in Doha Bay, the bathymetry presented by Al Mamoon et al. (2020) was preferred to the one of GEBCO. The two bathymetry are merged using a buffer distance of 500 meters over which a smooth transition is ensured.

Unlike the bathymetry, which doesn't depend on time, the other forcings are time dependent and need external dataset to be retrieved. The wind and atmospheric pressure are sourced from ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and accessed through the Copernicus Climate Data Store (CDS) API³. The dataset offers a spatial resolution of 0.25° (31 kilometers) and a temporal resolution of 1 hour. Wind stress is expressed as the two horizontal components of the wind speed taken 10 meters above the sea surface. Other forcing factors, such as sea surface elevation, currents, temperature, and salinity, are downloaded from the model outputs of the Copernicus Marine Service⁴.

Additional boundary condition need to be taken into account at the interface between the domain of interest and the rest of the Gulf. At the open boundary, the model is forced by large-scale ocean currents and tides. Currents, temperature, salinity and sea surface temperature are retrieved from the global ocean model NEMO provided by the Copernicus Marine Environment Monitoring Service (CMEMS) interface⁵. The tidal velocity obtained from the OSU TPX09-atlas dataset computed on a $1/30^\circ$ grid in the Gulf.

2.3.4 Observations

Due to the limited availability of publicly accessible data, we primarily relied on measurements provided to us by Dr. Aboobacker V.M.. The validation of the current, salinity, and temperature was performed by comparing the results obtained using SLIM3D with observations from four different locations: in Doha Bay (DB) (25.328733° N, 51.564366° E), two offshore locations near Doha (25.2946° N, 51.688533° E and 25.292° N, 51.710° E), and in Fuwairit (F) on the northeast coast of Qatar (26.123733° N, 51.373283° E). The location of the observation are shown on Figure 2.6. For the sake of clarity throughout this work, the offshore

³<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels>

⁴<https://resources.marine.copernicus.eu/products>

⁵<https://marine.copernicus.eu>

locations near Doha will be referred to as OD1 (25.2946° N, 51.688533° E) and OD2 (25.292° N, 51.710° E).

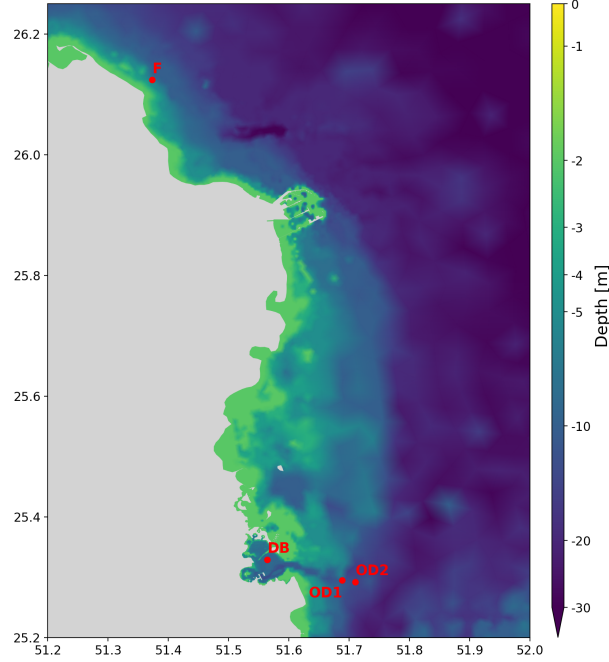


Figure 2.6: Bathymetry of the study area with the location where observations were collected.

In Doha Bay, measurements were taken every 15 minutes between December 8 and December 16, 2021, at a depth of approximately 5 meters below the surface. Salinity and temperature were also recorded simultaneously. These measurements were obtained using a Seaguard Recording Current Meter (RCM) equipped with wave and tide sensors. The mean accuracy of the RCM Doppler Current Sensor (DCS) is 0.15 cm.s^{-1} for current velocity within a range of $0\text{--}300 \text{ cm.s}^{-1}$ and $\pm 5^\circ$ for current direction over $0\text{--}360^\circ$. The RCM wave and tide sensors have an accuracy of $\pm 0.02\%$.

At the location OD1, current measurements were recorded at seven different depths, with each measurement separated by two meters. Data collection occurred every 10 minutes from December 8, 2021, to January 27, 2022. Additional data was also provided in OD2, where salinity, temperature, and density were measured across the entire water column at four different times: October 26, 2021; December 8, 2019; June 2, 2022; and March 2, 2023.

For the last location, in Fuwairit, current velocity, salinity, and temperature were measured every 10 minutes from October 29 to November 26, 2019. These measurements were also conducted using the Seaguard RCM.

2.4 Pollutant dispersion

2.4.1 Eulerian transport model

The Eulerian transport model simulates the transport of dissolved and suspended substances under the influence of the water currents. For this work, the substances of interest are the pollutants coming out of the stormwater outfalls, mainly the FC and the TSS. These substances are directly transported by the flow and therefore the Eulerian model runs simultaneously with the hydrodynamic model.

As the Eulerian model runs simultaneously with the hydrodynamic model, the equations of advection and diffusion are similar to the one of the salinity and temperature. For the pollutants, the equation can be adapted. For a tracer C , the general equation to solve can be written as follow:

$$\frac{\partial C}{\partial t} + \nabla_h \cdot (\mathbf{u}C) + \frac{\partial(wC)}{\partial z} = \nabla_h \cdot (\kappa_h \nabla_h C) + \frac{\partial}{\partial z} \left(\kappa \frac{\partial C}{\partial z} \right) \quad (2.31)$$

The variables are the same as the ones used for the salinity and temperature equation.

Feacal Coliform (FC)

To account for the decay of FC due to light exposure, an exponential decay term is applied, following the approach of de Brauwere et al. (2014). Let k be the exponential decay rate. The decay can then be described by the following differential equation:

$$\frac{dC(t)}{dt} = -k C(t) \quad (2.32)$$

$$C(t) = C_0 \exp(-kt) \quad (2.33)$$

where $C(t)$ is the concentration of FC at time t , and C_0 is the initial concentration. The decay rate k is taken from Al Mamoon et al. (2020) and is set to $k = 2.31481 \times 10^{-5} \text{ [s}^{-1}\text{]}$.

The decay is not directly integrated within the advection-diffusion (AD) equation. Instead, at each time step, the FC concentration is first computed using the AD equation. Then, using this result as the initial concentration, Equation (2.33) is applied to obtain the adjusted concentration taking into account the decay rate. This updated concentration is then used as the initial condition for the next time step in the AD calculation, and the process is repeated iteratively.

Total suspended solid (TSS)

For suspended solids, it was necessary to implement a vertical velocity to account for particle sedimentation. Settling velocity is a complex phenomenon influenced by numerous factors. While many studies have attempted to model it, their results show significant variability.

In their review, Li et al. (2024) examine previous experiments and the various factors that influence sediment settling velocity. They highlight the key role of flocculation, a process in which fine particles aggregate into larger clusters (flocs), which directly affects particle size and shape, two major parameters controlling settling speed. In addition to these, external conditions such as temperature, salinity, and the presence of organic matter also play an important role. The diversity in influencing factors and the differences in measurement methods lead to a wide range of settling velocities reported in the literature.

According to Portela et al. (2013), in a study conducted in Portugal, particle sizes range from 2 μm to 37 μm , with an average diameter of 9 μm . In a saline environment, the average settling velocity is 0.69 mm.s^{-1} , with a maximum observed value of 0.9 mm.s^{-1} . Another study in Belgium by Fettweis and Baeye (2015), using particles of 2 μm in diameter, reports settling velocities ranging from 0.18 mm.s^{-1} to 0.35 mm.s^{-1} .

As exact measurements of the size of particles discharged into the bay, nor their precise settling velocities, were available, and since Al Mamoon et al. (2020) did not provide specific values in their paper, our study focuses on four arbitrarily chosen sediment sizes (10 μm , 25 μm , 50 μm , and 100 μm) to model different types of sediments that could be present in Doha Bay. Although settling velocity can be linked to particle size through complex models, this study uses Stokes' law as a simplified yet reasonable approximation. This approach provides acceptable estimates of settling velocity while maintaining a relatively straightforward implementation. Stokes' law is expressed as follows:

$$w = \frac{(\rho_s - \rho_f)gd^2}{18\nu} \quad (2.34)$$

where $\rho_s = 2475 [kg.m^{-3}]$ and $\rho_f = 1030 [kg.m^{-3}]$ are the densities of the particles and seawater respectively, g is the acceleration due to gravity, d is the particle diameter, and ν is the kinematic viscosity of seawater. The corresponding settling velocities and particle sizes used in this study are presented in Table 2.2.

Particle diameter [μm]	Settling velocity [$mm.s^{-1}$]
10	0.0788
25	0.492
50	1.97
100	7.88

Table 2.2: Particles sizes and corresponding settling velocities estimated using Stokes' law

2.4.2 Calibration

Desalination plants

There are multiple desalination plants along the coast, but for this work, only the three main ones are selected. These are located in Ras Laffan, Ras Abu Fontas, and Umm Al-Houl. The first step to implement the desalination plants is to determine the boundary condition at the outfalls. To do so it is necessary to know the production capacity of each plant. Table 2.3 presents the capacities for each plant and the technology they use based on Qatar General Electricity & Water Corporation “KAHRAMAA” (2023) and Saleem et al. (2023). The plants of Ras Laffan and Ras Abu Fontas are divided in multiple sub-plant but they are all treated as one plant as the outfall is supposed common to all the sub-plant. Therefore, the capacity in Ras Abu Fontas is of $1.70 \text{ Mm}^3.\text{Day}^{-1}$ (Million cubic meter per Day) and the facility of Ras Laffan has a capacity of $0.74 \text{ Mm}^3.\text{Day}^{-1}$. Once the capacity of each plant is known, it is possible to find out the salt concentration in the brine and the temperature of brine water at the outfall. To do so, the same method as the one used by Nesterov (2025) was used. For each outfall, knowing the intake flow rate Q_{in} , the freshwater production rate P , and the fresh water recovery ratio r , the outfall flow rate can be determined as follows:

$$Q_{out} = Q_{in} - P \quad \text{with} \quad r = \frac{P}{Q_{in}} \quad (2.35)$$

The recovery ratio depends on the desalination technology used. The three main technologies are Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Multi-Effect Distillation (MED). Although recovery ratios vary in the literature, we adopt a uniform value of 40 % for all technologies, following Nesterov (2025).

Desalination plant	Capacity in MIGD	Capacity in Mm ³ /Day	Technology
Ras Abu Fontas			
RAF A1	44	0.20	MSF
RAF A2	35	0.16	MSF
RAF A3	35	0.16	RO
RAF B	33	0.15	MSF
RAF B2	29	0.13	MSF
Sub-Total	375	1.70	
Ras Laffan			
RL A	40	0.18	MSF
RL B	60	0.27	MSF
RL C	63	0.29	MED
Sub-Total	163	0.74	
Umm Al Houl			
UHP	198	0.90	MSF & RO

Table 2.3: Water Production Capacity and technology used in each desalination plant (Qatar General Electricity & Water Corporation “KAHRAMAA”, 2023; Saleem et al., 2023)

Once the flow rates have been defined, it is possible to calculate the salinity and temperature of the brine using the following equations:

$$S_{out}(t) = k S_{in} \quad (2.36)$$

$$T_{out}(t) = T_{in}(t) + \Delta T \quad (2.37)$$

where $k = Q_{in}/Q_{out} = 1/(1 - r)$ is the brine concentration factor and ΔT the excess temperature. As most of the technologies used are MSF, a typical value of $\Delta T = 11.1^\circ\text{C}$ was used (Nesterov, 2025). Accounting for the contribution of each technologies would have been complex, which justified the decision to use a common value for all of them.

Power plants

Along the coast, several power plants operate, often in conjunction with desalination plants, as is the case in Ras Laffan, Ras Abu Fontas, and Um Al Houl. However, some power plants operate independently, such as the one in Mesaieed.

The primary environmental impact of these power plants results from the heated water they discharge into the Gulf after being used for cooling purposes. The temperature increase of the cooling water varies depending on the plant, but specific data for those considered in this study were not available. Literature reports a range of temperature differences: Manjunatha et al. (2015) mention an increase of 7.2°C; Roy et al. (2022) report values between 7 and 10°C; Ko and Kim (2024) uses 6.6°C; and Leng et al. (2024) discusses a power plant in Iraq with a temperature increase between 1.2 and 5.8°C. In this study, a conservative temperature difference of 10°C between discharged water and Gulf water is assumed.

Although no direct data are available on the discharge flow rates of these power plants, their nominal capacities are known (Qatar General Electricity & Water Corporation “KAHRAMAA”, 2023). Assuming a typical efficiency of $\eta = 60\%$ for modern combined-cycle gas turbine (CCGT) power plants (Kotowicz et al., 2015), the thermal energy rejected into the cooling water can be estimated. Given a temperature difference of $\Delta T = 10^\circ\text{C}$ and the specific heat capacity of water $c_p = 4.18 [\text{kJ.kg}^{-1}.\text{K}^{-1}]$, an approximation of the discharged water volume can be computed using the following equations:

$$Q_{\text{waste}} = E_{\text{thermal input}} - E_{\text{elec}} \quad (2.38)$$

$$= E_{\text{elec}} \left(\frac{1 - \eta}{\eta} \right) \quad (2.39)$$

$$\dot{V} = \frac{Q_{\text{waste}}}{c_p \Delta T \rho} \quad (2.40)$$

where $\rho = 1000 [\text{kg.m}^{-3}]$ is the density of water, and $\dot{V}$ is the volume flow rate $[\text{m}^3.\text{s}^{-1}]$.

Stormwater outfalls

Regarding stormwater outfalls, our study focuses on those located in the vicinity of Doha Bay: Souq Waqif, Al-Rumailah, Tennis Court, and Diplomatic Area.

To assess the impact of stormwater discharge on the Gulf, our study follows the methodology described by Al Mamoon et al. (2020). Three scenarios were modeled

Power Plant	Energy Transmitted [MW]
Ras Abu Fontas	
RAF B	609
RAF B1	377
RAF B2	567
Sub-Total	1,553
Ras Laffan	
RL A	756
RL B	1,025
RL C	2,730
Sub-Total	4,511
Um Al Houl	
UHP	2,520
Mesaieed	
MPCL	1,990

Table 2.4: Energy capacity per power plant as of 2022 (Qatar General Electricity & Water Corporation “KAHRAMAA”, [2023](#)).

using the water quality parameters and discharge rates presented in Table 2.5. The first scenario represents dry weather conditions, simulating discharges in the absence of rainfall. The second scenario is a situation of first flush which models the discharge during a rainfall after a dry period. The third scenario corresponds to a representative storm event, simulating a period of heavy rainfall.

For the dry weather scenario, the simulation covers a 30-day period from June 1 to June 30, 2016. The first flush scenario spans 20 days, from November 25 to December 15, 2016. In this case, the first 15 hours simulate the first flush event, after which the model switches to dry weather discharge characteristics. The storm event scenario uses the same simulation period and structure with the first 15 hours simulating storm discharge conditions before switching to dry weather characteristics.

Each simulation is preceded by a 14-day spin-up phase in the dry conditions to allow the model to reach a quasi-steady state. This ensures a realistic background concentration before the main simulation begins, minimizing startup anomalies related to the initial mixing of pollutants in the environment.

Parameter	Diplomatic area	Souq Waqif	Tennis Court	Al-Rumailah
Dry weather				
TSS [mg.l ⁻¹]	18	31.5	13	26
Fecal Coliform [FC.100ml ⁻¹]	1900	2900	360	350
Flow rate [m ³ .s ⁻¹]	0.012	1.241	0.114	0.231
First flush				
TSS [mg.l ⁻¹]	2652	750	620	384
Fecal Coliform [FC.100ml ⁻¹]	147594	44438	44825	24044
Flow rate [m ³ .s ⁻¹]	0.500	5.760	5.045	3.215
Representative storm event				
TSS [mg.l ⁻¹]	592	361	227	160
Fecal Coliform [FC.100ml ⁻¹]	60230	36674	31628	9554
Flow rate [m ³ .s ⁻¹]	0.500	5.760	5.045	3.215

Table 2.5: Water quality characteristics and discharge rates for the four outfalls in Doha Bay and for the three scenarios (Al Mamoon et al., 2020).

