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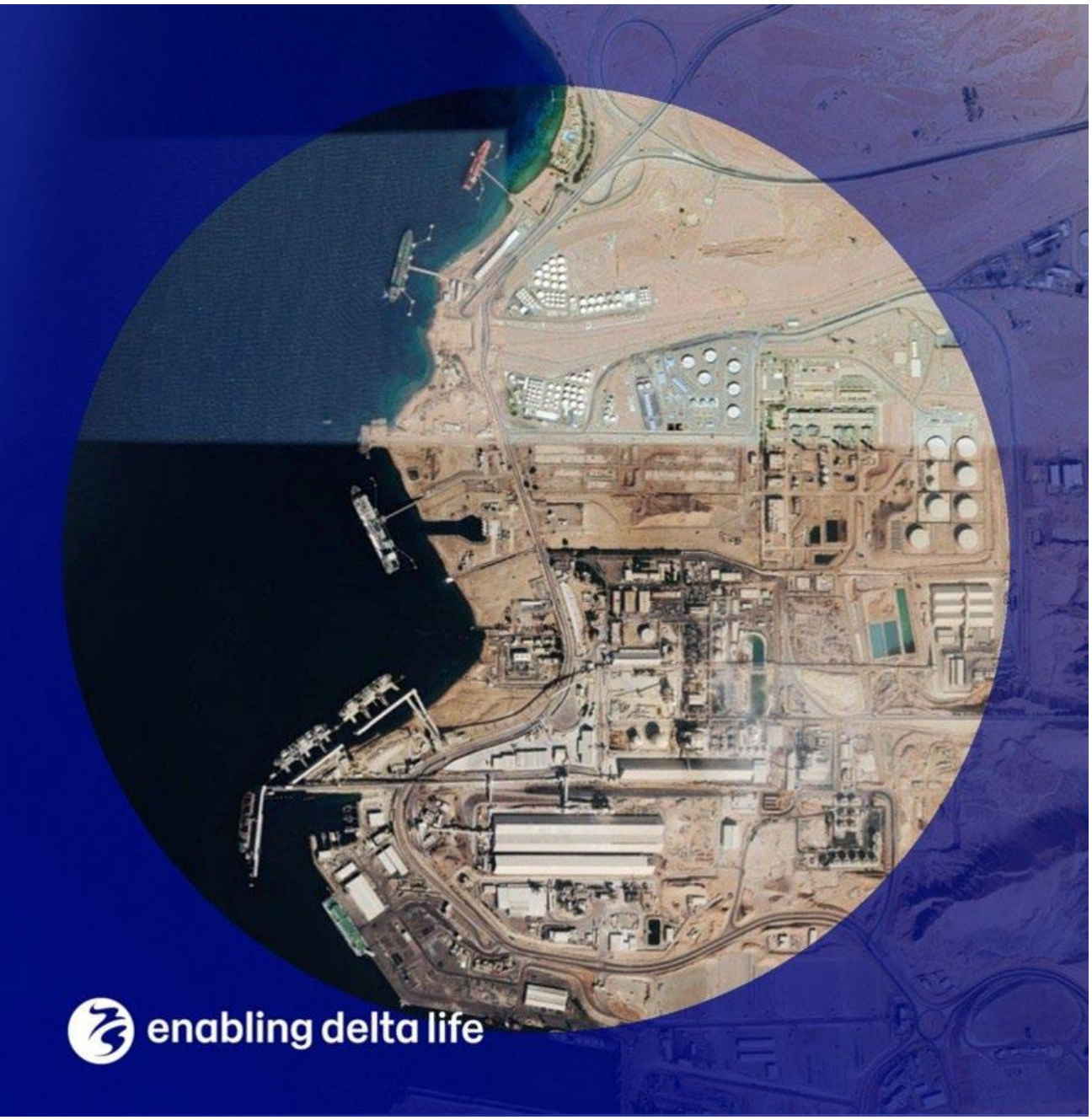
Aqaba-Amman Water Desalination and Conveyance Project: Brine Plume Dispersion Modelling, Sensitivity Analysis and CFD Comparison



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Aqaba-Amman Water Desalination and Conveyance Project:
Brine Plume Dispersion Modelling, Sensitivity Analysis and CFD Comparison

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Executive Summary

The Aqaba-Amman Water Desalination and Conveyance Project (AAWDCP) is a nationally strategic infrastructure project intended to address Jordan's long-term water-security challenge. As the project advances towards environmental approval and financial close, the behaviour of the proposed brine discharge into the Gulf of Aqaba is a central issue for regulators, lenders, financiers and government decision-makers. Deltares was commissioned by Energies Group to provide an independent assessment of the expected brine plume behaviour from the proposed AAWDCP marine outfall, combining Delft3D-FM modelling by Deltares for the outfall plume dispersion towards offshore with detailed CFD modelling results prepared by ATM for the immediate outfall area. This dual-modelling approach provides a strong pre-construction basis for assessment, because two fundamentally different modelling methods have been compared before the outfall is built and before operational monitoring data are available.

The results indicate that the proposed diffuser and canyon-based outfall concept provide a credible basis for managing the brine discharge. After initial mixing close to the diffuser, the dense brine plume is expected to collapse towards the seabed and move downslope as a gravity-driven density current, with the local submarine canyon guiding the plume towards deeper water and limiting lateral spreading towards sensitive nearshore areas outside the canyon. The Delft3D-FM and CFD results show broad consistency in the transition zone where both models are considered to provide reliable results, increasing confidence that the modelling provides a robust and conservative basis for environmental decision-making. The final model simulations use a 'most realistic' set of model parameters based on the sensitivity analysis and predict that the 5% excess-salinity contour remains close to the seabed and largely within the canyon pathway. Computed transboundary excess-salinity values are approximately 0.1 to 0.15 psu (i.e., a dilution factor of about 250 – 350). This corresponds to about 0.25% to 0.35% of the background salinity. Recirculation towards the intake is less than 0.1 psu, and any residual long-term salinity anomaly is expected to be small, diluted and dispersed over a wide offshore area. Overall, the assessment provides a reliable basis for progressing environmental assessment, permitting, lender due diligence and government-level decision-making, subject to final design confirmation and post-construction monitoring.

Summary

The Aqaba-Amman Water Desalination and Conveyance Project (AAWDCP) is a strategic large-scale infrastructure project that is central to Jordan's National Water Strategy (2023-2040) and aims to secure sustainable municipal water supply and reduce destructive groundwater over-pumping. AAWDCP is currently reaching its final stages of achieving environmental approvals necessary for securing project finance, and Deltares were commissioned by Energies Group to support the project's Environmental Impact Assessment Studies. This report presents the expected brine plume behaviour and supporting the environmental impact assessment of the proposed AAWDCP outfall.

As part of the marine works associated with the operation of the AAWDCP, the resulting concentrated brine from the proposed seawater reverse osmosis plant will be discharged through a marine outfall into the Gulf of Aqaba. This report details the modelling assessment undertaken to assess the proposed diffuser and near-field plume behaviour and compares modelling approaches using ATM's detailed CFD results for the immediate outfall area, and Deltares' Delft3D-FM model for the broader far-field plume dispersion. This includes sensitivity analysis of the expected brine plume dispersion to test how numerical and physical parameters affect the predicted plume extent, especially the 2% and 5% excess-salinity contours. The work builds on the original rapid assessment Delft3D-FM far-field modelling conducted in Q4 2025, and incorporates additional analysis to assess the robustness of the plume predictions, the suitability of the proposed diffuser design, and the consistency between Deltares' far-field modelling and the detailed CFD modelling undertaken by ATM.

The modelling work developed progressively throughout the project's lifecycle that started in October 2025, in response to requirements raised by the project sponsors, regulators, and to support the project proponent (The National Carrier Project Company) in achieving the necessary environmental approvals. It was initially set up as a rapid assessment, based on the information available at the time, to provide an early indication of plume behaviour. As the project design evolved, additional questions arose regarding a different diffuser outfall location and design, the diffuser performance, near-field behaviour, interaction with the submarine canyon bathymetry, and the potential extent of far-field dispersion. The assessment was therefore expanded to include a systematic sensitivity analysis, comparison with the ATM CFD simulations, and additional model simulations that define the Most Realistic and Conservative model settings and uses them to assess final plume behaviour, including side-slope intrusion, offshore transport, transboundary effects, and recirculation risk.

The outfall concept that was studied in the present project was proposed by and received from the EPC contractor and consists of a multiport diffuser discharging into a submarine canyon. The EPC design philosophy is intended to keep the dense brine plume largely confined within the canyon, thereby reducing the likelihood of interaction with nearby coral communities outside the canyon. The diffuser comprises six ports, with three smaller onshore ports and three larger offshore ports. Near-field analysis indicates that the discharge undergoes initial momentum-driven mixing close to the diffuser before collapsing back towards the seabed and continuing downslope as a dense gravity current. This transition from near-field jet behaviour to far-field density-current behaviour is central to the interpretation of the modelling results.

ATM's CFD model provides a detailed representation of the immediate outfall zone (in the first tens of metres around the outfall), where jet momentum, negative buoyancy, and entrainment dominate plume behaviour. Deltares' Delft3D-FM model provides the broader hydrodynamic and salinity-transport modelling approach needed to assess transport and dispersion beyond

this immediate diffuser region. The comparison between both approaches focuses on the transition zone (the area between the first and second narrowing of the canyon, between about -30m and -100m MSL), where outputs from the CFD and Delft3D-FM models overlap and can be meaningfully compared.

A Simplified Delft3D-FM model was developed alongside the Full Model to efficiently test key numerical, physical and operational sensitivities, after confirming that it sufficiently accurately reproduced the relevant plume behaviour; the results were then used to define the most realistic model settings, intended to provide the best estimate of expected plume behaviour, plume spreading and side-slope intrusion.

The overall findings indicate that the plume behaviour is governed primarily by the dense nature of the brine discharge and the local canyon geometry and slope. The proposed diffuser results in initial dilution close to the outfall, after which the plume follows the seabed downslope as a density current. The canyon acts as an important controlling feature for plume transport, helping to guide the plume towards deeper water. It is noted that the computed density-current velocities of about 1 m/s may mobilise fine bed material, potentially causing local seabed morphology changes and suspended sediment generation, although this has not been quantified in the present study and may require further assessment for environmental evaluation. The comparison between the Delft3D-FM and CFD results shows a broadly consistent prediction of plume behaviour in the overlapping region, supporting the robustness of the modelling approach.

The CFD modelling is considered most applicable in the immediate vicinity of the diffuser, where detailed jet-scale processes are important. Further away from the diffuser (from about 100m), the Delft3D-FM model is more appropriate because it better represents larger-scale bathymetry, stratification, ambient circulation, and far-field density-current behaviour. The combined use of both tools therefore provides a stronger basis for assessment than either model would provide in isolation. Although the CFD model has limitations for long-distance dispersion assessment, it remains a valuable independent benchmark for the near-field and transition-zone behaviour.

The final Full Model simulations using the most realistic model settings obtained from the sensitivity analysis provide the basis for assessing the expected plume extent at excess-salinity levels of 2% and 5% above background salinity. Based on the modelling results, the assessment indicates that the plume is expected to remain primarily within the canyon pathway. These simulations also support evaluation of potential transboundary transport (approximately 0.1 to 0.15 psu increase (i.e., a dilution factor of about 250 – 350), corresponding to about 0.25% to 0.35% of the background salinity) and recirculation towards the intake (<0.1 psu increase).

Overall, the robustness of the modelling results has been demonstrated through a comprehensive sensitivity analysis of the Delft3D-FM model and an independent comparison with detailed CFD simulations undertaken by ATM. While direct validation against field measurements is not yet possible because the outfall has not been constructed or operated, the study benefits from a unique opportunity to compare two fundamentally different numerical modelling approaches. Such detailed inter-model comparisons are rarely available during the pre-construction phase of major infrastructure projects. The strong level of agreement between the Delft3D-FM and CFD predictions therefore provides a high degree of confidence in the reliability of the modelling results and the predicted behaviour of the brine plume, and for supporting the environmental assessment of the proposed discharge.

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1 Introduction

1.1 Introduction

The Aqaba-Amman Water Desalination and Conveyance Project (AAWDCP) also known as the National Conveyance Project is the backbone of The Hashemite Kingdom of Jordan's future water supply. Jordan's National Water Strategy (2023 – 2040) recognises this large-scale infrastructure initiative as a primary non-conventional water source to address the increasing demand on water resources and enable groundwater recovery. When operational, the AAWDCP will desalinate 300 million cubic metres of water annually, bridging 45% of municipal supply gaps by 2040. AAWDCP will be achieved through the construction of marine infrastructure, a desalination plant in Aqaba (the Red Sea), a 438-kilometer pipeline, and the integration of c. 281 MWp of renewable energy.

The National Carrier Project Company (NCPC) was established as a Special Purpose Vehicle (SPV) to develop, finance, construct, operate, and maintain the AAWDCP. Further, the Engineering, Procurement, and Construction (EPC) contractor is responsible for producing the design documents that focus on the marine operational aspects of the plant. Whilst ATM is the specialist marine modelling consultant working for the EPC contractor, Deltares were commissioned by Energies Group[1] as an independent consultant and a third-party reviewer to assess the expected brine plume behaviour through comparison of models used by Deltares and ATM.

The operation of the AAWDCP will include the discharge of concentrated brine from the proposed seawater reverse osmosis (SWRO) plant through a marine outfall in the Gulf of Aqaba. As part of the environmental impact assessment requirements; plume dispersion modelling was conducted to evaluate the behaviour of the discharge and its potential impacts on the marine environment. Deltares' assessment was dedicated to the Brine Plume Dispersion. For this purpose, the outfall design parameters were produced and provided by the EPC. For the model validation assignment, ATM provided the results of their Computational Fluid Dynamics (CFD) modelling which Deltares utilised to perform the sensitivity analysis presented in this report.

The modelling work for the Aqaba-Amman Water Desalination and Conveyance Project has developed progressively during the project. It was originally initiated as a rapid assessment of brine plume dispersion in October 2025, intended to provide an early indication of the expected outfall behaviour based on the information available at that stage. As the project advanced, and as the outfall design was further developed by the EPC design team and other project parties, additional questions arose regarding diffuser performance, near-field and far-field plume behaviour, interaction with the canyon bathymetry, etc. The modelling scope was therefore expanded over time to address these questions in more detail. The present report brings together the results of this extended assessment. The modelling studies have now reached a stage where conclusions can be drawn on the EPC preferred outfall design, based on a robust combination of Delft3D-FM modelling and sensitivity analysis undertaken by Deltares, and comparison with the detailed CFD simulations undertaken by ATM.

[1] Energies Group is the Lead of the Environmental Impact Assessment Studies for AAWDCP and were commissioned directly by NCPC

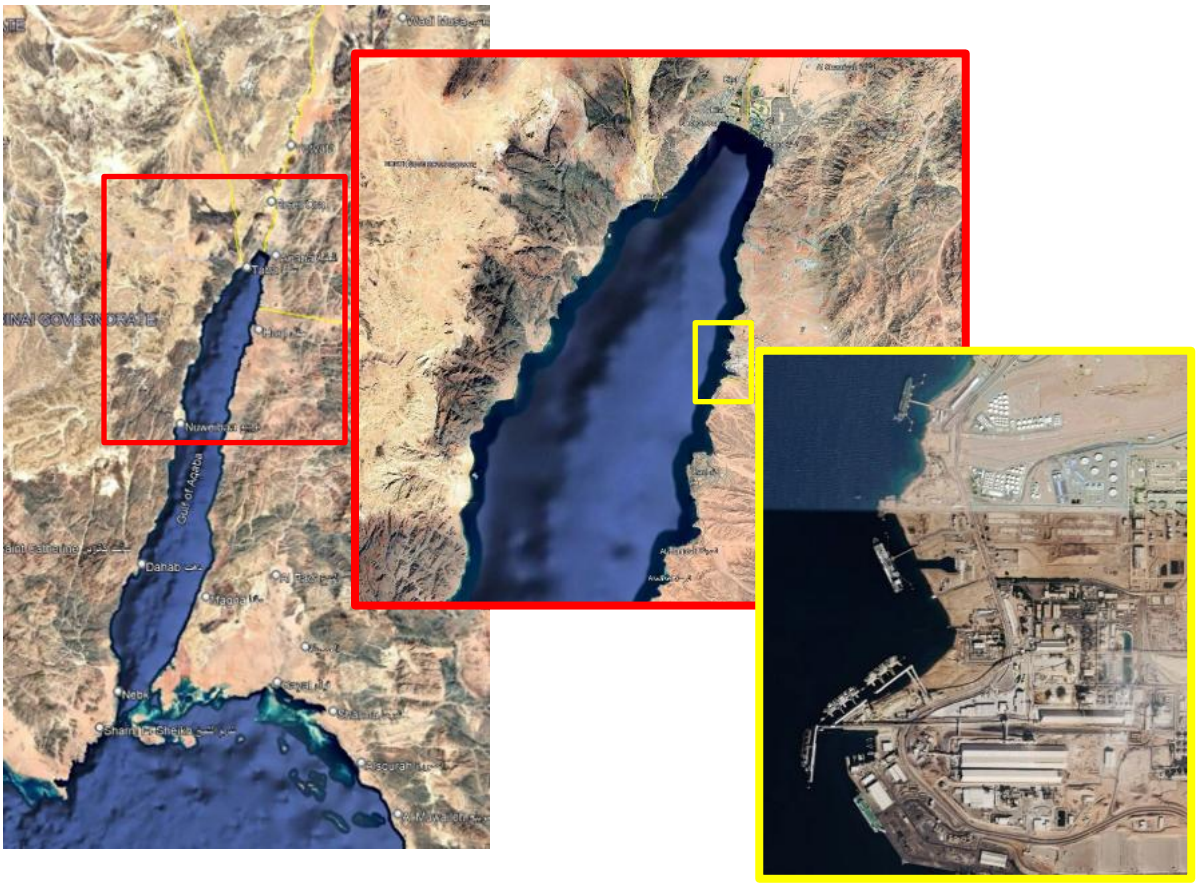

Figure 1.1 Overview project location

1.2 Objective of the study

The main objective of this study is to assess the expected dispersion of the AAWDCP brine discharge using near-field and far-field modelling, and to evaluate the robustness of the modelling results.

The modelling study was initially intended to provide a rapid assessment of the outfall plume dispersion earlier in the project. This initial rapid assessment was based on relatively limited available data and optimised result delivery speed over detail. Over time, the project scope extended and more detailed assessments were carried out, however, still based on the initial modelling assessment. A key component of the extension is a detailed sensitivity analysis on the modelling to assess the robustness of the modelling results. Furthermore, an inter-model comparison was carried out with the CFD modelling completed by ATM. In combination, this study now describes a robust assessment of the brine effluent outfall plume dispersion both in the near-field and far-field to support the environmental assessment of the outfall carried out by others.