2.4.3 Environmental risk assessment

To assess the impact of FC and TSS from the stormwater, a similar approach to that used by Al Mamoon et al. (2020) was applied. First, an impact assessment is conducted based on the mean quantity of pollutants present in the bay during the simulation period. Depending on this quantity, the impact due to the concentration of FC or TSS in the bay, is categorized as *negligible*, *small*, *moderate*, or *high*, according to the criteria defined in Table 2.6. The severity of the impact is then determined as a function of the magnitude of the impact, the size of the contaminated area, and the duration of exposure to the pollutant, following the ratings described in Table 2.6 and Table 2.7.

The probability of rainfall occurrence is low in Qatar, with only 8 to 9 rainy days per year. Moreover, during these events, the drained water can be redirected for irrigation instead of being discharged into the Bay (Hajri et al., 1992). Therefore, the exposure duration during first flush and storm events is considered *short*, and the probability of occurrence is *low*. In contrast, under dry weather conditions, the discharge is continuous and occurs for most of the year; hence, the exposure duration is considered *long*, and the probability is *high*.

Finally, the environmental risk is assessed by combining the severity of the impact with the probability of occurrence, using the matrix shown in Table 2.8.

	Criteria	Description
Extension of Impact	Small	Effects limited to an area of 500 meters of diameter
	Medium	Effects may occur anywhere inside Doha Bay (area of less than 10 kilometer of diameter)
	Large	Effects may occur outside Doha Bay (area of more than 10 kilometer of diameter)
Duration of Exposure	Short-term	A few days
	Long-term	Continuous
Magnitude of Impact: Bathing Water Quality	Small	Modeled FC ≤ 250 count.100ml ⁻¹ (excellent quality)
	Moderate	Modeled FC between 250 and 500 count.100ml ⁻¹ (good to sufficient quality)
	High	Modeled FC > 500 count.100ml ⁻¹ (poor quality)
Magnitude of Impact: Hazardous Contaminants	Negligible	Modeled net deposition of discharged TSS < 10 g.m ⁻²
	Small	Modeled net deposition of discharged TSS in between 10 to 25 g.m ⁻²
	Moderate	Modeled net deposition of discharged TSS between 25 to 100 g.m ⁻²
	High	Modeled net deposition of discharged TSS > 100 g.m ⁻²
Probability	High	It is certain that the scenario will occur (dry weather)
	Low	Not certain that the scenario will occur (first flush and storm event)

Table 2.6: Criteria for assessment of extension of impact, duration of exposure, magnitude of impacts and probability of occurrence (base on the work of Al Mamoon et al. (2020)).

	Relation with the criteria on extension, duration, and magnitude of impact of discharge
Insignificant Impact	• Negligible magnitude, with any combination of other criteria, or • Small magnitude, small extension, and short-term exposure
Minor Impact	• small magnitude, with any combination of other criteria (except for small extension and short-term exposure), or • Moderate magnitude, with small extension and short-term exposure
Moderate Impact	• Moderate magnitude, with any combination of other criteria (except for: small extension and short-term exposure; and regional extension and long-term duration), or • Large magnitude, with small extension and short-term exposure
Major Impact	• Moderate magnitude, with regional extension and long-term exposure, or • Large magnitude, with any combination of other criteria (except for small extension and short-term exposure)

Table 2.7: Criteria for assessment of the severity of the potential impacts of the discharge (base on the work of Al Mamoon et al. (2020)).

	Insignificant Impact	Minor Impacts	Moderate Impacts	Major Impacts
High Probability	Negligible Risk	Minor Risk	Moderate Risk	Major Risk
Low Probability	Negligible Risk	Negligible Risk	Minor Risk	Moderate Risk

Table 2.8: Risk assessment matrix based on the severity of the impact and the probability of occurrence of the scenario (based on the work of Al Mamoon et al. (2020)).

Chapter 3

Results

This chapter presents the main results of our research. First, the hydrodynamics in the study area is analyzed and compared with the available observations. Then, a closer examination of the desalination and power plants aims to assess their impact on water salinity and temperature. Finally, the situation in Doha Bay is addressed by analyzing the concentrations of FC and TSS and conducting an environmental risk analysis.

3.1 Hydrodynamics

3.1.1 Ocean currents

The validation of the hydrodynamic model was carried out by comparing the sea surface elevation (SSE) as well as the current magnitude and direction with measurements taken at different locations in the Gulf (Figure 2.6). For the SSE, measurements were collected at Fuwairit and in Doha Bay. Current speed and direction were also measured at these locations, with additional measurements collected offshore from Doha (OD1).

The simulated SSE agrees well with the measurements both in Doha Bay and in Fuwairit (Figure 3.1). The tidal cycle is correctly represented with a RMSE of respectively 0.1 m and 0.08 m for Doha Bay and Fuwairit. It is also interesting to mention the spring-neap tidal differences, with the spring tides having an amplitude of around 1.5 meter and the neap tides reaching less than 1 meter of amplitude.

The current speed and direction also agree well with the observations in Fuwairit (Figure 3.3). The current flows predominantly from northwest to southeast, with velocities reaching up to approximately 0.5 m.s^{-1} . The tidal cycle is also well

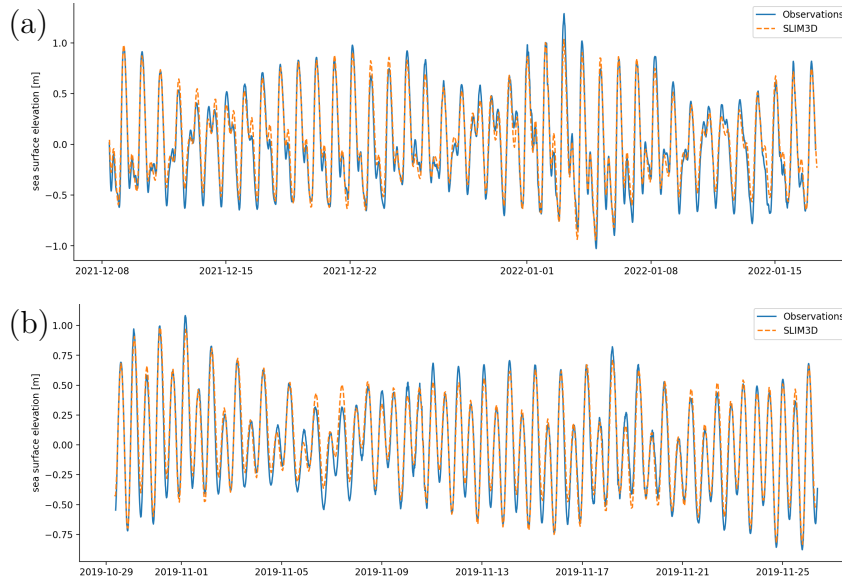


Figure 3.1: Comparison between the observed and simulated SSE in (a) Doha Bay (08 Dec 2021–15 Jan 2022), and (b) Fuwairit (29 Oct 2019–26 Nov 2019). In both cases, the tidal cycles are accurately reproduced, with RMSE values of 10 cm in Doha Bay and 8 cm in Fuwairit.

represented. At the other locations, the validation results are slightly less satisfactory. In Doha Bay (Figure 3.2), the observed current direction is predominantly northeastward, whereas the simulation shows a significant northwestward component in the current direction distribution. For the offshore location near Doha (Figure 3.4), the current velocity is again slightly underestimated, but the overall current dynamics are well captured, including the tidal events and the general south-southeastward flow. Additional data were available at the same offshore location but at different depths, and a comparison between the simulation and the measurements is presented in Appendix A. The model matches the observations well at depths below 6 m. However, at layers closer to the surface, the observations appear unreliable, and a meaningful comparison cannot be made. This discrepancy may be due to disturbances caused by the proximity of a navigational channel with significant boat traffic.

The residual current patterns, obtained by averaging the simulated velocity field over one month (August 2022), highlight the net water transport (Figure 3.5). The streamlines show the residual current direction and the background shows the mean current speed, hence including the tides. In locations such as Ras Abu Fontas and Um Al Houli, the streamlines show a relatively smooth southward circulation

following the coastline, with mean current speeds ranging from approximately 0.1 m.s^{-1} near the shore up to 0.3 m.s^{-1} offshore. Similar behavior is observed in Mesaieed, although with higher offshore mean current speeds reaching up to 0.5 m.s^{-1} . In Doha Bay, the enclosed geometry leads to weak currents, typically around 0.1 m.s^{-1} , except near the Pearl, where current speeds reach approximately 0.4 m.s^{-1} . The streamlines suggest a predominant inward circulation, accompanied by the formation of small eddies. No clear outward flow from the bay is observed. High mean current speeds, around 0.5 m.s^{-1} , are also observed near Ras Laffan. The circulation there is more complex, with several small eddies forming within the port area and a larger eddy located to the south of the port. While higher current speeds around the port were expected, lower speeds were anticipated inside the port itself, similar to those observed in Doha Bay. Contrary to these expectations, relatively high current velocities are observed within the port. This anomaly may be attributed to inaccuracies in the bathymetry, particularly due to shallow depths in the port area that do not account for the dredging required to accommodate large shipping vessels. Consequently, results in this region should be interpreted with caution.

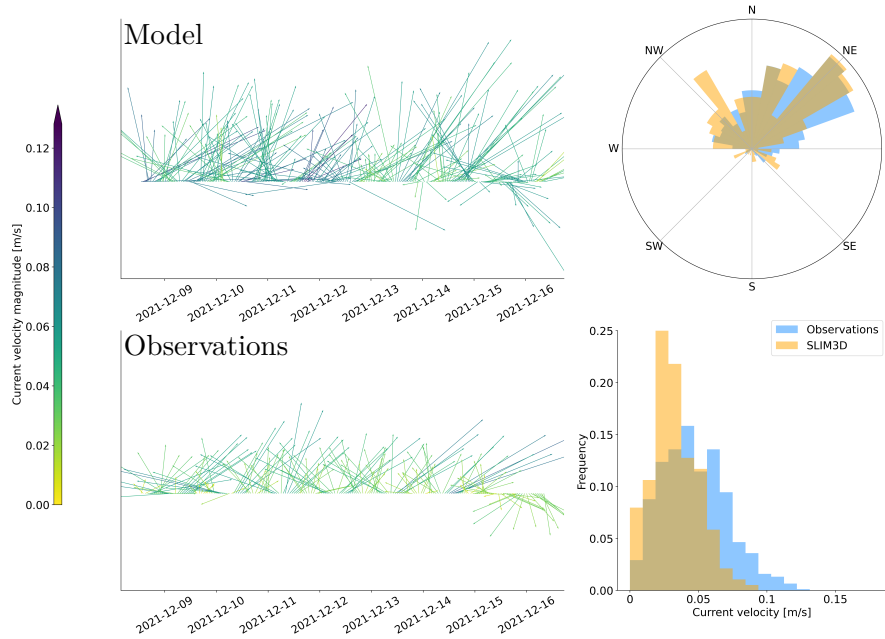


Figure 3.2: Comparison between modeled and observed currents in Doha Bay at a depth of -5 m (08 Dec 2021–15 Jan 2022). The RMSE value is 0.03. Histograms on the left compare the amplitude and direction of the currents.

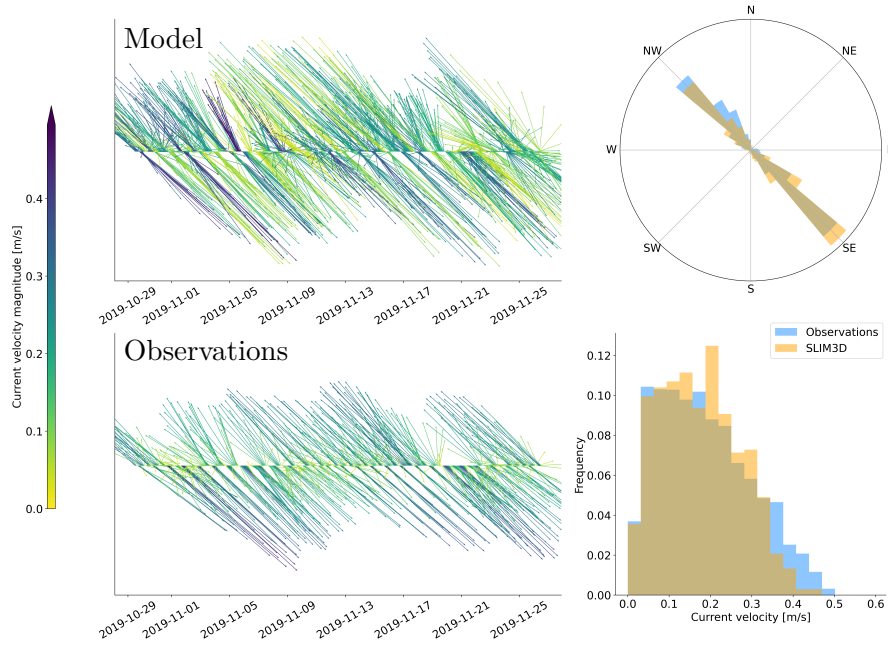


Figure 3.3: Same as Figure 3.2 but in Fuwairit at a depth of -4 m (29 Oct 2019–26 Nov 2019). The RMSE value is 0.14. Note the different colorbar scale.

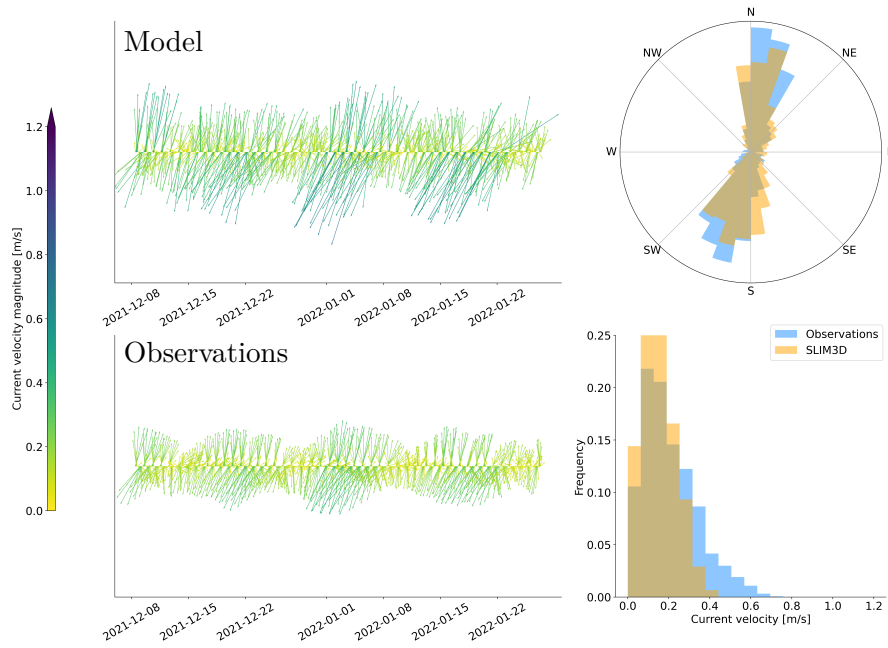


Figure 3.4: Same as Figure 3.2 but offshore of Doha (OD1) at a depth of -8 m (08 Dec 2021–27 Jan 2022). The RMSE value is 0.16. Note the different colorbar scale.