Deltares presented the results of the sensitivity analysis and inter-model comparison to the lenders on 22 July 2026. Following that, Deltares received lenders detailed feedback on *18 August 2026.* Section 2.1 of Document ***AAWDCP Marine Works: Required Deliverables to Support Technical and E&S Due Diligence 24062026 - AAWDCP - Marine Works DD road map - Update 28072026*** lists lenders' requirements and these have been listed in Table 1.1 below.

Table 1.1 Traceability of Deliverable 2.1 summarising lenders 'requirements

Deliverable 2.1 Requirement	How the requirement is addressed	Report section
Near-field/far-field integration	Description of the respective modelling scales, the relationship between the ATM and Deltares models and the representation of near-field behaviour in the far-field assessment	3.2
Diffuser design and near-field performance	Summary of the diffuser characteristics and relevant CFD/jet-plume outputs, including dilution, plume trajectory, terminal rise height and touchdown	3.1 and 3.2
Benefit of CFD	Explanation of the diffuser-scale processes resolved by CFD and the contribution of CFD results to interpretation of the far-field model	2.2, 2.2.3, 2.2.6, 3.2, 5.3, 6.2.1, 7.3, and 8
Third-party validation	Independent comparison of ATM and Deltares results, comparison of the Simplified and Full Models and sensitivity analysis of the Delft3D-FM settings	1.1, 1.2, 1.3, 2.2, 2.2.5, 2.2.6, 5.3, 6.1, 6.2, 6.2.1, 6.3, 7.1, 7.3 and 8
Final plume results at 2%, 3% and 5% salinity increase	Presentation and comparison of the final plume contours obtained with the Most Realistic and Conservative model settings	1.2, 1.3, 5.3, 6.2, 6.2.10, 6.3, 7.1, 7.2, 7.3 and 8
Long-term plume behaviour	Assessment of plume propagation, transboundary effects and recirculation over the modelled period	1.2, 1.3, 2.1, 4.1, 4.4, 5.2.2, 5.2.4, 6.2.10, 7.1, 7.2, 7.4, 7.5, 7.6 and 8

In accordance with the lenders requirements of Deliverable 2.1, the specific objectives of the study are to:

- Compare the Delft3D-FM results against the CFD simulations provided by ATM. This comparison aims to assess the robustness and consistency of both modelling approaches and to determine the region where the datasets overlap and can be directly compared.
- Assess the outfall plume dispersion modelling from near the outfall to offshore over the different scales (near-field and far-field), including the relationship between the CFD representation of the plume close to the diffuser and the Delft3D-FM representation of its subsequent transport and dispersion.
- Evaluate the diffuser design and associated near-field performance, including the predicted initial dilution, plume trajectory, terminal rise height, touchdown location and extent of the near-field zone.
- Perform an extensive sensitivity analysis of the Delft3D-FM model to evaluate the robustness of the plume predictions and to identify both the most realistic modelling configuration and a set of conservative yet realistic settings, supported by comparison with the CFD results provided by ATM.

- Present the final plume results at excess-salinity levels of 2%, 3% and 5% above the background salinity, using the selected Most Realistic Delft3D-FM model settings.
- Assess the longer-term behaviour of the plume, transboundary transport and recirculation towards the intake based on expert judgement.

Note that the extensive sensitivity analysis does not only quantify the effect of individual Delft3D-FM parameter choices, it also provides the basis for defining a plausible range of plume behaviour and for supporting the inter-model comparison between the ATM and Deltares modelling results. In particular, the comparison focuses on the extent and vertical structure of the plume along the cross-shore direction, where differences were previously identified in the predicted extent of the 2% and 5% excess-salinity contour.

1.3 Approach

The assessment builds on the Full Delft3D-FM model developed during the initial rapid assessment phase of the study. This model provided the starting point for the present work and was used to represent the large-scale hydrodynamic conditions, density-driven plume transport and far-field dispersion of the AAWDCP brine discharge. The rapid assessment was prepared under time constraints and with limited available data. The present study therefore further develops that initial modelling basis through a systematic sensitivity analysis and comparison with the detailed CFD simulations provided by ATM.

The CFD results were used as supporting information for the inter-model comparison. They provide a detailed representation of the near-field behaviour close to the diffuser, where jet momentum, negative buoyancy and entrainment dominate the plume dynamics. The comparison with the Delft3D-FM results was focused on the Transition Zone, where both modelling approaches provide relevant information and where the far-field model starts to govern the predicted plume development. This comparison was used to assess the consistency between the two modelling approaches and to support the definition of appropriate Delft3D-FM model settings.

To enable a rigorous sensitivity analysis within a practical computational effort, a Simplified Delft3D-FM model was developed from the Full Model. The Simplified Model uses a reduced computational domain around the outfall area and plume trajectory, while retaining the main processes relevant to the density-current behaviour of the plume. This faster model was first checked against the Full Model to confirm that it reproduced the plume behaviour in the area of interest with sufficient accuracy. It was then used to test the sensitivity of the results to key numerical and physical model parameters, including vertical layering, mixing coefficients, bed roughness, grid resolution and near-field dilution.

The outcomes of the sensitivity analysis, together with the comparison against the ATM CFD results, were used to derive two representative sets of Full Model settings. The Most Realistic settings were selected to provide the best estimate of plume behaviour based on the available evidence. The Conservative settings were selected to provide a realistic upper estimate of plume spreading and side-slope intrusion. Both configurations were subsequently implemented in the Full Delft3D-FM model, including the full hydrodynamic forcing and model extent.

The final Full Model simulations were used to evaluate the predicted plume behaviour under the selected Most Realistic and Conservative settings. The assessment considers the spatial extent and vertical structure of the plume, its transport along and across the canyon, possible transboundary effects and the potential for recirculation towards the intake. In this way, the modelling approach provides both a best-estimate prediction and a conservative assessment of the environmental behaviour of the discharge.

2 Main data and starting points for the numerical modelling

This chapter summarises the main information and data used to support the modelling approach, assumptions and starting points of the assessment. The material consists primarily of information received from the Client, supplemented with in-house knowledge and publicly available sources. The chapter does not aim to provide an exhaustive inventory; instead, it identifies the main sources and explains how they were used in the study.

A key source of information is the CFD modelling study carried out by ATM. This detailed hydrodynamic modelling was undertaken specifically to assess flow dynamics and velocities in the immediate vicinity of the outfall, over the first tens of metres from the diffuser. The CFD results also provide useful information slightly farther downstream and were therefore used to support comparison between the CFD and Delft3D-FM modelling approaches.

2.1 Environmental conditions

For the assessment of the near-field behaviour, stagnant ambient conditions were assumed. This is considered conservative for near-field dilution, because ambient currents would generally enhance mixing and increase plume dilution close to the diffuser. The assumption is also considered realistic for the project area, where ambient flow velocities are generally weak, particularly near the seabed, typically only several centimetres per second only. The tidal range is typically about 0.5 m during neap tide and about 0.7 m during spring tide. The influence of the tide on local flow conditions is limited.

All Full Model simulations include a complete spring-neap tidal cycle. Although the tidal variation in the project area is relatively small, it was included to represent the full range of astronomical water-level forcing during the simulations. Due to the limited tidal range and weak tidal currents, the tide is expected to have only a minor influence on the local plume behaviour compared with the density-driven transport of the brine plume.

Seasonal variations mainly affect the ambient water temperature. During the peak summer months, from July to September, surface water temperatures reach approximately 31°C, while temperatures decrease to around 21°C by late March. The surface temperature is typically about 1°C to 3°C higher than the temperature at a depth of approximately 50 m. In contrast, salinity shows only small periodic variations and remains relatively constant throughout the year, oscillating around approximately 40.7 psu. These temperature and salinity conditions were used to define the ambient density structure for the modelling.

A set of representative wind scenarios was selected on the basis of a 10-year historical ERA5 wind dataset from ECMWF[2]. The selected scenarios cover both typical wind conditions and persistent winds from other directions. The typical wind condition represents winds varying between north-northwest and north-northeast, with daily wind speeds generally between 2 and 5 m/s. All wind scenarios were modelled under winter conditions, as near-field dilution is lowest in winter and winter is therefore expected to represent the normative condition for the plume assessment. As part of the sensitivity analysis, additional summer simulations were carried out. These simulations confirmed that the conclusions drawn from the winter simulations remain valid under summer conditions.

[2] Climate reanalysis | ECMWF

2.2 AAWDCP diffuser configuration and effluent characteristics

The EPC design team developed a multiport diffuser for the discharge of AAWDCP brine effluent into a submarine canyon. The concept is based on the assumption that confining the effluent to the canyon will reduce potential impacts on nearby coral communities, which are predominantly located outside the canyon. Consequently, the diffuser was designed to provide a relatively low degree of initial dilution, thereby limiting the spread of the discharge beyond the canyon boundaries and enhancing the gravitational descent of the dense brine plume into deeper parts of the canyon.

The proposed diffuser comprises six ports oriented at a vertical angle of 45° (upward from the riser), see Figure 2.1 and Table 2.1. The first three ports have a diameter of 0.75 m and together convey approximately 30% of the total discharge flow. The remaining three ports have a diameter of 1.0 m and convey the remaining 70% of the flow.

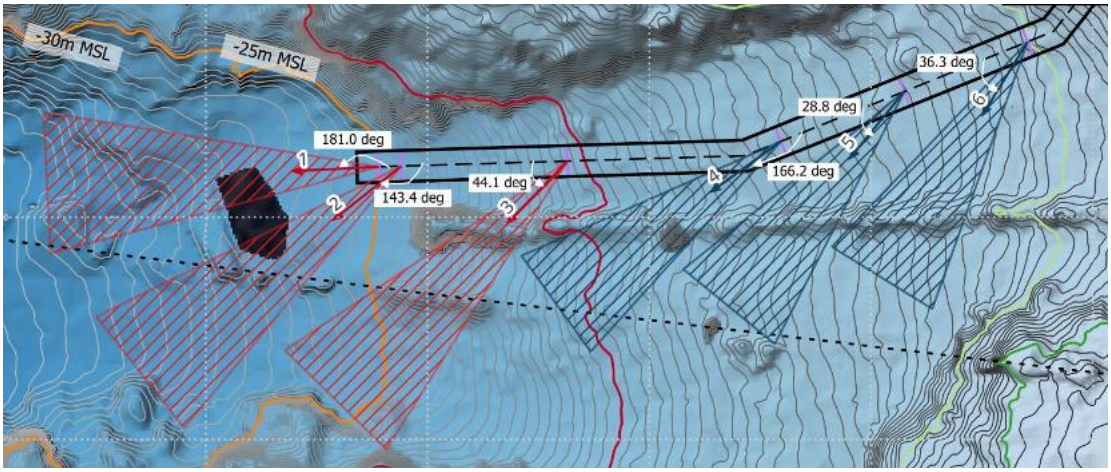

Figure 2.1 Outfall diffuser layout provided by the EPC contractor for use in the present study

In the below table, the characteristics of the SWRO effluent and diffuser, as provided by the EPC contractor are summarized.

Table 2.1 Characteristics of the SWRO intake, outfall effluent and diffuser

Intake	
Flow rate	21.8 m^3/s
Depth at intake locations	About -8 m MSL
Type of intake	Open

Outfall	
Flow rate	11.7 m^3/s
Excess Salinity	+34.8 psu
Excess Temperature	+1 °C
Diffuser length	60m
Outfall pipeline length (from coast to start of diffuser)	~60m
Depth at diffuser	about -16 m MSL to -27 m MSL
Number of risers	6
Number of ports per riser	1 ports per riser
Horizontal orientation of the ports	Variable, see previous slide
Vertical orientation of the ports	45° upward
Port diameter	0.75 m (first 3 ports), 1 m (last 3 ports)
Port spacing	Variable

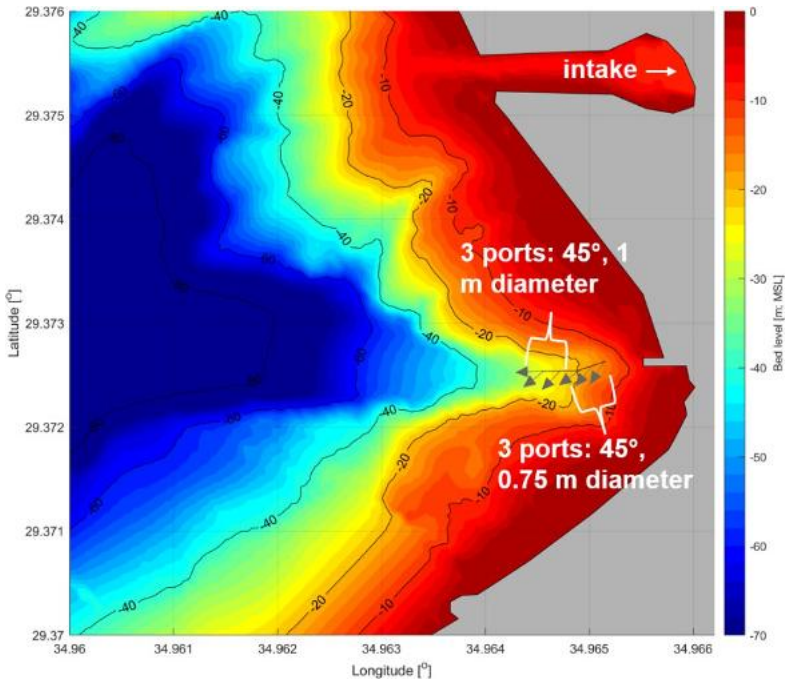

Figure 2.2 Overview of the intake and outfall layout considered in this study

2.3 Nearby industrial charges

The following information on nearby industrial discharges was provided by the Client (see also Figure 2.3):

<u>Phosphates Plant (KEMAPCO)</u>

- Outfall:
  - Single pipe at the seabed at a depth of about -24 m MSL (yellow circle)
  - Flow rate: 5 m^3/s
  - Excess salinity: +1.19 psu
  - Excess temperature: +0.5 °C to +3 °C
- Intake:
  - Open intake (red circle)

<u>NRU</u>

- Outfall:
  - Open outfall at the shore
  - Flow rate: 4.75 m^3/s
  - Excess temperature: -7 °C
- Intake
  - At surface

<u>CEGCO</u>

- Outfall:
  - Outfall pipeline at seabed
  - Flow rate: 4.33, 6.67 or 13 m^3/s
  - Excess temperature: between +0.5°C (average based on operational data) and +3°C (max)
  - Only operational a few days a year. Therefore, it has not been included in this modelling study.
- Intake:
  - Open intake

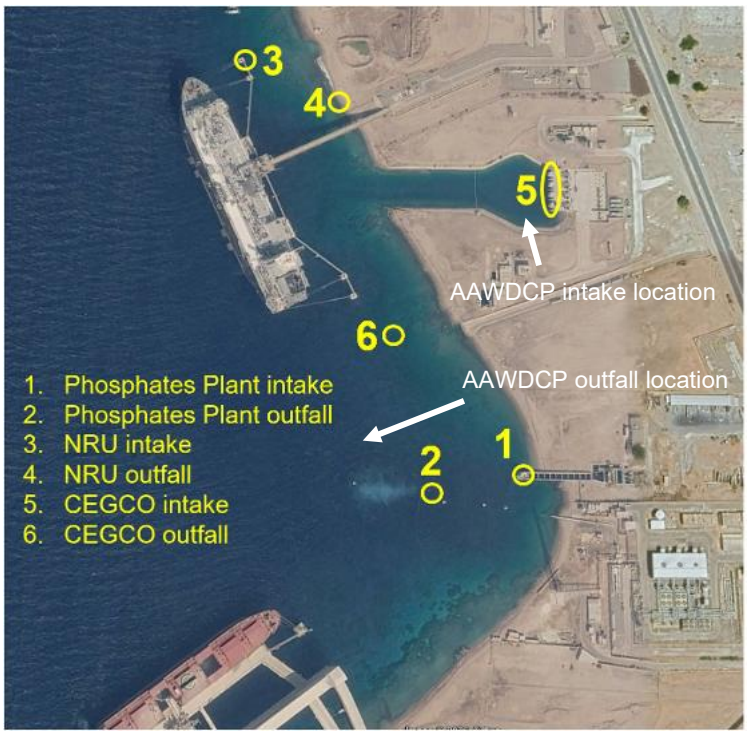

Figure 2.3 Overview of other intakes and outfalls in the project area.

3 ATM CFD modelling study as input to this study

The Client provided the CFD study carried out by ATM as input information to the present study. The CFD results were used to support the inter-model comparison between the CFD model and the Delft3D-FM model. They also informed the sensitivity analysis of the Delft3D-FM model. It is noted that the CFD modelling was set up for a different purpose and with different starting points than the present outfall plume dispersion assessment. A review of the CFD model setup and results was therefore carried out to place the CFD outcomes in the correct context; the main findings of this review are summarised below.

3.1 Background of the ATM CFD modelling study

ATM performed Computational Fluid Dynamics (CFD) modelling of the discharged brine plume[3] with the Flow3D modelling software, see Figure 3.1 for illustration. The primary objective of the CFD analysis was to evaluate flow velocities in the vicinity of the outfall and to assess the associated scour potential. The CFD results also provide valuable insight into plume behaviour close to the diffuser, where the governing processes are dominated by jet momentum, negative buoyancy, and entrainment.

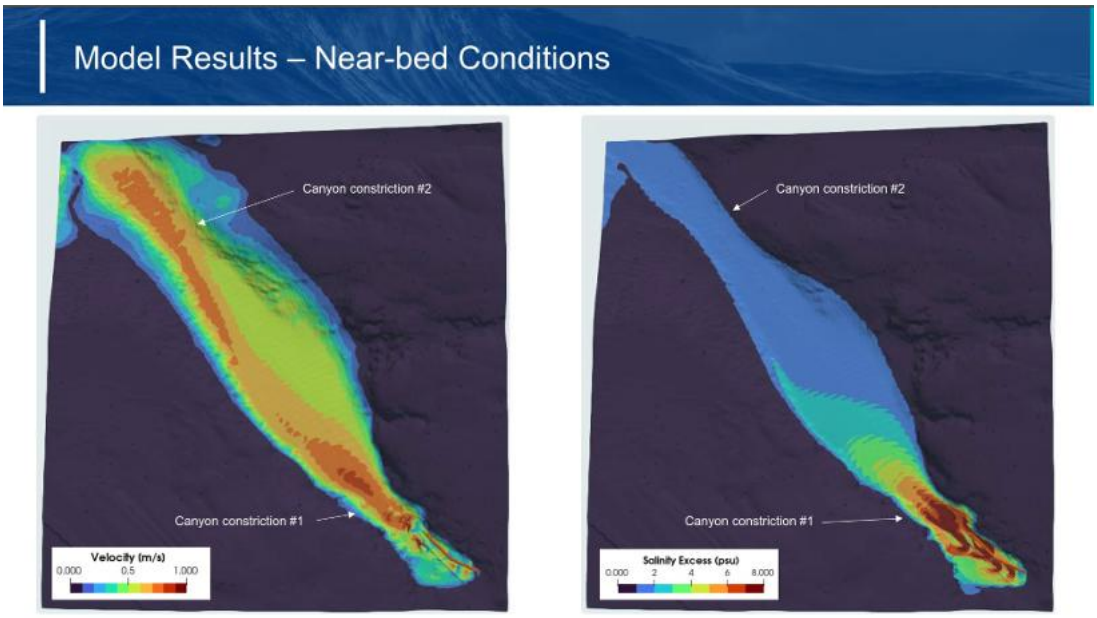

Figure 3.1 Example output from the CFD modelling by ATM (source: ATM's Outputs Summary for Petrofac's Assessment dated 7/7/2026) – for illustration.