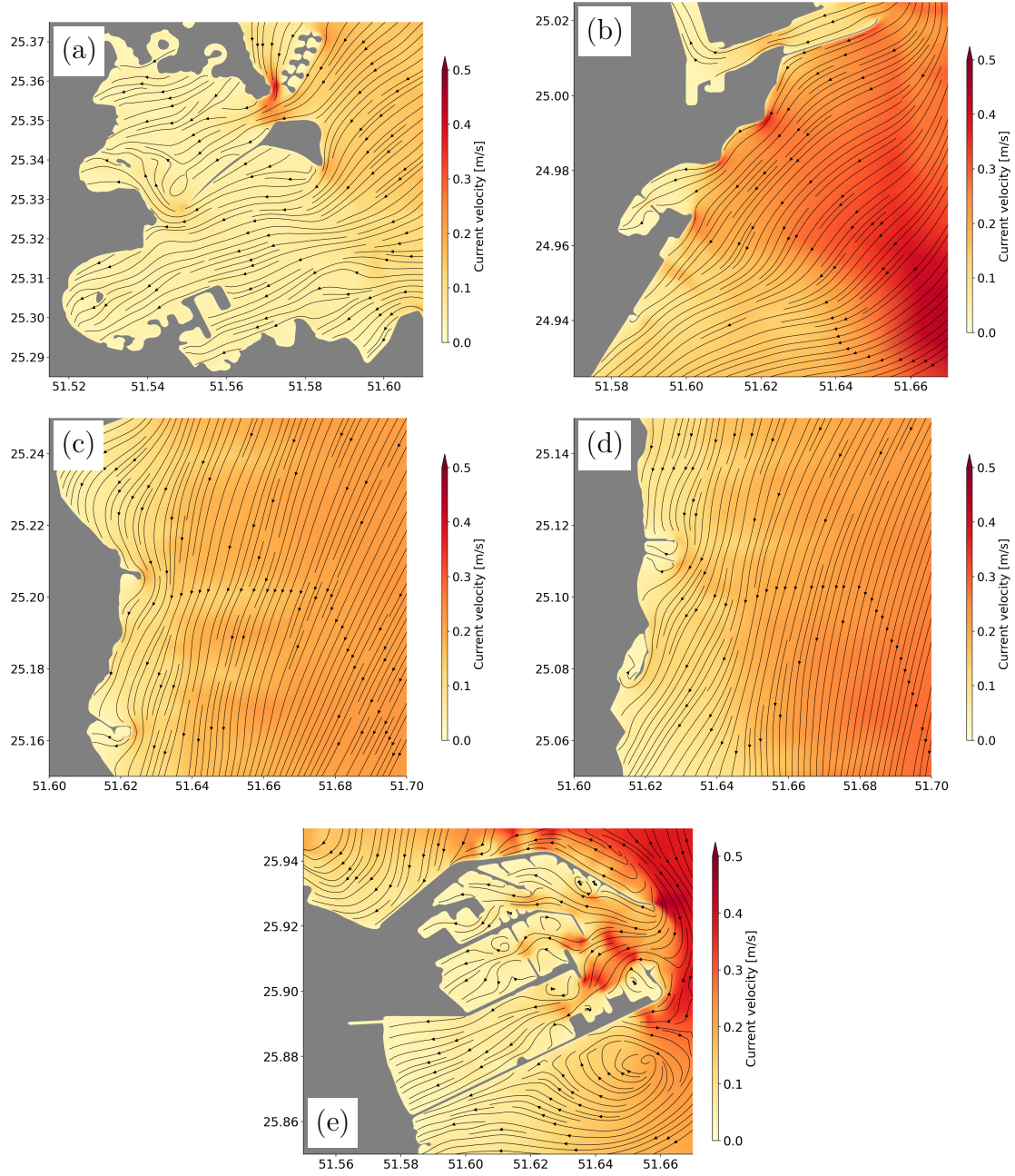


Figure 3.5: Monthly-averaged currents during August 2022 in (a) Doha Bay, (b) Mesaieed, (c) Ras Abu Fontas, (d) Um Al Houl, and (e) Ras Laffan. The colormap shows the mean current speed in m.s^{-1} , while the streamlines illustrate the residual circulation patterns obtained by averaging the current velocity.

3.1.2 Temperature and salinity profiles

Temperature and salinity measurements were collected in Fuwairit and in Doha Bay (Figure 3.6). The data were recorded over approximately one week, except for the temperature measurements offshore of Fuwairit, which cover a longer period of about one month. Additional measurements were taken offshore of Doha (OD2) at four different times, providing insights into the vertical variation of temperature and salinity throughout the water column (Figure 3.7).

The simulated temperature agrees well with the observation, with RMSE values of 0.27 and 0.52 in Doha Bay and in Fuwairit, respectively. The night and day cycles are clearly visible with oscillation of temperature on a daily basis. With only one week of data available in Doha Bay, it is difficult to identify a clear long-term trend. However, the longer time series offshore of Fuwairit reveals a progressive cooling as winter approaches, with temperatures decreasing by approximately 6°C over the course of one month.

For salinity, the simulation results differ more significantly from the observations, with RMSE values exceeding 3.5 in Doha Bay and approaching 1.85 in Fuwairit. In Doha Bay, despite this gap, the overall trend is relatively well reproduced, with a quasi constant salinity both for the observation (around 43°C) and for the simulation (around 39.5°C). In Fuwairit, the simulation also captures some key features of the measurements. Several short-term oscillations observed in the data are partially reflected in the model. However, a sharp drop in the simulated salinity occurs around November 2nd, which does not appear in the observations. Aside from this sudden decrease, the rest of the figure would suggest that the simulation was not using the right forcings. This issue will be discussed in more detail in [chapter 4](#).

The additional measurements taken offshore of Doha (OD2) at four different times and at multiple depths show that both temperature and salinity remain relatively constant throughout the water column Figure 3.7. The simulation results are generally in good agreement with the observations, except for the salinity in March, but again, this could be due to wrong forcings. Both the temperature and the salinity are quite consistent over depth except for the first 2 meters where the temperature is slightly higher in the simulation. A variation of less than 1°C in December and March, and around 1.5°C higher in June. This variation is probably due to high external temperature forcings which may once again not be completely accurate.

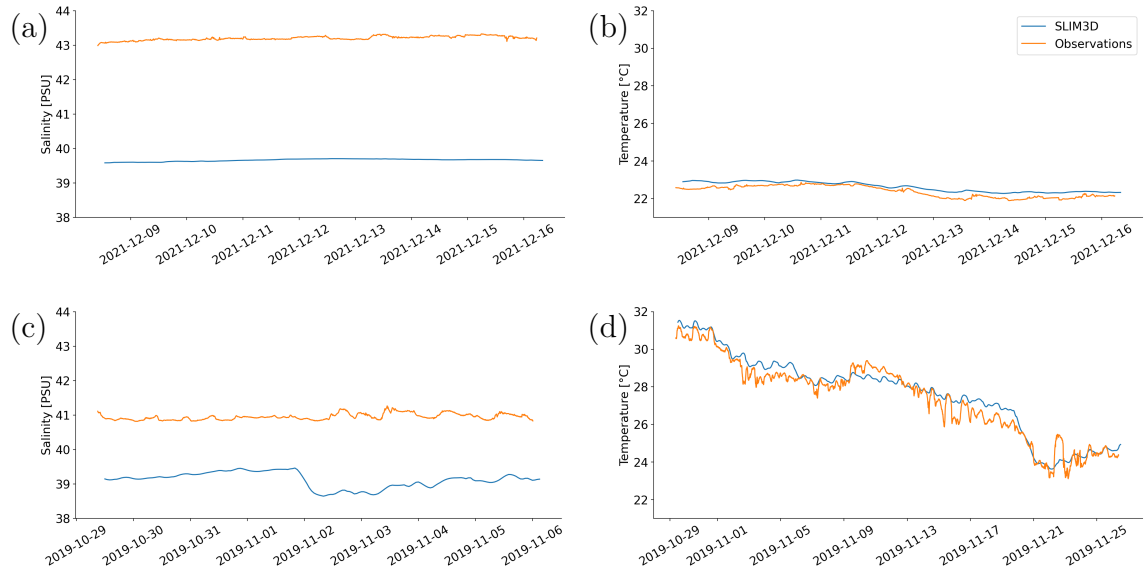


Figure 3.6: Comparison between the observations and the model for (a) salinity in Doha Bay (08 Dec 2021–16 Dec 2021), (b) temperature in Doha Bay (08 Dec 2021–16 Dec 2021), (c) salinity in Fuwairit (29 Oct 2019–26 Nov 2019), and (d) temperature in Fuwairit (29 Oct 2019–06 Nov 2019). The model shows good accuracy for temperature, with RMSE values of 0.27 in Doha Bay and 0.52 in Fuwairit. However, salinity is underestimated by the model, with RMSE values of 3.54 in Doha Bay and 1.85 in Fuwairit.

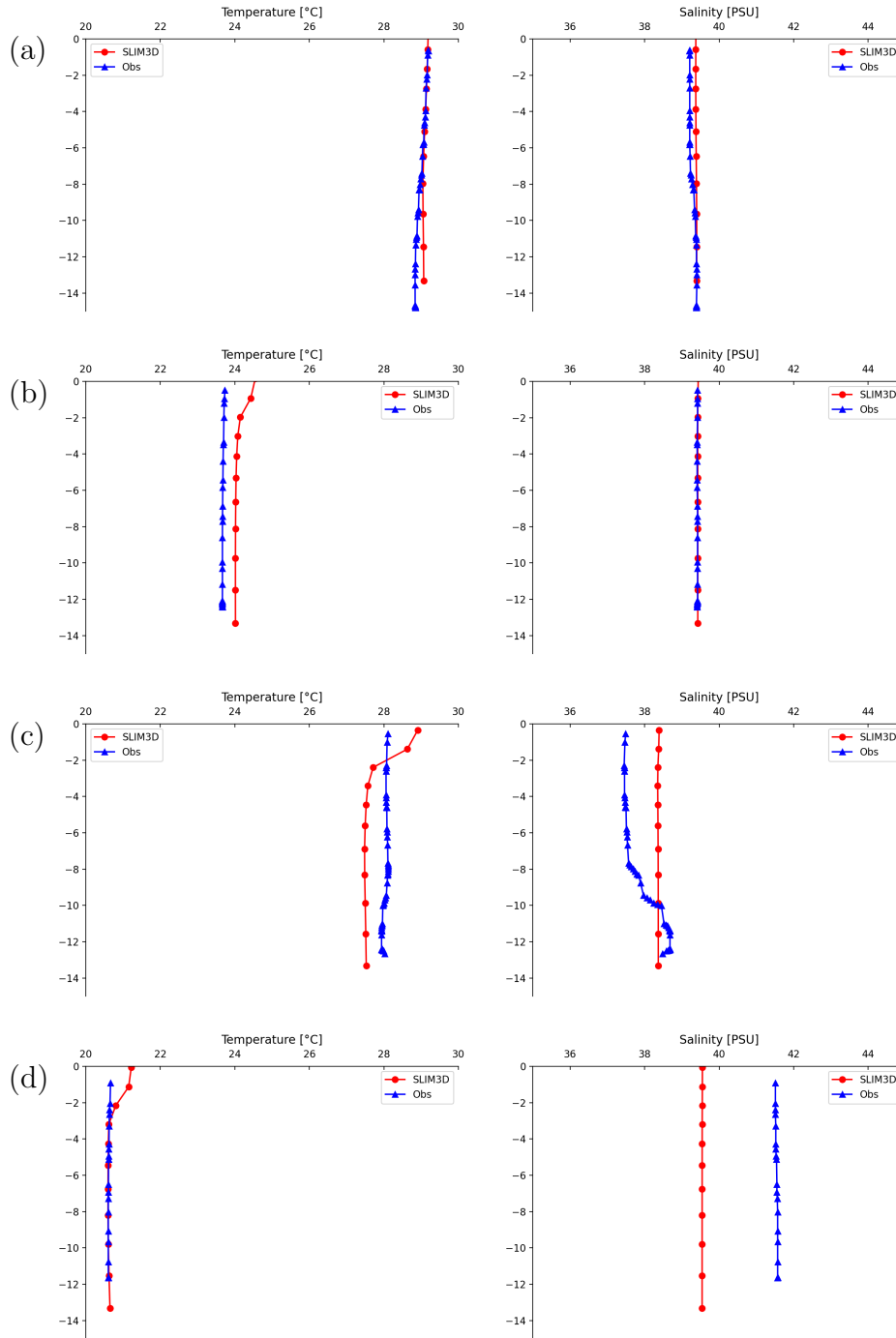


Figure 3.7: Comparison of temperature (left) and salinity (right) offshore of Doha (OD2) at four different times: (a) 26 Oct 2021; (b) 08 Dec 2021; (c) 02 June 2022; and (d) 02 March 2023. The model closely matches the observations most of the time, except in March 2023, where it underestimates salinity.

3.2 Impact of the desalination and power plants

This section analyzes the combined impact of desalination and power plants on seawater temperature and salinity. The effects vary depending on several factors, including the outfall's location, exposure to prevailing currents, local bathymetry, and whether the facility operates as a standalone power station or is coupled with a desalination unit. As the Mesaieed site does not include a desalination plant, it is excluded from the salinity analysis.

Figures 3.8 to 3.11 show the temperature at the surface, at the bottom, and through the water column, and highlight significant differences between the types of installations. At the Mesaieed power plant, the warmer thermal discharge spreads primarily near the surface, with heat gradually diffusing downward. In the immediate vicinity of the outfall, water temperatures reach up to 40°C, approximately 5°C above background levels, before tapering off to a 2°C increase at distances up to 2 km. Beyond this range, the plume becomes more exposed to currents circulation, accelerating dilution and reducing its thermal impact.

By contrast, when a power plant is combined with a desalination facility, both temperature and salinity effects become more important at the bottom than at the surface (Figures 3.12 to 3.14). The brine is not only warmer but also significantly denser due to high salinity. This denser effluent sinks rapidly, concentrating the thermal and saline impacts near the seabed. This results in an increase of the temperature to more than 40°C and the salinity to more 45 PSU in the areas closer to the outfalls. This represents respectively an increase of over 14% in salinity and nearly 13% in temperature compared to ambient conditions. Meanwhile, surface salinity increases are more limited, reaching around 40 PSU near Ras Abu Fontas and Um Al Houl, and remaining below 42 PSU within the port of Ras Laffan.

The extent and distribution of these impacts are strongly influenced by local bathymetry and current exposure. In shallow bathymetry, the thermal and saline impacts are significant but they quickly diminish with increasing depth. Comparing the results obtained for the port of Ras Laffan and Mesaieed to the ones obtained in Ras Abu Fontas and Um Al Houl also highlights the importance of the currents dynamics. In Ras Laffan and Mesaieed, the relatively enclosed configuration restricts the dispersal of the discharged water, resulting in localized accumulation within a 2 km radius of the outfall. The temperature and salinity in this area can increase up to 2°C and 2 PSU on average near the surface and around 5°C and 5 PSU on the seabed. In Ras Abu Fontas and Um Al Houl, however, the open coastal setting allows the plume to spread further, especially southward, in alignment with the dominant current direction. The impacted area is hence larger but the dilution

is more important as well and the surface temperature increase generally remains around 1°C and 1 PSU. On the seabed, the impact remains significant in the direct vicinity of the outfalls, with increases similar to those observed at Ras Laffan and Mesaieed, but quickly decreases as a result of a more effective dispersion.

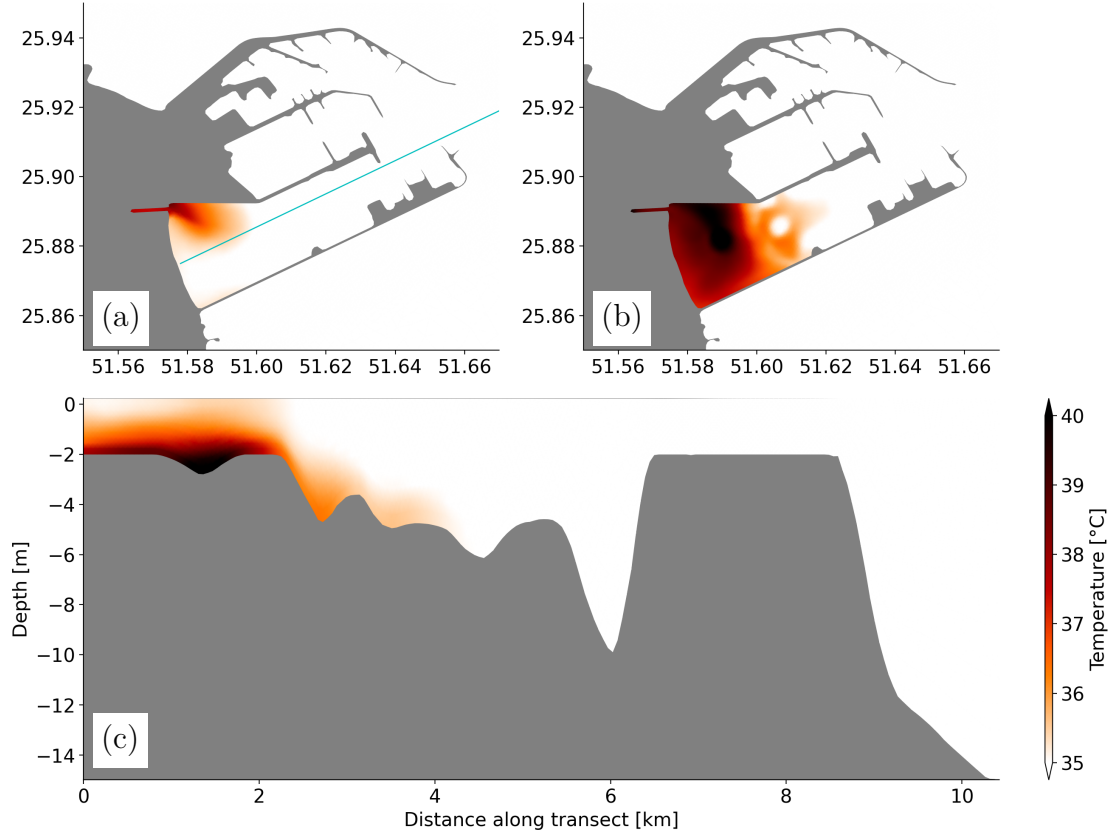


Figure 3.8: Monthly-averaged (August 2022) temperature in Ras Laffan, showing the impact of the desalination and power plant. (a) Surface temperature, (b) seabed temperature, and (c) vertical cross-section along the blue line shown on figure (a). The colorbar is the same for all figures.