As Section 5.3 will discuss, plume behaviour further downslope (i.e. beyond 'Canyon constriction #1' as indicated in Figure 3.1) becomes increasingly sensitive to model assumptions as the discharge transitions into a density current. Consequently, a dual-modelling approach was adopted, with CFD applied to the immediate outfall zone, Delft3D-FM to the far field, and the overlap between both models evaluated within a defined transition zone (see e.g. Figure 5.6).

[3] *Aqaba-Amman Water Desalination and Conveyance Project (AAWDCP), ME255043 – EGC Gas Pipeline Interface – CFD Study: Outputs Summary for Petrofac's Assessment*, dated 07 July 2026.

ATM provided a 3D salinity dataset with values defined for each grid cell in a local project coordinate system. To facilitate comparison with the Delft3D model results, the dataset was transformed to UTM Zone 36N, assuming that the local origin (0,0) corresponds to x = 690,672 m and y = 3,250,874 m. A 45° rotation was subsequently applied to align the coordinate systems.

The Computational Fluid Dynamics (CFD) modelling undertaken by ATM was originally developed to evaluate the hydraulic performance of the proposed diffuser and to assess flow velocities in the immediate vicinity of the outfall. The primary objective of the CFD simulations was therefore not the assessment of large-scale or long-term brine plume dispersion, but rather the evaluation of local hydrodynamic conditions relevant to diffuser performance and potential scour development around the outfall structure. The CFD model provides a detailed representation of flow behaviour within the first tens of metres surrounding the diffuser where jet momentum, negative buoyancy and entrainment processes dominate the plume dynamics. This zone is commonly referred to as the Immediate Outfall Zone or Near-Field Zone.

As the project progressed, the CFD results were also used as a secondary source of information for interpretation of the brine plume behaviour beyond the immediate outfall region. In particular, the CFD results were compared with the Delft3D-FM far-field modelling performed by Deltares to assess the consistency of the predicted plume behaviour within the Transition Zone, where both modelling approaches can provide meaningful information. This comparison provided a valuable opportunity to compare two fundamentally different modelling methodologies and thereby increase confidence in the predicted plume behaviour.

Although the CFD model provides a highly detailed representation of local flow processes, several aspects of the model setup and numerical schematisation require careful consideration when interpreting the results for plume dispersion purposes. During the course of the review, a number of observations and discussions were held with ATM regarding factors that may influence the predicted plume behaviour.

3.2 Numerical Modelling Approach

The CFD model was developed primarily to resolve local velocity fields and turbulence around the diffuser structure. Such models are generally optimised for resolving jet behaviour and local velocity gradients rather than long-distance transport of density currents. Consequently, numerical settings that are appropriate for local hydraulic assessments are not necessarily optimal for prediction of plume evolution over larger distances.

One important consideration concerns the numerical treatment of salinity transport and mixing. The predicted plume dimensions and dilution rates can be substantially influenced by the selected advection scheme, turbulence closure formulation and scalar transport method. Numerical diffusion associated with the selected numerical schemes may artificially increase dilution rates and plume spreading if not appropriately controlled. During discussions with ATM, particular attention was therefore given to this aspect to assess the applicability of the CFD results for the plume dispersion.

3.3 Computational Domain Size

The CFD computational domain was developed primarily for the assessment of velocity fields around the diffuser and therefore extends only a limited distance offshore. Based on the received model output, the computational domain covers the immediate vicinity of the diffuser and extends downslope to approximately 100-120 m water depth.

For evaluation of local diffuser hydraulics this domain size is considered appropriate. However, for assessment of plume dispersion the limited model extent introduces constraints because the dense brine plume progresses well beyond the CFD model boundaries. As a result, the CFD domain only captures the initial stages of plume development and does not fully represent the subsequent density-current behaviour that governs transport towards deeper sections of the canyon.

The finite domain extent can also influence plume behaviour close to the downstream model boundaries. If boundary effects occur before the plume has fully adjusted to ambient conditions, the predicted plume dimensions and dilution rates may no longer be representative of the actual physical behaviour. For this reason, the CFD results were primarily considered representative within the Immediate Outfall Zone and parts of the Transition Zone only.

3.4 Grid Resolution and type

A significant strength of the CFD model is its extremely high spatial resolution near the diffuser, which is in the order of a 0.2 meters. The fine computational mesh enables detailed resolution of the individual diffuser jets, entrainment processes and local turbulence structures which cannot be represented explicitly in the Delft3D-FM model.

However, maintaining this high level of resolution over larger distances would require prohibitively large computational resources. Consequently, grid cell sizes increase further away from the diffuser and the effective resolution of density-current processes reduces with distance from the source. This is an unavoidable compromise in practical CFD modelling but should be recognised when interpreting plume behaviour at larger distances from the diffuser.

Particular attention was therefore paid to determining the spatial range over which the CFD results can be considered more reliable than the far-field model results. It was concluded that the CFD model provides the most reliable information close to the diffuser, while further offshore the far-field Delft3D-FM model becomes increasingly appropriate and has a higher resolution in the vertical dimension.

In addition to the (vertical) grid resolution, also the type of vertical grid is different in the CFD model (Z-layers) than in the Delft3D-FM model (sigma-layers). Z-layers are layers with a fixed thickness for each layer regardless of the water depth (e.g., 1m thick layers), while sigma-layers are defined as a fixed *percentage* of the water depth (e.g., 10% of the local water depth), and these therefore vary with water depth. A substantial advantage of sigma-layers for modelling a density current near the bed (like the outfall plume), is that sigma-layers are significantly less numerically diffusive compared to Z-layers. This means that while going down the slope, Z-layers (used in the CFD modelling) introduce more (artificial) dilution to the plume than sigma-layers (used in the Delft3D-FM modelling). The sigma-layers therefore generally produce more reliable and realistic results for this type of modelling applications.

3.5 Representation of Ambient Conditions

The primary focus of the CFD model was the representation of the discharge plume itself, rather than the full range of ambient hydrodynamic conditions present within the Gulf of Aqaba. Consequently, ambient forcing conditions such as regional currents, wind-induced circulation, water-level variability and larger-scale density gradients are represented in a simplified manner compared to the far-field Delft3D-FM model.

For local near-field behaviour this simplification is generally acceptable because discharge momentum and negative buoyancy dominate the flow field. However, further away from the diffuser the relative importance of ambient environmental forcing increases. This is one of the

primary reasons why far-field transport and long-term plume development are generally assessed using regional hydrodynamic models instead of CFD models.

It should be noted that ambient conditions in this project area are generally mild, with relatively weak currents and limited external forcing. The influence of these conditions on both the CFD and Delft3D-FM modelling results is therefore expected to be limited.

3.6 Coordinate Transformation and Dataset Interpretation

To facilitate comparison between the CFD results and the Delft3D-FM simulations, the CFD output was transformed from the local project coordinate system to UTM Zone 36N coordinates. During this process, assumptions were required regarding the origin location and coordinate rotation of the CFD dataset.

Although every effort was made to ensure accurate co-registration of both datasets, minor spatial uncertainties may remain in the presented comparison plots. Consequently, the CFD contours should not be interpreted as exact validation targets but rather as an independent benchmark for assessing the overall consistency of the predicted plume behaviour.

3.7 Overall Assessment

The review concluded that the CFD modelling performed by ATM provides valuable information regarding diffuser performance, local flow velocities, plume trajectory and initial dilution near the outfall. The model is considered particularly suitable for assessing processes within the Immediate Outfall Zone where momentum-driven jet behaviour dominates the plume dynamics.

For assessment of larger-scale plume dispersion, several limitations become increasingly important, including the finite computational domain, simplified representation of ambient forcing conditions and the increasing importance of density-current processes beyond the primary CFD focus area. These limitations do not invalidate the CFD results but should be recognised when interpreting plume behaviour at larger distances from the diffuser.

The availability of the CFD modelling study and results for this project does provide a unique and very valuable opportunity for an inter-model comparison with the Delft3D-FM model to validate the results of both models in the absence of the (future) SWRO plant outfall and its operation.

4 Full Delft3D-FM model setup

4.1 Introduction

To evaluate the far-field transport and dispersion of the AAWDCP brine discharge, a three-dimensional Delft3D Flexible Mesh (Delft3D-FM) hydrodynamic model was developed covering the entire Gulf of Aqaba, with highest resolution in the project area. The model was designed to simulate the dispersion of the desalination plant discharge from the outfall diffuser towards deeper waters and to assess possible effects on the surrounding marine environment.

The model represents the relevant hydrodynamic processes influencing plume transport, including ambient circulation, density gradients, stratification, turbulent mixing and interaction with the local bathymetry. Particular attention was paid to the steep canyon bathymetry near the proposed outfall location, as this feature strongly influences the transport pathway of the dense brine discharge.

The Delft3D-FM model was applied in three-dimensional mode to ensure an accurate representation of the negatively buoyant plume behaviour and associated density-current dynamics. The far-field model was coupled with the near-field assessment through the inclusion of the initial dilution and plume characteristics derived from the near-field analysis (Table 3.2).

4.2 Computational Grid

The numerical model was constructed using the Delft3D Flexible Mesh framework, enabling local grid refinement around the outfall while maintaining computational efficiency over a larger regional model domain.

The computational domain extends from 29.55˚in the north to 27.12˚in the south and from the Jordanian coastline towards offshore waters reaching depths exceeding 1700 m.
Grid refinement was applied in the vicinity of the outfall and along the anticipated plume trajectory through the submarine canyon. The highest horizontal resolution was applied near the diffuser location, where cell dimensions are approximately 8 m × 8 m. Grid resolution gradually decreases towards the model boundaries, where cell sizes increase to approximately 3000 m × 3000 m at the most offshore locations.

The flexible mesh approach allows the complex canyon geometry and steep bathymetric gradients to be represented accurately without excessive computational costs.
The model was run in three-dimensional mode using 20 vertical layers. A sigma-layer approach was adopted to accurately represent density-current behaviour near the seabed while maintaining sufficient vertical resolution throughout the water column.

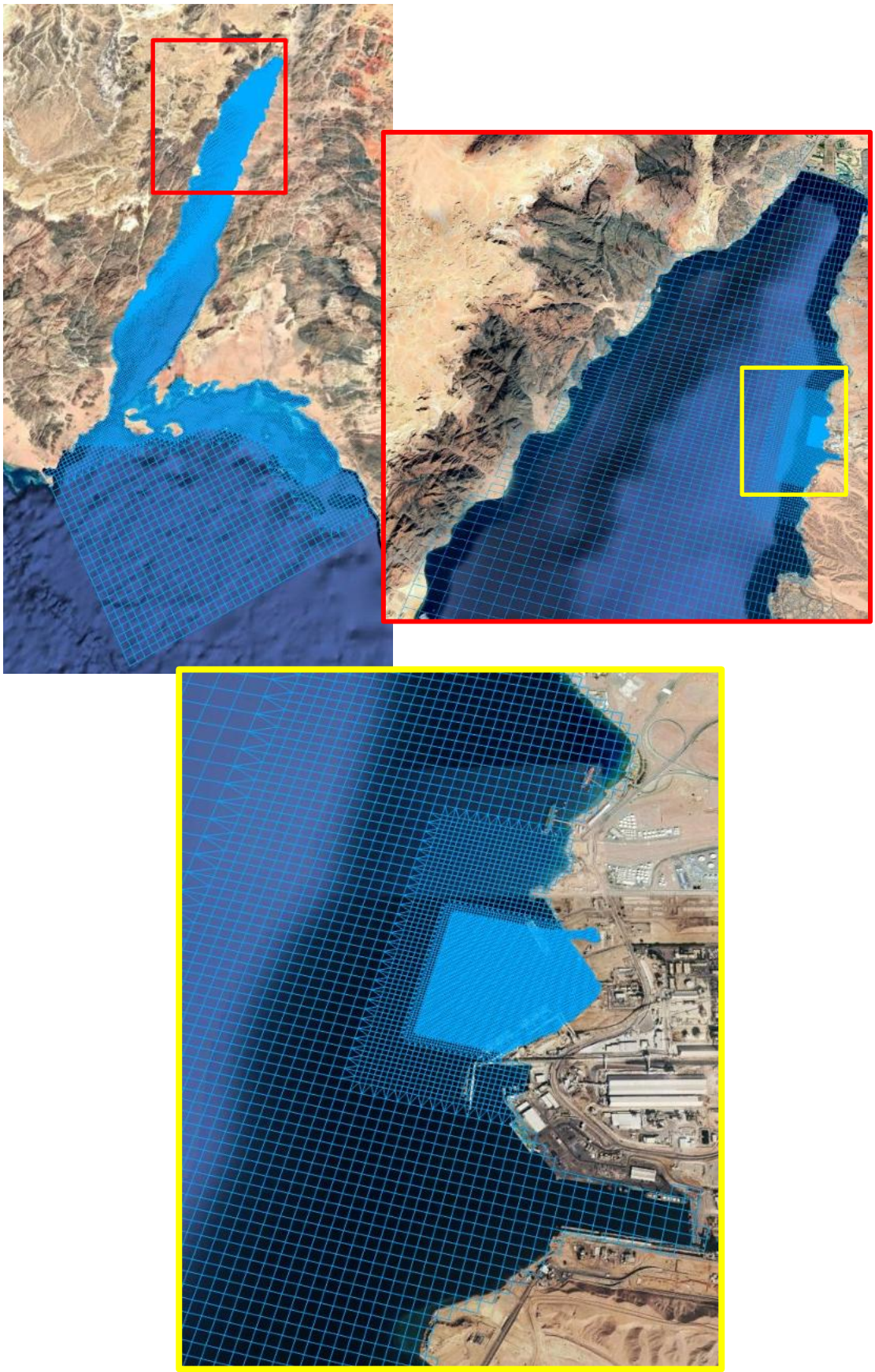

Figure 4.1 Overview of the complete Delft3D-FM computational grid

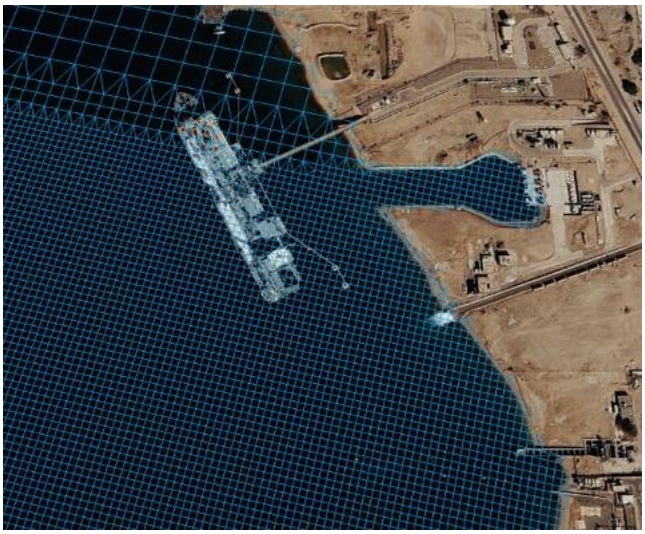

Figure 4.2 Detailed view of the computational mesh around the intake and outfall location showing local mesh refinement.

4.3 Bathymetry

Bathymetry forms one of the most critical inputs to the numerical model because the discharged brine is expected to propagate primarily as a density current following the canyon morphology.

The overall model bathymetry was based on publicly available data from GEBCO and in the vicinity of the project area, the bathymetry was updated from in-house bathymetry datasets as well as a bathymetry dataset provided by the Client. The combined dataset was interpolated to the computational mesh while ensuring preservation of the major bathymetric features relevant to plume transport.

Water depths within the model domain range from approximately 0 m MSL in nearshore areas to more than 1700m MSL in the deeper parts of the Gulf of Aqaba.

The proposed outfall is located at approximately 16 - 27 m MSL, directly adjacent to a submarine canyon that extends towards greater depths offshore. This canyon is expected to provide a preferential transport pathway for the dense brine discharge and therefore has been represented in detail within the model bathymetry.

Special attention was given to:

- Representation of canyon side slopes;
- Preservation of bathymetric gradients;
- Consistency of bathymetric data near the diffuser location;

The resulting model bathymetry is presented in Figure 4.3.

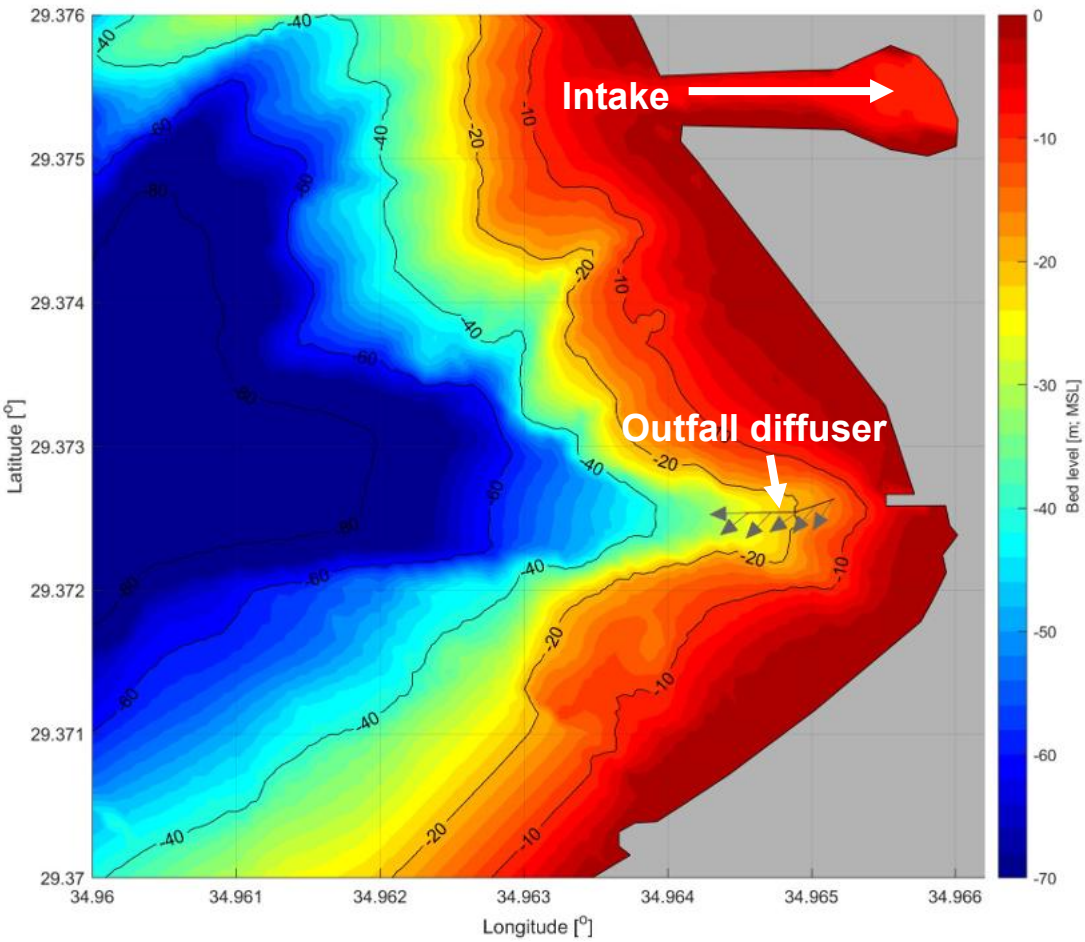

Figure 4.3 Detailed bathymetry around the intake and outfall location.