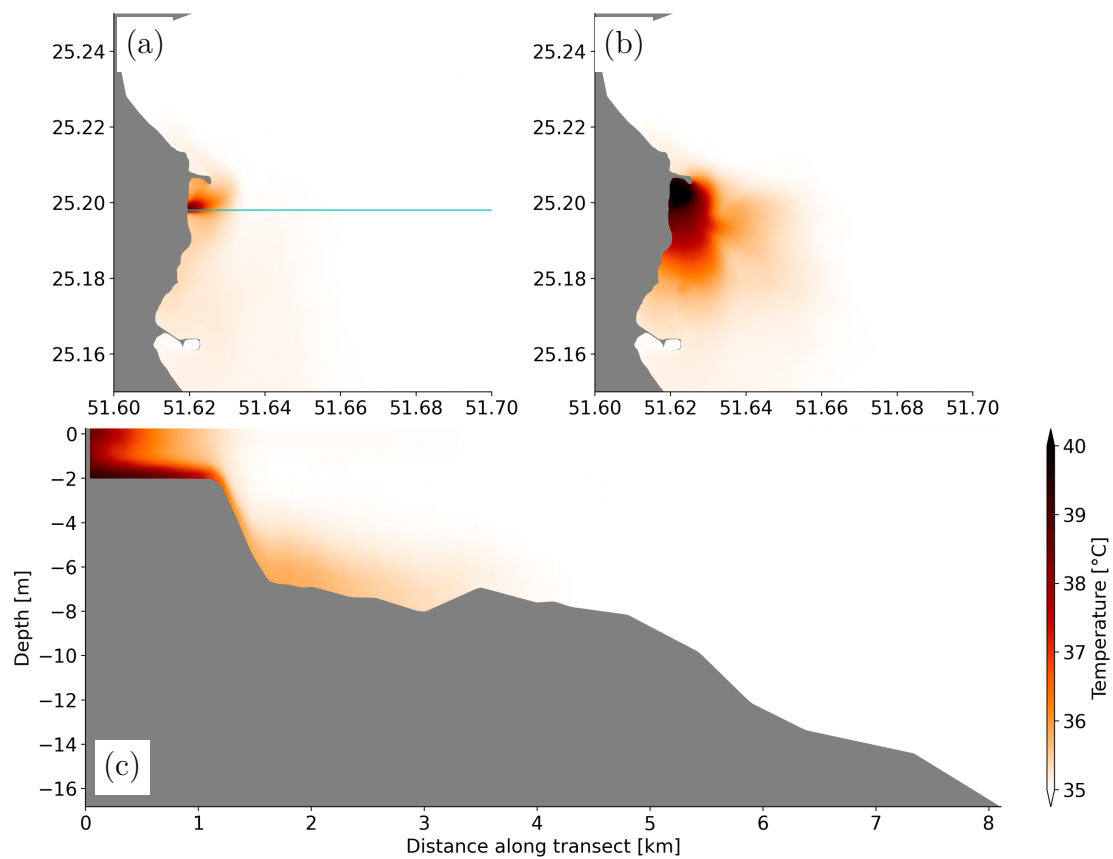


Figure 3.9: Same as Figure 3.8 but in Ras Abu Fontas.

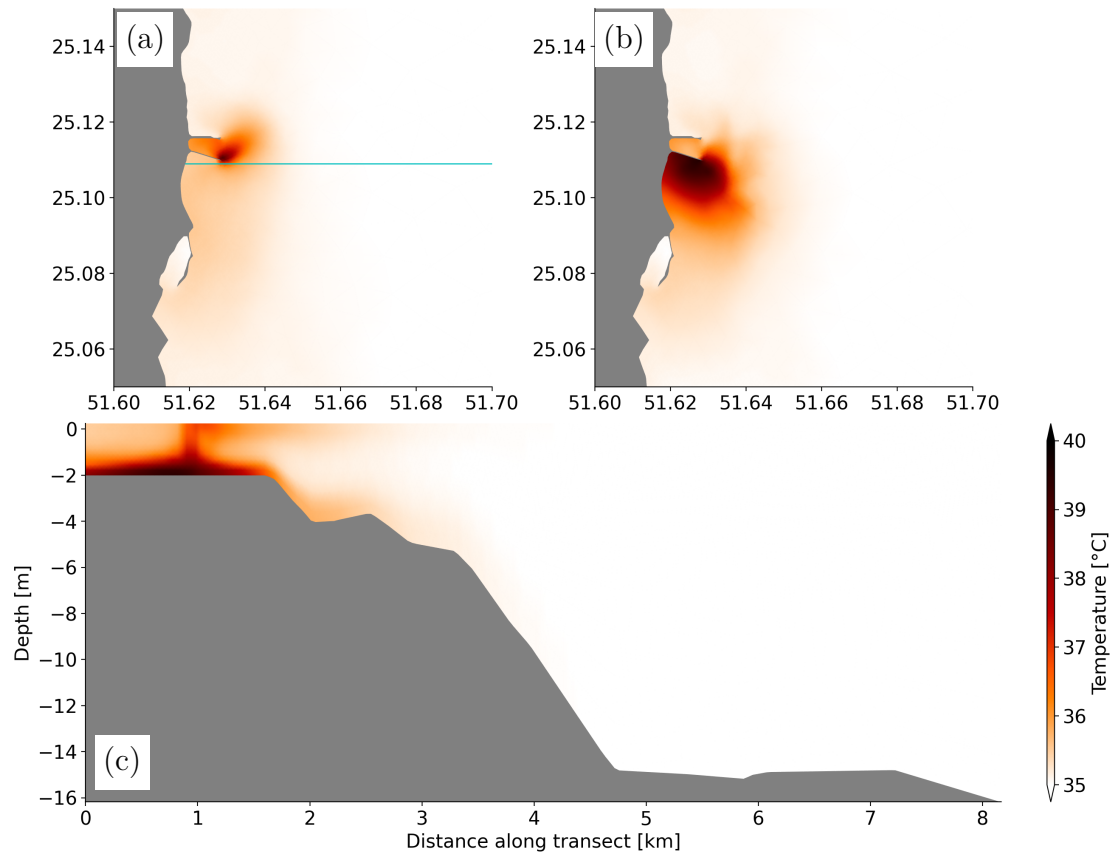


Figure 3.10: Same as Figure 3.8 but in Um Al Houl.

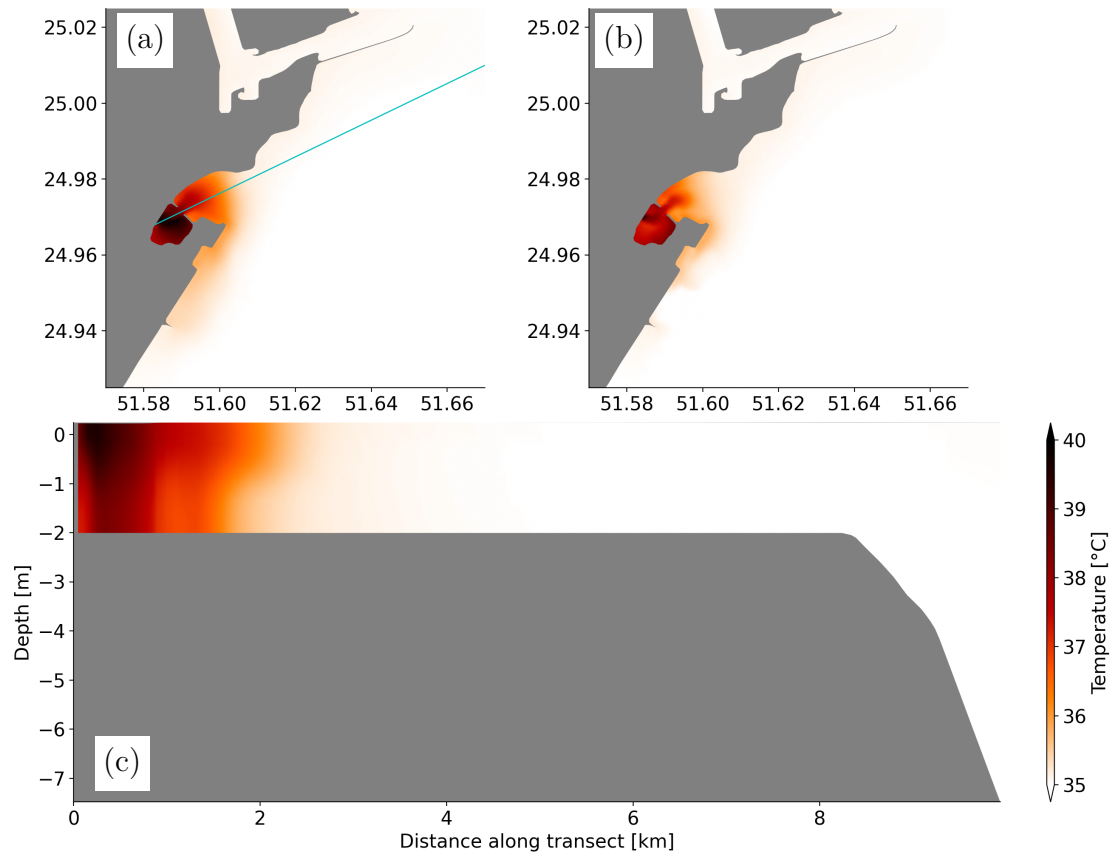


Figure 3.11: Same as Figure 3.8 but in MESAIEED, except that only a power plant is present.

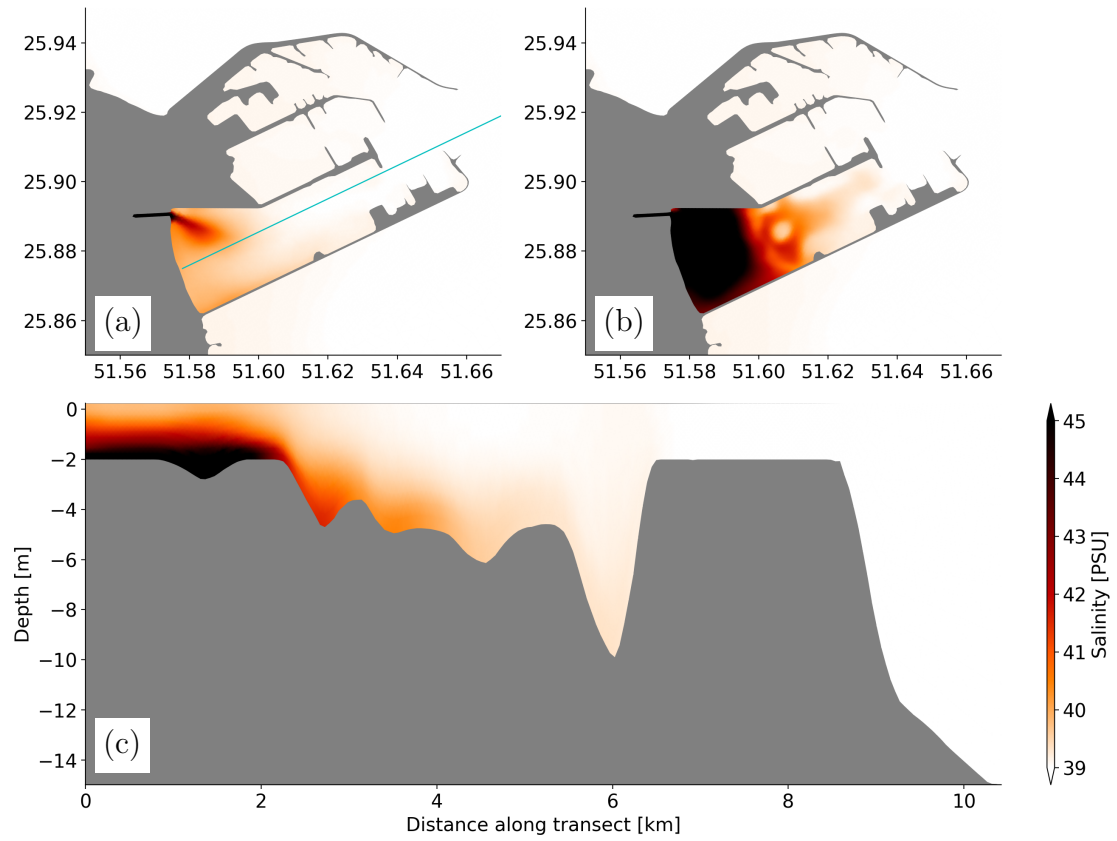


Figure 3.12: Monthly-averaged (August 2022) salinity in Ras Laffan, showing the impact of the desalination and power plant. (a) Surface temperature, (b) seabed temperature, and (c) vertical cross-section along the blue line shown on figure (a). The colorbar is the same for all figures.

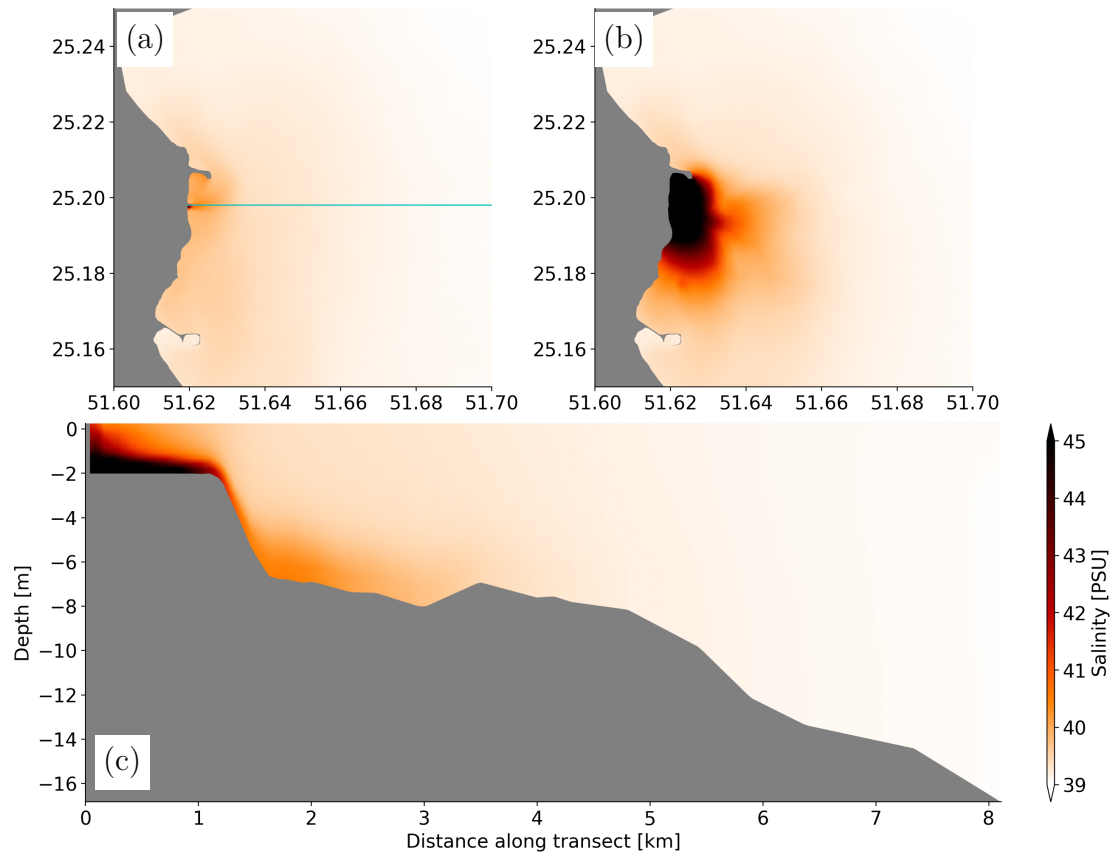


Figure 3.13: Same as Figure 3.12 but in Ras Abu Fontas.

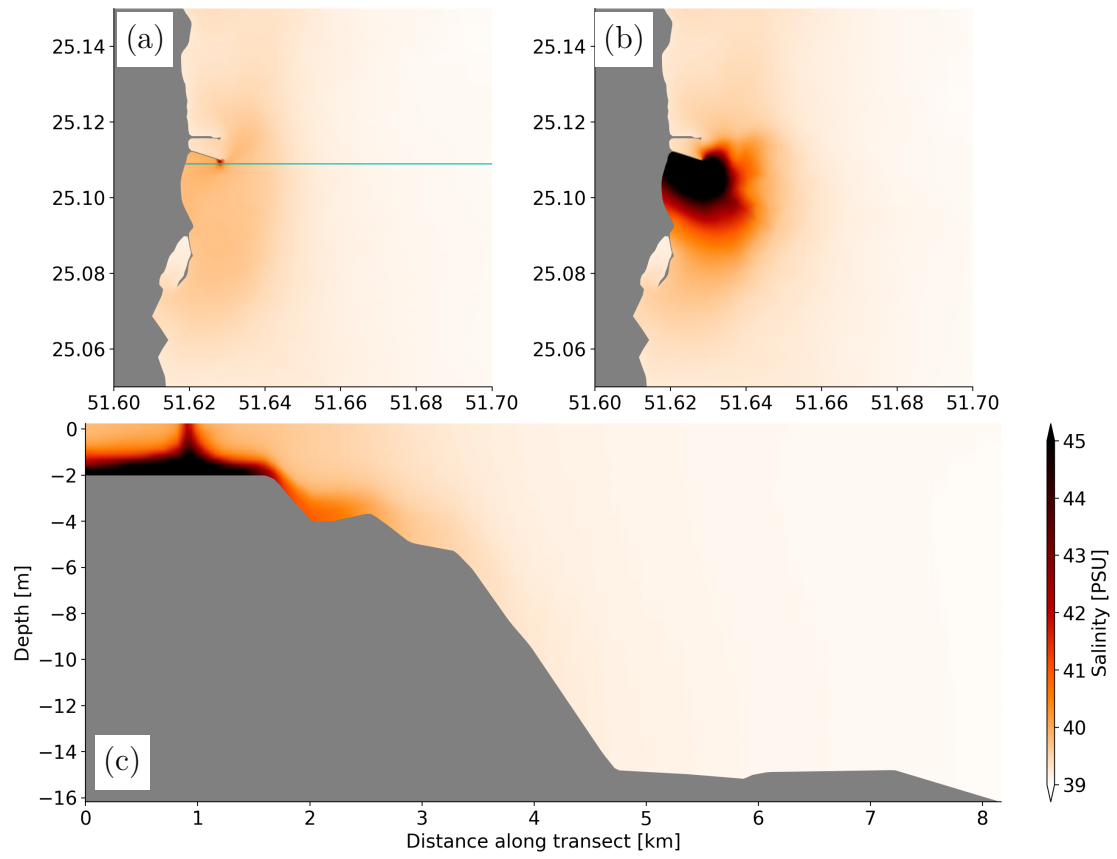


Figure 3.14: Same as Figure 3.12 but in Um Al Hou.

3.3 Impact of the stormwater outfalls

3.3.1 Fecal coliforms

The concentration of FC per 100 milliliters appear fairly similar across all scenarios (Figure 3.15). The dry weather scenario shows slightly lower concentration overall, but the differences remain minimal. The most notable variations are observed near Tennis Court and Al-Rumailah outfalls, where concentrations remain around 100 FC.100ml⁻¹ during dry conditions, compared to over 500 FC.100ml⁻¹ during first flush and storm events. In contrast, the Diplomatic Area and Souq Waqif outfalls consistently exhibit higher concentrations across all scenarios, reaching approximately 1000 FC.100ml⁻¹. The elevated concentrations in Souq Waqif are likely due to the outfall's enclosed location, which limits water exchange and promotes the accumulation of contaminants. Although the Diplomatic Area is less confined, the concentration of FC in the discharged water is generally 2 to 3 times higher than that of the other outfalls. Away from the immediate vicinity of the outfalls, FC concentrations drop rapidly, falling below 10 FC.100ml⁻¹ outside the two embayment where the discharges occur.

To assess the quality of bathing water, the method described in Section 2.4.3 was applied. As expected, water quality is slightly better under dry weather conditions. In this scenario, poor water quality is observed only within 750 m of the Souq Waqif outfall and 250 m of the Diplomatic Area outfall. Moderate impact is detected up to 1 km from Souq Waqif and 750 m from the Diplomatic Area. Elsewhere in the bay, the impact is small to negligible, indicating excellent water quality. For the first flush and storm event scenarios, the situation near Souq Waqif remains similar to the dry weather case. However, in Diplomatic Area, the impact is more significant, with poor water quality extending up to 1 km from the outfall in the first flush scenario and 750 m in the storm event. The moderate impact zones stretches up to around 1.3 km and 1.1 km, respectively. Additionally, water quality deteriorates slightly near the Tennis Court and Al-Rumailah outfalls under these two wet weather scenarios, with moderate impact observed within 200 m of the outfalls. In the rest of the bay, water quality remains excellent.

Knowing the quality of the bathing water and the extent of the impacted area, the environmental risk assessment can be conducted. The results of the environmental matrix are presented in Table 3.1 and Table 3.2. Due to the long term exposure and the high probability of the dry scenario, it is the one that represents the highest environment risk, with major risk in the vicinity of the Diplomatic Area and near Souq Waqif, and moderate to minor risk in the rest of the Bay. For the two other scenarios, the risk stays moderate to minor near the

outfalls and becomes negligible in the rest of the Bay.

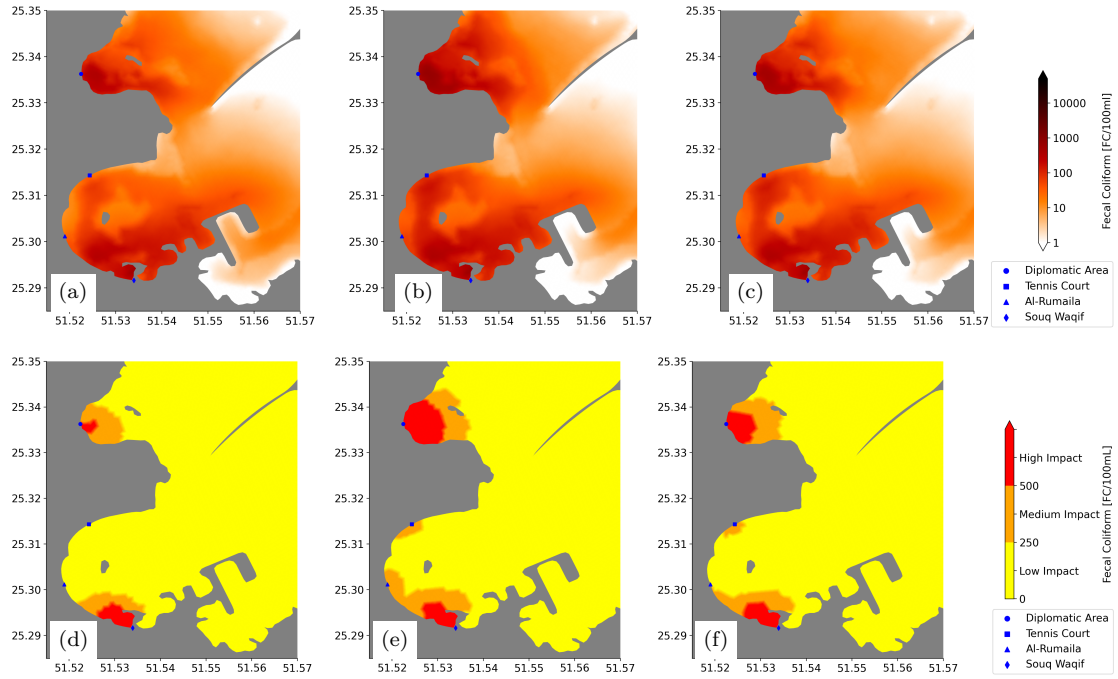


Figure 3.15: Modeled FC concentrations at the water surface resulting from the discharge of the four outfalls. Subfigures (a)-(c) show the average concentration during dry weather (01 June 2016-30 June 2016), the first flush (25 November 2016-15 December 2016), and a representative storm event (25 November 2016-15 December 2016), respectively. Subfigures (d)-(f) illustrate the impact on bathing water quality, as defined in Table 2.6, for the same three periods.

	Concentration >500 FC.100mL ⁻¹ in an area of more than 500 m of diameter	Concentration >500 FC.100mL ⁻¹ in an area of less than 500 m of diameter	Concentration between 250 and 500 FC.100mL ⁻¹ in an area of more than 500 m of diameter	Concentration between 250 and 500 FC.100mL ⁻¹ in an area of less than 500 m of diameter	Concentration below 250 FC.100mL ⁻¹
Magnitude of impact	High	High	Moderate	Moderate	Small
Extension of impact	Medium	Small	Medium	Small	Medium
Duration of exposure	Long	Long	Long	Long	Long
Severity of impact	Major	Major	Moderate	Moderate	Minor
Probability	High	High	High	High	High
Environmental risk	Major	Major	Moderate	Moderate	Minor

Table 3.1: Environmental risk matrix for bathing water quality under the dry weather scenario.

	Concentration >500 FC.100mL ⁻¹ in an area of more than 500 m of diameter	Concentration >500 FC.100mL ⁻¹ in an area of less than 500 m of diameter	Concentration between 250 and 500 FC.100mL ⁻¹ in an area of more than 500 m of diameter	Concentration between 250 and 500 FC.100mL ⁻¹ in an area of less than 500 m of diameter	Concentration below 250 FC.100mL ⁻¹
Magnitude of impact	High	High	Moderate	Moderate	Small
Extension of impact	Medium	Small	Medium	Small	Medium
Duration of exposure	Short	Short	Short	Short	Short
Severity of impact	Moderate	Moderate	Moderate	Minor	Minor
Probability	Low	Low	Low	Low	Low
Environmental risk	Moderate	Minor	Minor	Negligible	Negligible

Table 3.2: Environmental risk matrix for bathing water quality under the scenarios of first flush and representative storm event.

3.3.2 Total suspended solids

To assess the environmental impact of TSS, the deposition of sediment on the seabed must first be analyzed for each size of particles (Figure 3.17). Next, the magnitude of impact of hazardous contaminants adhered to solids can be evaluated. Finally, the environmental risk is determined using Table 3.3 and Table 3.4.

Similarly to the dispersion of FC, there are no major differences in TSS dispersion between the dry scenario, the first flush, and the representative storm event. The only noticeable change is a slightly higher concentration in the northern part of the bay during the dry scenario. However, the difference does not exceed 5 mg.m^{-2} , and thus does not represent a significant increase on the environmental impact in Doha Bay. Moreover, this must be analyzed in regard to the currents dynamics happening in the bay at the time of the simulation. The dry event has a different period of simulation and hence the circulation in the bay is different as well (Figure 3.16). The average circulation between the 1st and the 30th of June 2016 is mainly going southeast and the currents hence flush the pollutants coming out of the outfalls outside of the embayment. In the other two scenarios (25th of November to 15th of December 2016), the average circulation shows that the current inside the two embayment is pushing the pollutants back towards the outfalls, which could explain why impacted area is smaller.

While the overall concentration of TSS does not vary significantly between scenarios, differences emerge when different particle sizes are considered. The finest particles of $10 \text{ }\mu\text{m}$, which have lower settling velocities, show much lower concentrations compared to larger particles with higher settling speeds. Due to their smaller size, these particles remain suspended in the water for longer periods and can be transported and diluted over a wider area. As a result, the concentration remains low throughout the bay, with a maximum value below 10 mg.m^{-2} (Figure 3.18). The magnitude of the impact is therefore negligible across the entire bay for all scenarios, and so is the associated risk (see Table 3.3 and Table 3.4).

For the larger particles with higher settling velocities, sedimentation within the bay increases. For particles of $25 \text{ }\mu\text{m}$, the most critical zone is located on the west side of Palm Tree Island, in the center of the southern embayment, covering an area approximately 1 km in diameter. Concentrations range between 25 and 100 mg.m^{-2} , even exceeding 100 mg.m^{-2} in some localized areas (Figure 3.18). Medium to high concentrations are also found near Souq Waqif and the port of Doha, although the affected areas do not extend beyond 500 m in diameter. In both the first flush and storm scenarios, concentrations ranging from 10 to 100 mg.m^{-2} are also observed near the Diplomatic Area. Outside the two embayment, concentrations decrease

rapidly, and most of the remaining bay shows little to no presence of suspended solids originating from the outfalls. Environmental risks are most critical under the dry scenario and are considered moderate to major in the area west of the Palm Tree Island, in the port of Doha, and near Souq Waqif (Table 3.3). In contrast, under the first flush and storm event scenarios, the risks remain minor to negligible (Table 3.4).

When examining the concentration of 50 μm particles, the results for the first flush and representative storm events are fairly similar to those obtained for 25 μm particles. However, in the dry weather scenario, the difference is more pronounced, with TSS concentrations increasing in both embayment. Moderate concentrations between 25 and 100 mg.m^{-2} are observed over an area extending up to 1.5 km from the outfalls in the southern embayment, exceeding 100 mg.m^{-2} within 750 m from Palm Tree Island and the Souq Waqif outfall. Moderate concentrations are also observed within 250 m of the outfall in the Diplomatic Area, with minor concentrations extending up to 1 km (Figure 3.18). According to the environmental risk matrix for the dry scenario (Table 3.3), most of the southern embayment is subject to major risk, while moderate risk is also observed near the Diplomatic Area. The risk levels for the two other scenarios are similar to those observed for 25 μm particles, except in the first flush scenario, where a minor risk is observed in the northern embayment due to elevated concentrations extending over more than 500 m from the Diplomatic Area outfall.

Interestingly, for particles of 100 μm , the dispersion of the pollutant in the bay is reduced compared to 50 μm particles. Due to their higher settling velocity, these particles tend to settle much closer to the outfalls, resulting in higher concentrations but over smaller areas. According to the magnitude of impact (Figure 3.18), areas of high concentration are found within 750 m of the Souq Waqif outfall, as well as in smaller zones (less than 500 m in diameter) near the Al-Rumailah and Diplomatic Area outfalls, and close to the island. In the dry scenario, moderate concentrations are also observed between Al-Rumailah, Tennis Court and the Palm Tree Island, and within 750 m of the Diplomatic Area. Regarding environmental risk under the dry scenario, it is considered major near the Souq Waqif outfall, between the Tennis Court and Al-Rumailah outfalls up to Palm Tree Island, and within 750 m of the Diplomatic Area outfall. In the rest of the bay, the risk decreases to minor (east of the island) or negligible. For the first flush and representative storm event scenarios, the risk is mainly confined in the direct vicinity of the outfalls. It remains minor at all outfalls except Souq Waqif, where it is moderate. Elsewhere in the bay, the risk is negligible.

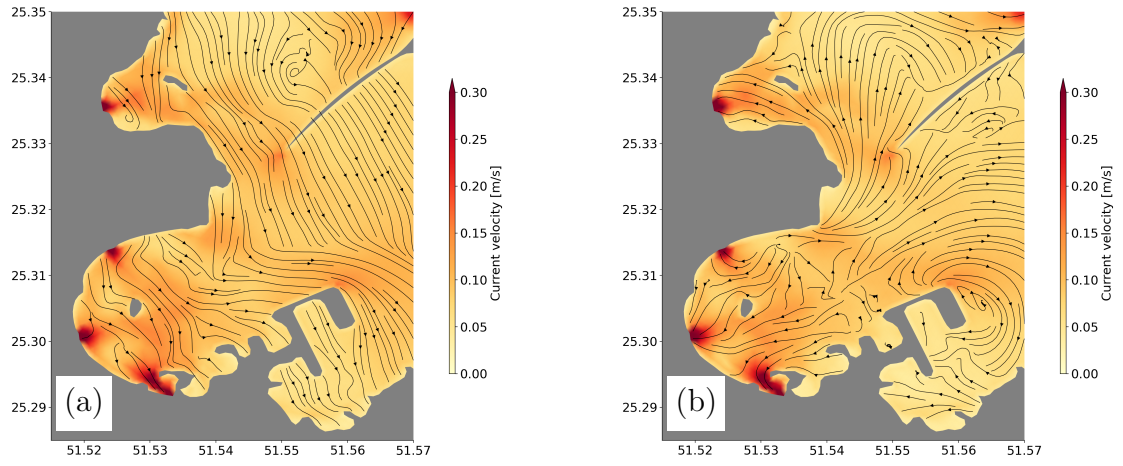


Figure 3.16: Averaged currents and circulation patterns for (a) the dry weather scenario and (b) the scenarios of first flush and storm event.