4.4 Ambient Conditions

4.4.1 Introduction

The hydrodynamic behaviour of the Gulf of Aqaba is influenced by a combination of density stratification, wind forcing, water level variations and regional circulation patterns.
To capture the range of conditions relevant to plume transport, the model incorporates representative ambient environmental conditions based on available measurements and project information.

The following environmental factors were considered:

- Ambient salinity;
- Ambient temperature;
- Vertical density stratification;
- Wind forcing;
- Regional circulation;
- Water level forcing.

The resulting ambient wind conditions are described in the following section.

4.4.2 Wind Forcing

Wind forcing was applied using spatially varying meteorological data derived from ECMWF's ERA5[4] reanalysis database.

The wind forcing covers the simulation period from 2024-03-01 to 2024-03-15 and represents realistic meteorological conditions during the assessment period (see Figure 4.4), with typical wind speeds ranging between 2 m/s and 5 m/s, and a maximum wind speed of approximately 7.5 m/s.

Wind forcing primarily influences the upper water column and can generate secondary circulation patterns affecting plume transport in shallow and intermediate water depths. It is noted however that the outfall plume dispersion occurs at depths of several tens to hundreds of meters and that wind conditions of this magnitude are not expected to significantly influence the plume dispersion.

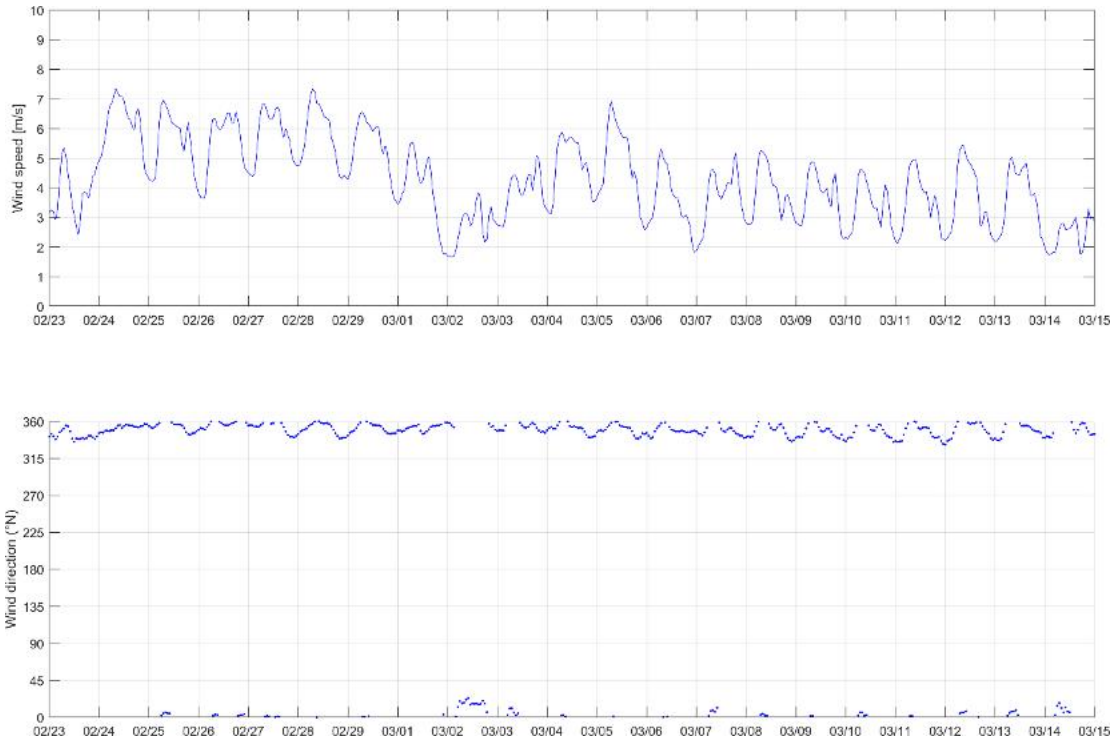

Figure 4.4 Time series of wind speed and wind direction used in the model.

4.5 Outfall near-field analysis and inclusion in far-field modelling

When modelling a submerged diffuser outfall, a near-field assessment is necessary to compute the initial mixing and plume behaviour of the effluent as it exits the diffuser. The initial diffuser jets and mixing processes play on a small scale and include physical (non-hydrostatic) processes that are not included in the Delft3D-FM model. Therefore, the near field outfall behaviour was assessed based on different near field model formulations, including Abessi and Roberts (2015) to analyse the near field hydrodynamics and to determine a proper coupling to the far-field Delft3D-FM model. This ensures that the characteristics of the outfall hydrodynamics will be preserved in the coupling to the far field model. This is important since it determines the dispersion of the outfall plume and interaction with its environment.

[4] https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

The initial dilution and the dimensions of the plume were included in the far field model by means of the Distributed Entrainment Sinks Approach (DESA) by Choi and Lee (2007) and translated to the Delft3D far field model by means of the Deltares C-SUMO coupling interface. The DESA technique includes several sinks along the (near field) plume trajectory in the far field model, which extracts surrounding water that is subsequently used to dilute the original source before inclusion in the far field model. This technique is illustrated in Figure 4.5. This comprehensive technique ensures that the physical properties and behaviour of the plume are preserved in the best possible way to allow for more accurate modelling of the outfall plumes as compared to traditional modelling methods (i.e. releasing a volume of non-diluted effluent in a single computational cell).

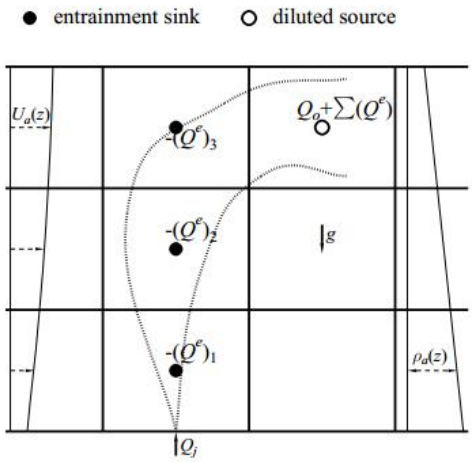

Figure 4.5 Illustration of DESA technique, showing several sinks (black dots) along a plume trajectory in the far field model (from: Choi and Lee, 2007)

A submerged outfall diffuser will effectively mix the discharged brine close to the outfall with ambient water. A schematization of the plume in the near field is presented in Figure 4.6. After discharge from the diffuser port (located near the seabed) under an upward angle, the effluent will rise (maximum height dilution, St) by its initial momentum and sinks back to the seabed by gravity (point of impact, Si) effectively mixing with the surrounding water. From here the brine spreads by its remaining momentum and as a density current following the bottom slope. Further from the outfall less mixing occurs and the spreading and mixing of the plume depends on the ambient hydrodynamic conditions, density gradients and bottom gradients. The point where the mixing of the plume is no longer affected by the initial momentum of the plume, and consequently mixes less rapidly, is called ‘the end of the nearfield’ (Sn).

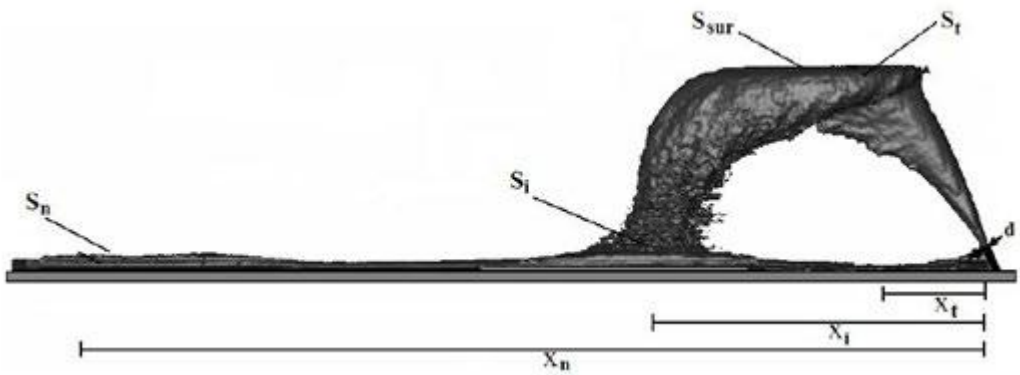

Figure 4.6 Dense jet plume trajectory from a laboratory experiment, indicating the different zones in the dense plume behaviour (Abessi and Roberts, 2015)

The table below shows the most relevant near-field analysis results based on the Abessi and Roberts formulations, which have been used in the subsequent Delft3D-FM modelling through the C-SUMO coupling. In the table, distinction is made between the two different port diameters. The analysis is performed for winter conditions (ambient temperature of 21°C, ambient salinity of 40.7 psu) as the dilution is lowest in winter.