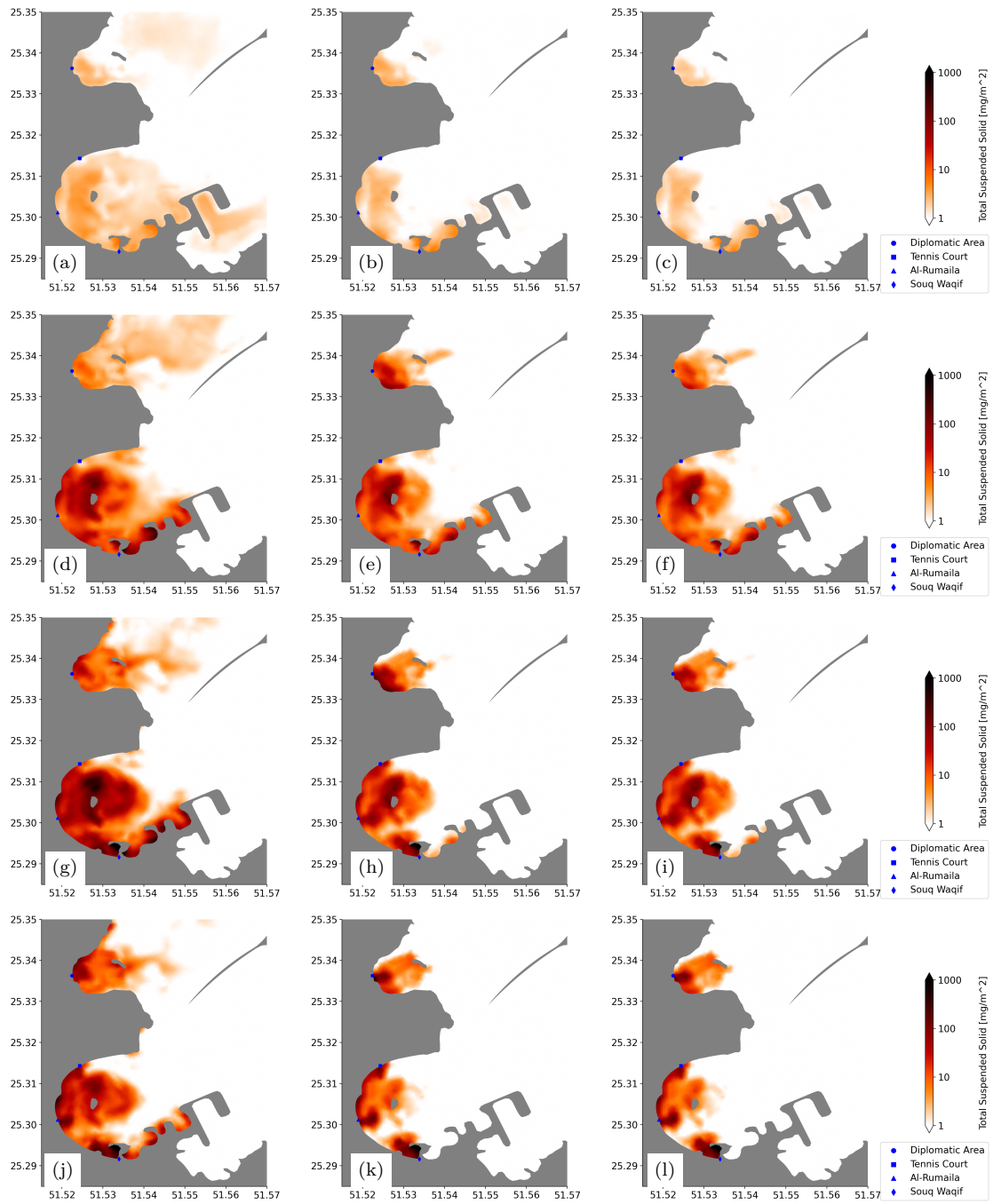


Figure 3.17: Modeled TSS concentrations on the seabed resulting from the discharge of the four outfalls. Subfigures (a)-(c) show the average concentration of particles of $10\ \mu\text{m}$ during dry weather (01 June 2016 - 30 June 2016), the first flush (25 November 2016 - 15 December 2016), and a representative storm event (25 November 2016 - 15 December 2016), respectively. Subfigures (d)-(f) show the same results but for particles of $25\ \mu\text{m}$. Subfigures (g)-(i) show the same results but for particles of $50\ \mu\text{m}$. Subfigures (j)-(l) show the same results but for particles of $100\ \mu\text{m}$.

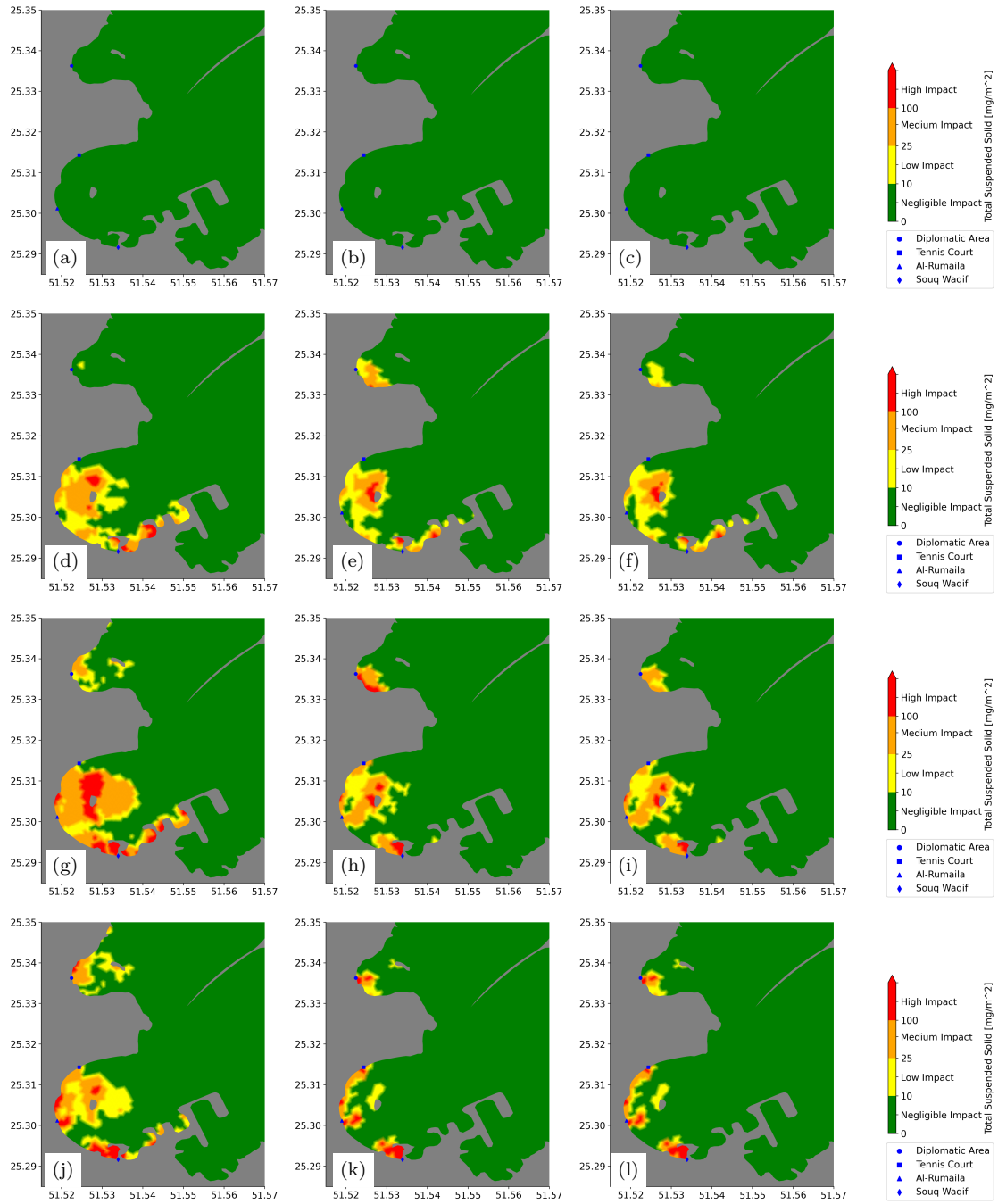


Figure 3.18: Illustration of the magnitude of impact due to discharge of hazardous contaminants adhered to suspended solids, as defined in Table 2.6. Subfigures (a)-(c) show the impact for particles of 10 μm during dry weather (01 June 2016 - 30 June 2016), the first flush (25 November 2016 - 15 December 2016), and a representative storm event (25 November 2016 - 15 December 2016), respectively. Subfigures (d)-(f) show the same results but for particles of 25 μm . Subfigures (g)-(i) show the same results but for particles of 50 μm . Subfigures (j)-(l) show the same results but for particles of 100 μm .

	Concentration >100 mg.m ⁻² in an area of more than 500 m of diameter	Concentration >100 mg.m ⁻² in an area of less than 500 m of diameter	Concentration between 25 and 100 mg.m ⁻² in an area of more than 500 m of diameter	Concentration between 25 and 100 mg.m ⁻² in an area of less than 500 m of diameter	Concentration between 10 and 25 mg.m ⁻² in an area of more than 500 m of diameter	Concentration between 10 and 25 mg.m ⁻² in an area of less than 500 m of diameter	Concentration lower than 10 mg.m ⁻²
Magnitude of impact	High	High	Moderate	Moderate	Small	Small	Negligible
Extension of impact	Medium	Small	Medium	Small	Medium	Small	Large
Duration of exposure	Long	Long	Long	Long	Long	Long	Long
Severity of impact	Major	Major	Moderate	Moderate	Minor	Minor	Negligible
Probability	High	High	High	High	High	High	High
Environmental risk	Major	Major	Moderate	Moderate	Minor	Minor	Negligible

Table 3.3: Environmental risk matrix due to discharge of hazardous contaminants adhered to suspended solids, under the scenarios of first flush and representative storm event.

	Concentration >100 mg.m ⁻² in an area of more than 500 m of diameter	Concentration >100 mg.m ⁻² in an area of less than 500 m of diameter	Concentration between 25 and 100 mg.m ⁻² in an area of more than 500 m of diameter	Concentration between 25 and 100 mg.m ⁻² in an area of less than 500 m of diameter	Concentration between 10 and 25 mg.m ⁻² in an area of more than 500 m of diameter	Concentration between 10 and 25 mg.m ⁻² in an area of less than 500 m of diameter	Concentration lower than 10 mg.m ⁻²
Magnitude of impact	High	High	Moderate	Moderate	Small	Small	Negligible
Extension of impact	Medium	Small	Medium	Small	Medium	Small	Large
Duration of exposure	Short	Short	Short	Short	Short	Short	Short
Severity of impact	Major	Moderate	Moderate	Minor	Minor	Negligible	Negligible
Probability	Low	Low	Low	Low	Low	Low	Low
Environmental risk	Moderate	Minor	Minor	Negligible	Negligible	Negligible	Negligible

Table 3.4: Environmental risk matrix due to discharge of hazardous contaminants adhered to suspended solids, under the scenarios of first flush and representative storm event.

Chapter 4

Discussion

Overall, the 3D hydrodynamic model used in our study produces satisfactory results and accurately reproduces key oceanographic features along the east coast of Qatar. The main finding is that the impact of the discharge depends primarily on the location of the outfall. In more enclosed areas, the effluent tends to accumulate within a limited region, whereas in locations more exposed to current circulation, it becomes more diluted and dispersed over a broader area. Bathymetry also plays a significant role in pollutant dilution. In shallow zones, the limited water volume results in higher pollutant concentrations, whereas further offshore, concentrations decrease rapidly with increasing depth and water volume.

In the vicinity of desalination and power plants, brine discharge primarily affects the seabed due to its higher density. In contrast, the thermal discharge from standalone power plants, being less dense, has a more pronounced impact near the surface and a limited effect on the seabed. In Doha Bay, the environmental impact of FC and TSS is mainly confined to the two embayment where the outfalls are located, with negligible influence in the rest of the bay. Additional analysis of TSS particle's size highlights its critical role in dispersion and sedimentation. A critical size of around $50\ \mu m$ appears to show the highest environmental impact. Smaller particles remain suspended longer, allowing for wider dispersion and lower concentrations. In contrast, larger particles settle more rapidly, concentrating their effects near the outfalls and limiting the spatial extent of impact.

Whether the pollution originates from desalination and power plants or from stormwater discharges, the results of our study indicate that the impact remains predominantly local, typically extending only a few kilometers from desalination and power plant outfalls, and within a few hundred meters from stormwater outfalls.

4.1 Ocean circulation model

To accurately assess the impact of pollution along the coast of Qatar, it is essential to first validate the ocean circulation model employed. Current velocity, circulation patterns, and background temperature and salinity all play an important role in determining the transport and dispersion of pollutants. A model that fails to reproduce the key hydrodynamic features of the study area cannot give reliable results for pollution impact assessment.

The results for current velocity and circulation are consistent with previous studies using SLIM2D (Hanert et al., 2023; Lecart et al., 2024), as well as with available field measurements. In offshore areas near Fuwairit and Doha, current speeds of up to 0.4 m.s^{-1} were recorded. It was also shown that the currents near Fuwairit follow the neap-spring tidal cycle, with tidal ranges varying between 1 and 1.5 meters. Mean current speeds approaching 0.5 m.s^{-1} were observed around artificial structures such as the port of Mesaieed, the LNG terminal of Ras Laffan, and the Pearl. In more enclosed regions, such as Doha Bay, current speeds are significantly lower, generally around 0.1 m.s^{-1} . In other coastal areas subject to less urbanization, mean current speeds remained below 0.3 m.s^{-1} , underlining the influence of artificial infrastructures on ocean dynamics. Additionally, circulation patterns near these artificial structures were found to exhibit more eddies, which can significantly affect the dispersion of pollutants.

The model also shows good agreement with observed sea surface temperatures (SST) reported by Aboobacker et al. (2024) and with other studies. Sheppard et al. (2010) presented temperature values in Qatar ranging from 14.1°C to 36°C , while Hasna et al. (2024) reported average seawater temperatures of approximately 31°C in summer and 23°C in winter. The model used in this work also shows that the temperature is consistent throughout the water column, with peak temperatures offshore of Doha occurring in June and October, reaching approximately 29°C and 28°C , respectively. In December and March, modeled temperatures decrease to approximately 24°C and 21°C . A noticeable temperature drop is also observed between October and November, from around 31°C to 24°C . According to Al-Ansari et al. (2022), this period corresponds to the seasonal transition from summer to winter, during which the Shamal winds contribute to the cooling of the SST. However, Al-Ansari et al. (2022) reported a smaller temperature drop, ranging from 2.9°C to 4.5°C , whereas the model used in this work predicts a larger decrease of approximately 7°C near Fuwairit.

While the modeled salinity offshore of Doha agrees well with the observations reported by Aboobacker et al. (2024) (Figure 3.7), discrepancies are observed when

compared to other field measurements and previous studies. Nesterov (2025) reports a mean salinity over a two-year period ranging from 41 PSU in northern Qatar to 44 PSU in the south. Similar values have been presented by Belthaji (1983), Michael Reynolds (1993), and Elobaid et al. (2022), suggesting that salinity in the Gulf remains relatively stable over time. Although the model used in this work does not simulate salinity over long time periods, the values obtained are consistently lower. Nevertheless, the simulated salinity appears to remain relatively constant, at around 39 PSU. A seasonal variation of approximately 1 PSU is observed between June and March (Figure 3.7). This result is consistent with the findings of Nesterov (2025) and Aboobacker et al. (2024), who note that evaporation driven by strong Shamal winds in winter may have a more significant impact on salinity than high surface temperatures in summer. In summary, although the model underestimates the salinity values compared to most other studies, the general seasonal behavior of the salinity field is consistent with the literature. This suggests that the discrepancy may be due to inaccuracies in the external forcing data from the CMEMS' global ocean physics reanalysis (GLORYS) used to initialize and force the model on the open boundaries.

4.2 Pollution analysis

In this study, two main types of pollution were examined. The first involves discharges from industrial facilities: brine from the desalination plant and thermal discharge from the power station. Since these facilities are often co-located, modeling both together provides a clearer picture of their combined environmental impact. The second type of pollution comes from stormwater discharged directly into Doha Bay. This part of the study focuses on FC and TSS to evaluate bathing water quality and the potential contamination from hazardous substances attached to solid particles. A key finding is that the environmental impact of pollutants largely depends on the location of the outfall. Pollutants discharged from outfalls more exposed to the currents tend to disperse more effectively, whereas in sheltered areas, protected by artificial structures, the concentration in the vicinity of the outfall is higher. Another important factor is bathymetry. In shallow areas, the limited volume of water results in less dilution and therefore higher pollutant concentrations. In contrast, deeper offshore areas allow for greater dilution, leading to significantly lower concentrations of pollutants.

Lattemann and Höpner (2008), Nesterov (2025), and Roberts et al. (2010) have also noted that the choice of discharge location is the primary factor influencing the extent of environmental impact. In areas such as the ports of Ras Laffan and Mesaieed, where discharges occur in more enclosed locations, the environmental

impact is greater due to poor water flushing. However, because of limited circulation, the impact tends to remain localized within the artificial structures, with minimal influence in the rest of Gulf. In contrast, at sites like Ras Abu Fontas and Um Al Houl, where outfalls are more exposed and benefit from better water exchange, the impacted area is larger but exhibits lower concentration.

While surface concentrations drop rapidly within a few tens of meters from the outfalls, elevated concentrations can persist on the seabed over several kilometers. This observation aligns with findings from Gacia et al. (2007) and Purnama et al. (2005), who showed that brine, being denser than seawater, tends to spread further along the seafloor than at the surface. While the impact near the outfalls of Ras Abu Fontas and Um Al Houl is significant and extend over a larger area than those from outfalls in more enclosed locations, they remain geographically limited and do not affect the Gulf's overall temperature or salinity levels. This conclusion is also supported by Roberts et al. (2010) in his review of multiple studies on the environmental impact of desalination plant discharges.

This work also highlights the significant influence of bathymetry on pollutant dispersion. Since the discharge locations are nearshore, the bathymetry is relatively shallow. As a result, dilution occurs in a smaller water volume, causing salinity and temperature to increase by up to 15% compared to background conditions. In contrast, deeper waters offer more favorable conditions for dilution due to a greater water volume and, in well-flushed areas, stronger currents that enhance mixing. Under these conditions, the impact of the discharge plume decreases substantially, with temperature and salinity differences reduced to approximately 1°C and 1 PSU, respectively, compared to ambient levels. The results also indicate that in well-flushed areas such as Ras Abu Fontas and Um Al Houl, the plume tends to spread more along the coastline than offshore. However, these findings should be interpreted with caution due to imperfections in the bathymetry data used. For example, a flat "plateau" at a depth of 2 meters appears in the Ras Laffan cross-sections (Figures 3.8 and 3.12), which is unrealistic given that the port must be significantly deeper to accommodate large vessels. Additional inaccuracies occur near the coast, as the model requires a minimum depth of 2 meters for computational stability. A more accurate bathymetry would likely reveal a gradual slope toward deeper waters, rather than a constant depth extending up to 2 km offshore, as seen in this model (for a detail view of the bathymetry around the discharge location of the desalination and power plants see Appendix B). Although the results suggest that bathymetry plays an important role in pollutant dispersion, this is based on imperfect data and should therefore be interpreted with caution. Other studies, such as Shao and Law (2009), suggest that the dispersion occurring

mostly alongshore instead of offshore may be primarily driven by currents, without evaluating the specific role of bathymetry.

The second focus of this work is the analysis of pollution in Doha Bay resulting from stormwater discharge. Although the environmental risk assessment model used in our study is based on that of Al Mamoon et al. (2020) and uses the same discharge data, many parameters from their model are not disclosed, making a direct comparison difficult. Nevertheless, similarities between the results of both models reveal a general trend which is that the environmental risk of bathing water contamination by FC, as well as the risk associated with the accumulation of TSS on the seabed, is mostly local and remains minor to negligible in the most of the bay. While the global impact in the bay is similar for the two models, differences emerge near the outfalls. The model developed in our study tends to consistently show a larger impacted area, occasionally extending beyond the immediate vicinity of the outfalls. In contrast, the study of Al Mamoon et al. (2020) consistently limits the impacted area within a few hundred meters of the discharge location. In particular, our study identifies a hotspot on the west side of Palm Tree Island for the risk associated with TSS (Figure 3.18), a location not highlighted by Al Mamoon et al. (2020).

Regarding the parameters influencing the extent of environmental impact in Doha Bay, the key factors are similar to those identified for desalination and power plant discharges, the most critical factor being the location of the outfall. The impact near Souq Waqif is consistently greater than at other outfalls due to its enclosed location. Currents also play a significant role in pollutant dispersal, particularly for TSS. A zone of reduced current speed on the west side of Palm Tree Island corresponds with an area of higher TSS concentration on the seabed. Circulation patterns further influence the impact extent and may explain why the dry weather scenario shows a larger impacted area compared to the other two scenarios. The average circulation for the dry weather scenario (1st of June to the 30th of June 2016) is mainly going southeast and the currents will flush the pollutants coming out of the outfalls outside of the embayment. In the other two scenarios (25th of November to 15th of December 2016), the average circulation shows that the current inside the two embayment is pushing the pollutants back towards the outfalls (see Figure 3.16). It is also noteworthy that the impacted zones consistently remain within the two embayment where the circulation is less effective and the bathymetry shallower. In contrast, in the central part of the bay, where bathymetry is deeper and circulation more effective, pollutant concentrations become negligible. This study also highlights the role of particles size in determining environmental risk. There is a critical size of $50\text{ }\mu\text{m}$ for which the impact is the highest. Particles of

smaller size will tend to stay in suspension longer and be transported and diluted over a larger area, whereas bigger particles will have a higher sedimentation speed and will settle much closer to the outfalls, reducing the size of the impacted area.

Whether the pollution originates from desalination and power plants or from stormwater discharges, our study shows that the impact remains mostly local, typically extending at most a few kilometers from the outfalls. On a larger scale, the waters of the Gulf do not appear to be significantly affected. However, this localized impact should not be underestimated. As noted by Leng et al. (2024), discharges from desalination and power plants can substantially alter the physical and chemical characteristics of the surrounding environment, modifying parameters such as dissolved oxygen, pH, and bottom sediment composition. Marine organisms are highly sensitive to such changes in their ecosystems, and effluents from industrial facilities can significantly affect their growth and reproductive patterns (Gao et al., 2023; Kim et al., 2017; Mariu et al., 2023; Michie et al., 2020). These ecosystem alterations are even more pronounced on the seabed due to the higher density of the brine plume, which tends to settle at the bottom (Leng et al., 2024; Roberts et al., 2010). Benthic organisms are especially vulnerable because of their limited mobility, which reduces their capacity to escape adverse conditions (Smith et al., 2023). Similar concerns have been raised by Hasna et al. (2024) and Mamoon et al. (2019) regarding the vulnerability of benthic communities to pollutants from stormwater, particularly due to sedimentation of TSS on the seabed. Changes in benthic communities may also trigger cascading effects throughout marine ecosystems. Benthic organisms play a crucial role in the aquatic food web, serving both as prey for higher trophic levels and as decomposer that maintain ecosystem health (Leng et al., 2024).

Several studies have explored methods to reduce the environmental impact of marine pollution. As it is already the case for many desalination plants, Einav and Lokiec (2003) and Hashim and Hajjaj (2005) for instance recommend for the combination of desalination and power plants, using the cooling water from the power plant to dilute the desalination brine. According to Lattemann and Höpner (2008), minimizing environmental impact involves selecting exposed rocky or sandy shorelines with strong currents to enhance dilution and dispersion of the effluent. Similarly, Al-Barwani and Purnama (2007, 2008) and Shao and Law (2009) emphasize that discharge points should be located further offshore to benefit from greater flushing capacity. Leng et al. (2024) suggests that the use of cooling towers or heat exchangers can lower the temperature of the effluents, thereby reducing their environmental impact. Regarding stormwater pollution in Doha Bay, El-Magharaby et al. (2008) proposes several recommendations: monitoring the quality of discharged water, applying primary treatment before discharge,

increasing green spaces to reduce runoff, and improving the sewage network to cover all urban areas. Although these measures do not eliminate environmental risks entirely, their combined implementation could significantly reduce the overall impact. It is also noteworthy that a new drainage infrastructure project is currently under development in southern Doha (Verros et al., 2023). This project includes a 10 km underwater outfall tunnel designed to discharge stormwater from new suburbs south of Doha into a well-flushed offshore area. A diffuser will be installed at the tunnel’s end to promote better mixing and prevent pollutant accumulation at the outfall site.

4.3 Limitations and perspectives

While our study provides valuable insight into the impact of pollution on the east coast of Qatar, it is subject to several assumptions and limitations. This section discusses the most important of these and suggests improvements for future studies.

One of the major limitations of our model is the coarse resolution of the bathymetry. As highlighted multiple times in this work, the GEBCO bathymetry lacks precision, especially near the coast. This is particularly problematic for our model, as most of the impacted areas are located close to the shoreline. In some regions, such as Doha Bay, finer bathymetry data are available, but this is not yet the case on a larger scale. While switching to a higher-resolution bathymetry may not drastically change the overall results, it would likely produce more accurate and reliable outputs.

Another source of inaccuracy is caused by the salinity forcing provided by the CMEMS GLORYS product. The salinity values obtained in our study are significantly lower than some observed values and those reported in other studies (Belthaji, 1983; Elobaid et al., 2022; Michael Reynolds, 1993; Nesterov, 2025). To improve accuracy, the simulation should be extended over a longer period of time and the domain expanded to include the entire Gulf and the Strait of Hormuz. This would allow the open boundary to be located in a region with more reliable external forcing, enabling the model to converge towards realistic salinity values.

To assess the impact of desalination and power plants, several assumptions were necessary to cover for the lack of detailed data on the characteristics of the discharged effluents. It was assumed that all desalination plants operate with a uniform recovery ratio ($r = 40\%$) and an excess temperature of $\Delta T = 11.1^\circ\text{C}$. In practice, these parameters vary according to the technology employed, leading to

variations in the salinity and temperature of the discharged brine. For instance, RO desalination plants rely on electricity and therefore have only a minor thermal impact compared to plants using thermal processes such as MSF and MED. For the sake of simplicity, identical values were applied across all plants. A more accurate approach would involve incorporating the relative contribution of each technology type to better represent discharge characteristics. Assumptions were also made for thermal power plants, with thermal discharges estimated using a temperature difference of 10°C and a plant efficiency of 60%. These values could be adjusted for each facility to improve accuracy. For instance, although modern combined-cycle gas turbines (CCGT) can achieve efficiencies up to 60%, older power plants might be less efficient and therefore require greater volumes of water for cooling. The model's reliability could also be enhanced through validation with in situ salinity and temperature measurements; however, such data were not publicly available at the time of our study.

Although some data are available for the stormwater outfalls in Doha Bay, it is important to note that these data are nearly ten years old and may no longer accurately reflect today's conditions. Aboobacker et al. (2024) mention that since the FIFA 2022 World Cup, there are more controls in the discharge which improved the water quality. While FC and TSS concentrations were not directly assessed, it is likely that their levels have decreased since 2016. This work employs a simplified approach to modeling FC dynamics. As highlighted by de Brauwere et al. (2014) in a review of multiple studies on fecal indicator modeling, numerous environmental and biological factors can influence FC concentration and dispersion. For example, some studies suggest that, rather than assuming a constant decay rate, FC degradation may follow a biphasic pattern with a rapid initial decay followed by a slower phase. Moreover, field observations indicate that a significant fraction of FC may be attached onto suspended solids, which tend to settle over time. These particle-associated FC exhibit slower decay rates due to reduced exposure to sunlight compared to free-floating particles. In addition, the sediment layer, which is typically nutrient-rich, may promote regrowth of FC (Thupaki et al., 2013). Thupaki et al. (2013) also emphasize that resuspension of FC from sediments can represent a substantial secondary source of contamination, particularly at site far from stormwater outfalls. As emphasized by de Brauwere et al. (2014), the modeling of FC is complex and depends on multiple factors that are often specific to the study domain and objectives. Including all influencing processes is not always the most effective approach, as it can introduce additional uncertainties. Given the data availability for Doha Bay, the model used in our study provides a reasonable approximation of the situation. Nonetheless, the incorporation of more recent and site-specific measurements could improve the model's output.

While our study focuses on the coastal areas of Qatar, its findings are likely applicable to other Gulf countries such as the UAE, Saudi Arabia, and Kuwait, where rapid industrialization and intense coastal urbanization pose similar pollution challenges. Although the results cannot be directly applied to other study areas, it is reasonable to assume that desalination and power plants, along with stormwater outfalls, could have comparable environmental impacts. Applying our modeling approach to other coastal areas would allow for a better understanding of pollutant dispersion across the Gulf and could support regional strategies for marine ecosystems protection and sustainable coastal development.

Chapter 5

Conclusion

Over the past few decades, Qatar has experienced rapid urbanization and industrialization, raising growing concerns about the environmental impacts on marine ecosystems. Our study assessed the effects of urban and industrial discharges, particularly focusing on desalination and power plants along Qatar's east coast, as well as stormwater discharges into Doha Bay.

The first step was to accurately model the hydrodynamics in the study area using SLIM3D, which simulated current circulation, salinity, and temperature. An Eulerian transport model was then employed to simulate the dispersion of various pollutants. Our study focused on the impact of brine and thermal discharges from desalination and power plants, and the impact of FC and TSS from stormwater outfalls.

Despite some limitations related to Gulf bathymetry and salinity forcing, the results are consistent with previous studies. The impact of discharges is highly dependent on the outfall location, with bathymetry and exposure to current circulation being the most influential factors. Deeper bathymetry and stronger currents promote dispersion, while shallower, more enclosed areas with limited circulation lead to higher concentrations, mostly located around the outfalls. The density of the pollutant also plays a key role. Brine and TSS, being denser, tend to accumulate near the seabed, whereas FC and thermal discharges remain closer to the surface. Although the extent of the impacted area varies with outfall location, the effects remain mostly local.

An environmental risk assessment was then conducted in Doha Bay to evaluate bathing water quality and the potential contamination by hazardous substances adhered to TSS. The most affected areas are the two embayment, particularly in the vicinity of the outfalls, while the rest of the bay experiences only minor or

negligible impact. Our study also highlights the role of particle size in pollutant dispersion. Smaller particles remain suspended longer and disperse more widely, reducing their concentration, while larger particles settle more quickly, confining the impact to the immediate vicinity of the outfalls.

Overall, the model provided valuable insights into the environmental impact of coastal discharges on marine ecosystems. It demonstrated the importance of outfall location, local hydrodynamics, and pollutant characteristics in determining dispersion patterns and environmental risks in the coastal waters of Qatar.

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Appendix A

Validation of the current at multiple depth

Comparison between modeled and observed currents offshore of Doha (OD1) at multiple depths. From -6 m to -10 m, the model show good agreement with the observations. At -2 m and -4 m, the model shows similar current characteristics to those observed at greater depths, but the observations appear to be unreliable. Given the proximity of the observation site to a navigation channel, it is likely that boat traffic introduced disturbances in the measured data.

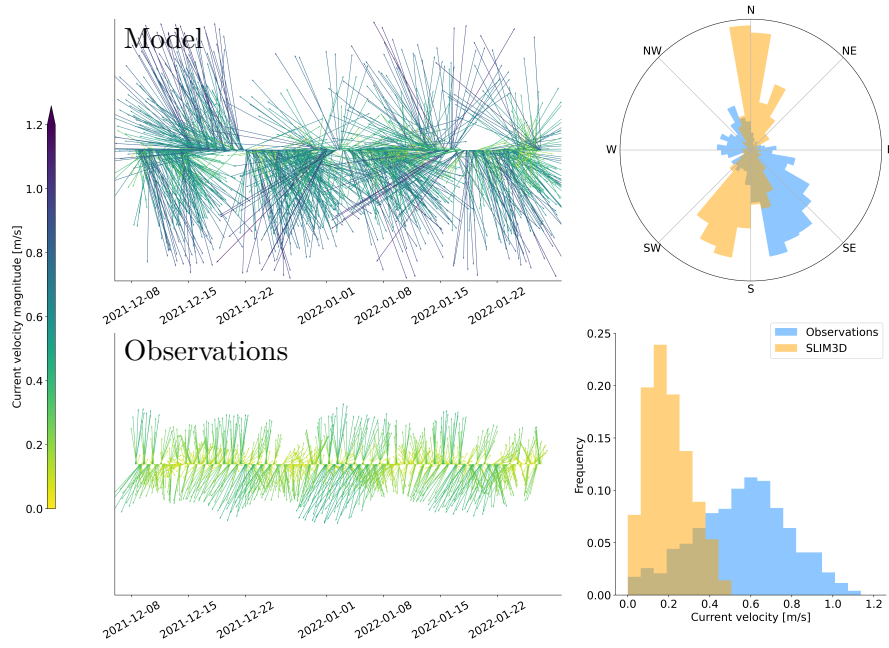


Figure A.1: Comparison of the modeled and observed current offshore of Doha (OD1) at -2 m. Histograms on the left compare the amplitude and direction of the currents.

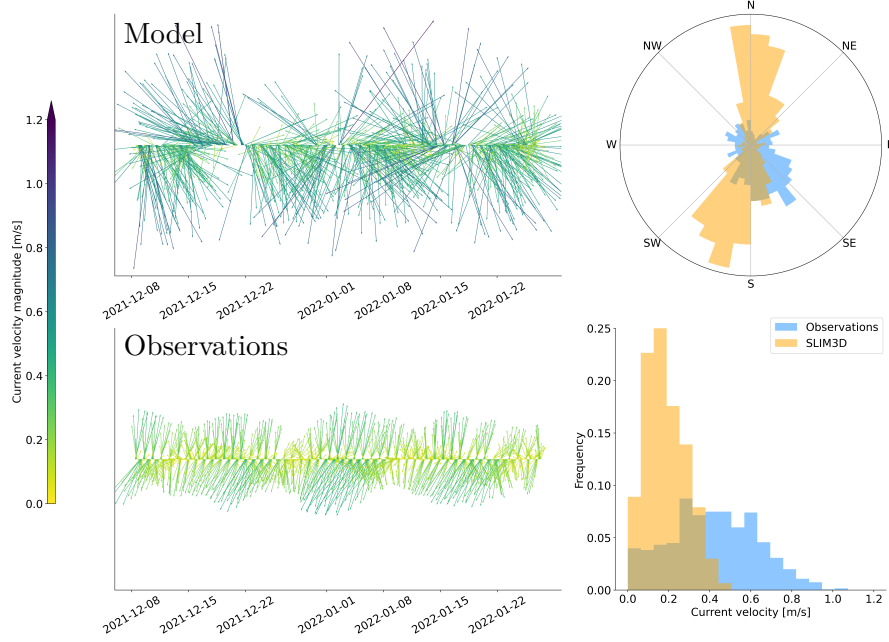


Figure A.2: Same as [Figure A.1](#) but at -4 m.

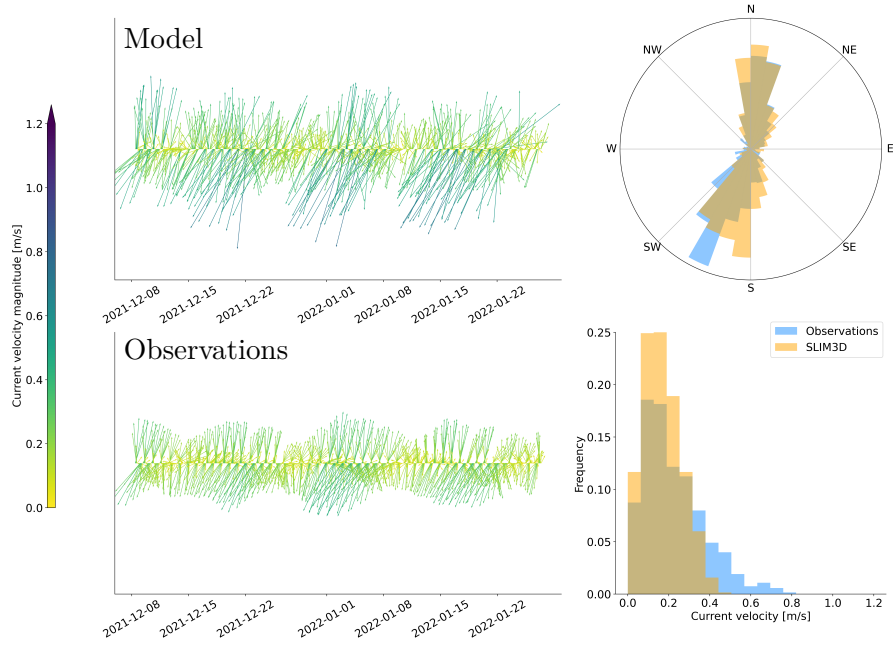


Figure A.3: Same as Figure A.1 but at -6 m.

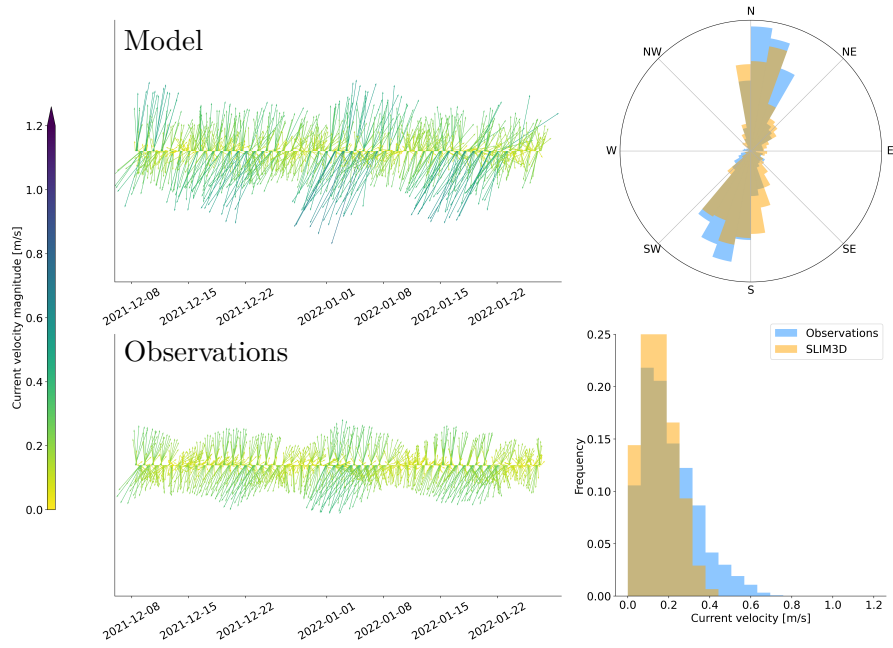


Figure A.4: Same as Figure A.1 but at -8 m.

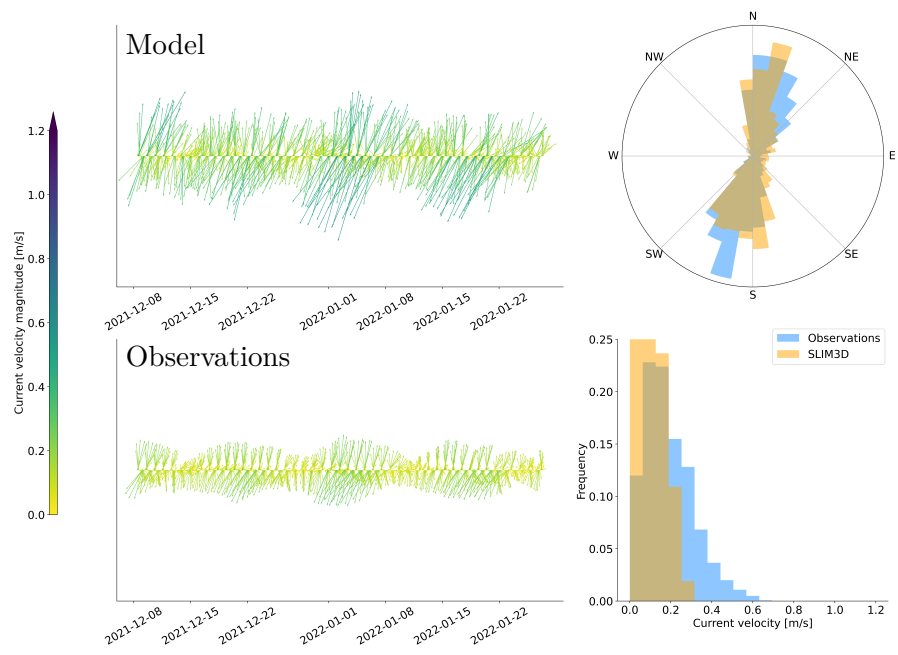


Figure A.5: Same as [Figure A.1](#) but at -10 m.

Appendix B

GEBCO bathymetry at the location of the desalination and power plants

The GEBCO bathymetry indicates that the outfalls of the desalination and power plants are located in areas with depths of approximately 2 meters. While this may be a good approximation of the real conditions in Ras Abu Fontas and Um Al Houl, it is likely that the actual bathymetry in Ras Laffan and Messaieed is significantly deeper in order to accommodate large commercial vessels.

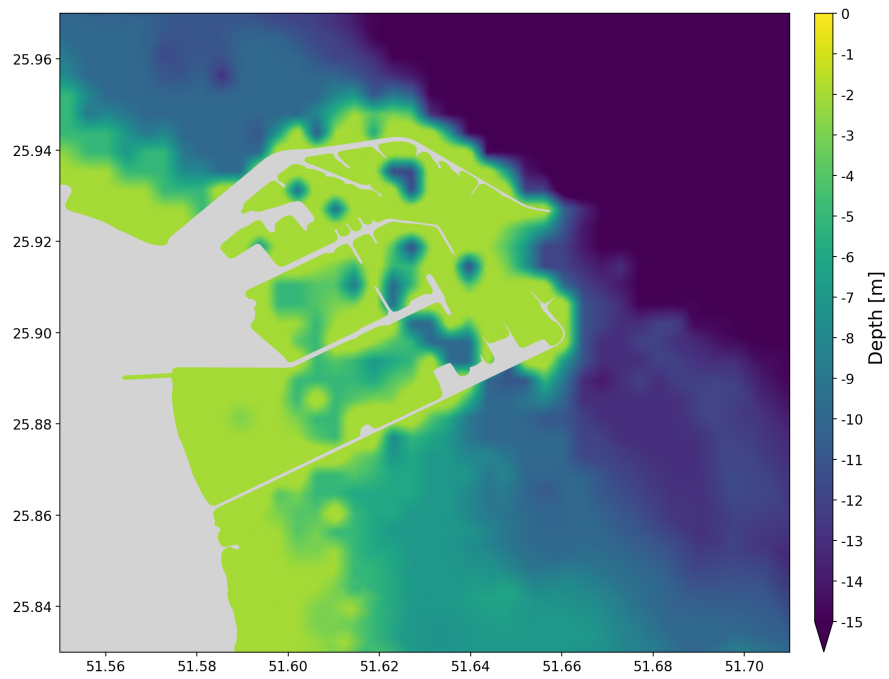


Figure B.1: Bathymetry in Ras Laffan

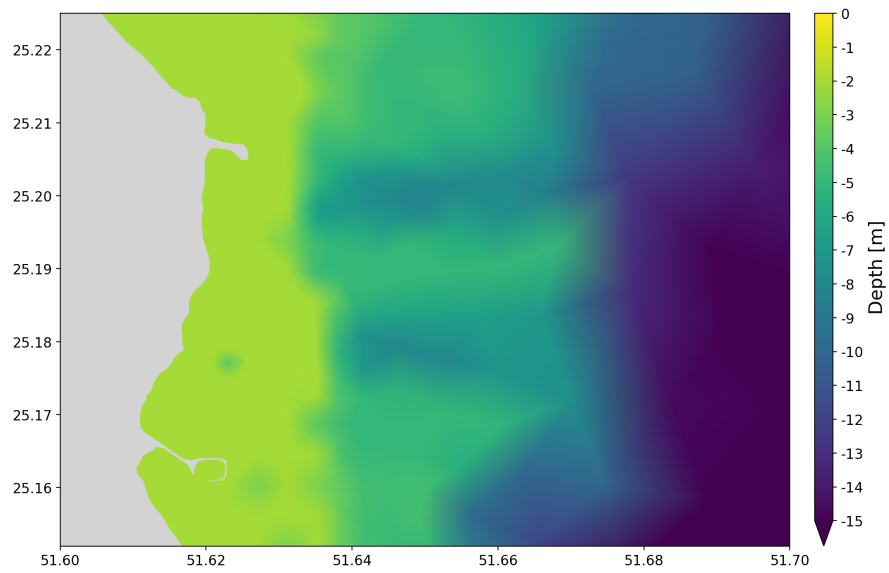


Figure B.2: Bathymetry in Ras Abu Fontas

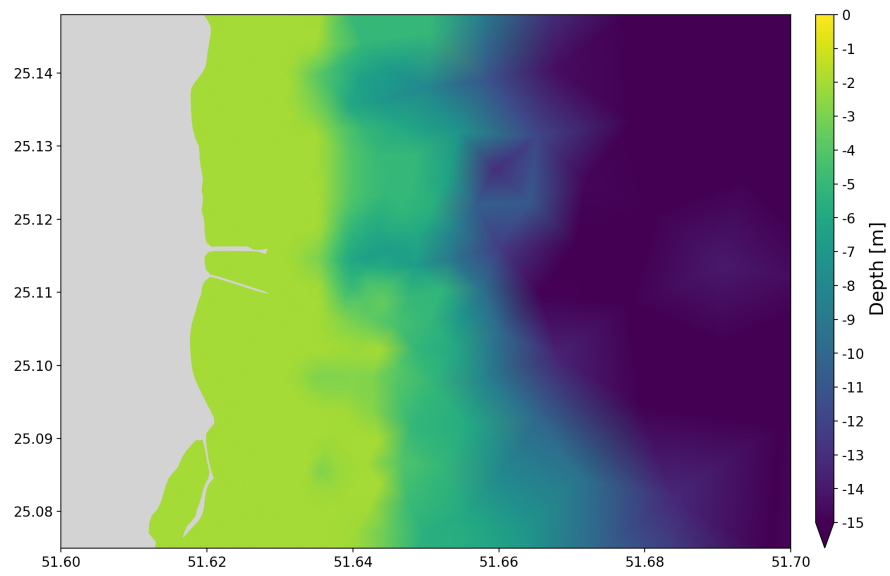


Figure B.3: Bathymetry in Um Al Houl

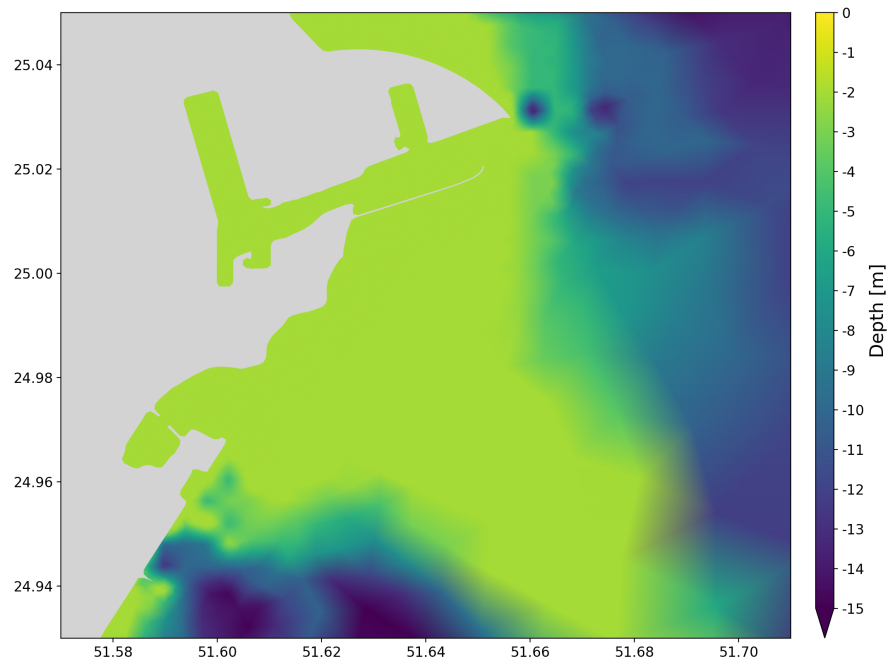


Figure B.4: Bathymetry in Mesaieed

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