Table 4.1 Diffuser characteristics and dilutions

	Onshore 3 ports (0.75 m diameter)	**Offshore 3 ports (1 m diameter)**
Port exit velocity [m/s]	2.6	3.5
Froude number [-]	6	7
Distance to terminal rise height (Xt) [m]	9	14
Vertical extent of terminal rise height, relative to seabed [m]	8.3	12
Distance to impact point (Xi) [m]	15	23
Dilution at impact point (Si) [-]	8.4	9.6

4.6 Boundary Conditions

Open-boundary conditions were prescribed along the offshore boundaries (situated in the Red Sea) of the Delft3D-FM model and included water levels, salinity, temperature and current velocities. These boundary conditions provide the large-scale hydrodynamic forcing required to represent the hydrodynamic conditions at the project site. The boundary conditions were obtained from CMEMS[5] (temperature, salinity, non-tidal water level variations) and FES2014[6] for tide.

4.7 Numerical Settings

The hydrodynamic and transport simulations were performed using the three-dimensional Delft3D-FM modelling suite[7]. The model was configured specifically for the simulation of dense brine plumes and density-current behaviour in steep submarine canyon environments. Particular attention was given to the vertical discretisation of the water column, the representation of turbulent mixing and the density-driven transport of the plume. The parameters used in the final simulation are the result of the sensitivity analysis described in Chapter 6.

Table 4.2 Numerical model settings

Parameter	Value
Simulation type	3D Delft3D-FM
Horizontal mesh resolution	Approximately 8 × 8 m in the area of interest
Number of vertical layers	20
Vertical layering method	Sigma layering
Vertical layer distribution	Stretched sigma layers with increased resolution near the bed (up to 2% layer thickness close to the bed)
Maximum computational time step	0.5 s
Horizontal diffusivity	0.1 m^2/s
Horizontal viscosity	0.1 m^2/s
Vertical diffusivity	1×10^{-6} m^2/s
Vertical viscosity	1×10^{-6} m^2/s
Bed roughness	Manning coefficient = 0.024 $s/m^{1/3}$
Density formulation	UNESCO equation of state
Advection scheme	Monotone central limiter for momentum and salinity transport
Turbulence closure	k-ε (k-epsilon) turbulence model

[5] Copernicus Marine Service. (n.d.). Copernicus Marine Data Store. https://data.marine.copernicus.eu/
[6] Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., & Picot, N. (2021). FES2014 global ocean tide atlas: Design and performance. Ocean Science, 17(3), 615–649. https://doi.org/10.5194/os-17-615-2021
https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html
[7] https://www.deltares.nl/en/software-and-data/products/delft3d-flexible-mesh-suite

5 Setup of Simplified Model for the Sensitivity Analysis

5.1 Introduction

To be able to perform a comprehensive sensitivity analysis with the Delft3D-FM model, a large number of simulations had to be run. To make this feasible within a reasonable computational effort, a Simplified Model was developed based on the Full Model as described in the previous chapter. The Simplified Model was specifically designed to investigate the influence of key numerical and physical parameters on plume behaviour in the vicinity of the outfall and within the Transition Zone. The model simplifications were selected such that the dominant physical processes governing the density-current behaviour of the plume were retained, while processes expected to have a limited influence on the sensitivity-analysis results were omitted. The suitability of the Simplified Model was subsequently evaluated through comparison with the Full Model before it was used for the sensitivity analysis.

5.2 Model simplifications

5.2.1 Cut-out of computational network

The Simplified Model consists of a cut-out of the original Delft3D-FM network centred on the outfall area and plume trajectory (Figure 5.1). The selected model extent fully contains the plume footprint relevant for the sensitivity analysis (Figure 5.2) while substantially reducing computational cost compared to the Full Model.

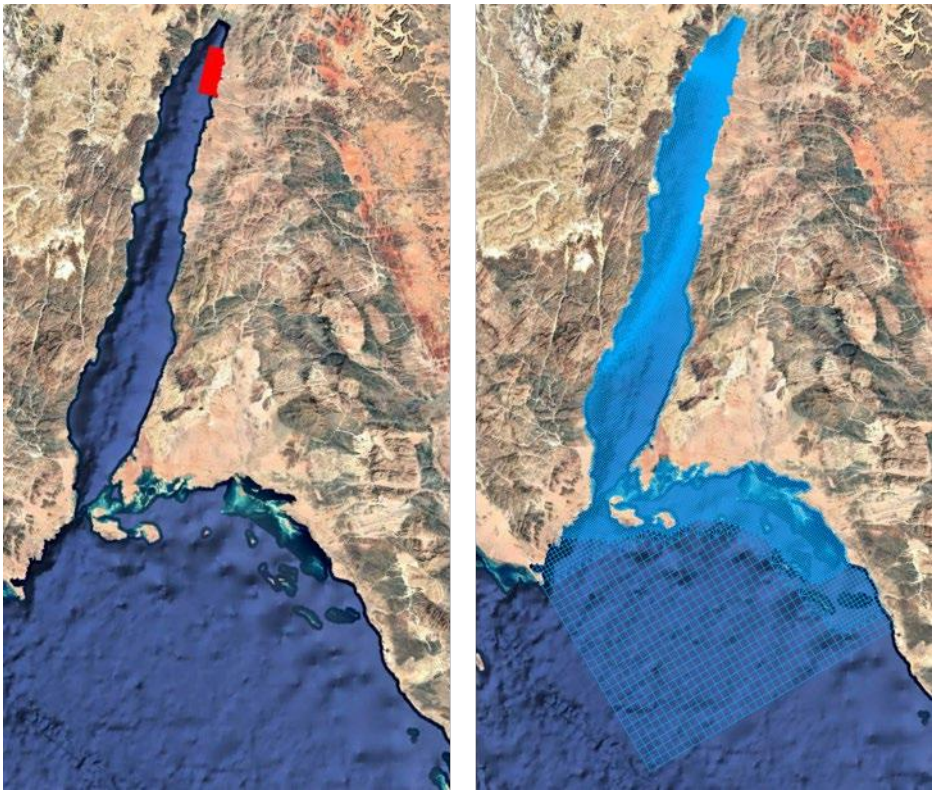

Figure 5.1 Simplified Delft3D-FM model domain (left) and the Full Model domain (right). The Simplified Model consists of a cut-out of the original computational network focused on the outfall area and plume trajectory.

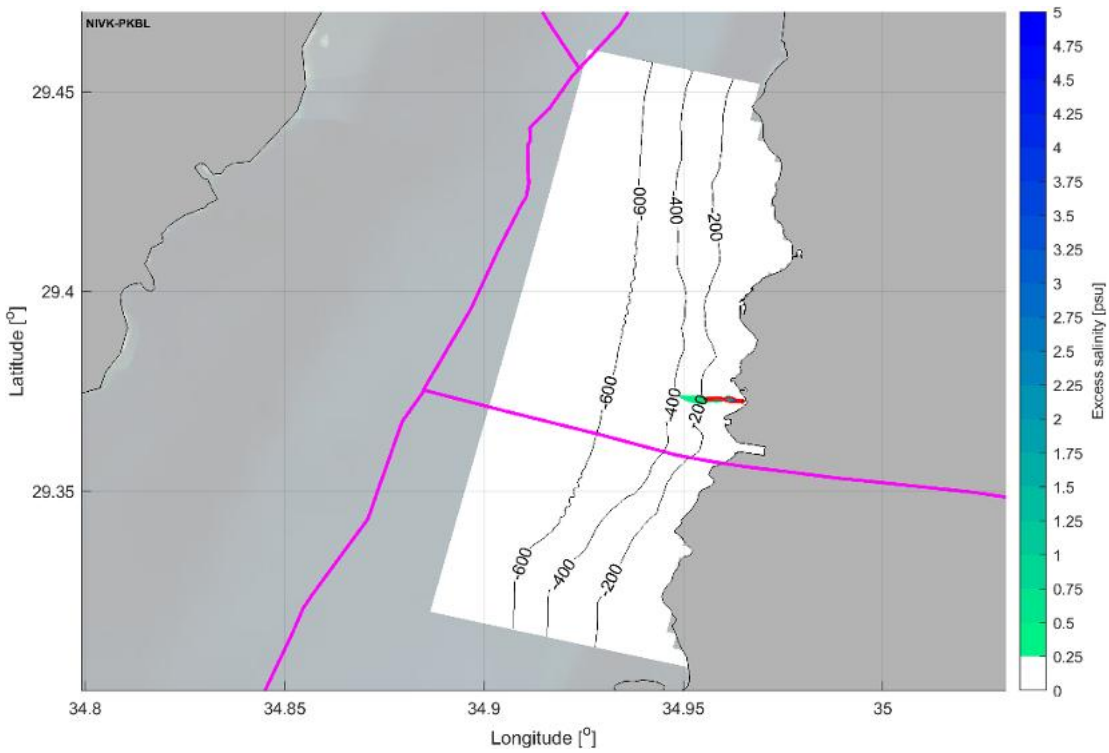

Figure 5.2 Predicted excess-salinity footprint within the Simplified Model domain, demonstrating that the area of interest is fully covered by the reduced computational network.

5.2.2 No ambient stratification

Natural ambient stratification in the surrounding waters was excluded from the Simplified Model in order to reduce computational complexity and focus the sensitivity analysis on the processes governing plume transport within the Transition Zone. Simulations performed with the Full Model showed that the discharged brine continues to descend along the canyon as a density current until it becomes trapped at depths of approximately -300 to -600 m MSL, depending on the ambient stratification (Figure 5.3). However, the primary area of interest for the sensitivity analysis is limited to the plume behaviour from the diffuser depth up to approximately -200 m MSL. Within this depth range, the plume trajectory and extent were found to be only weakly influenced by ambient stratification. Therefore, stratification was omitted from the Simplified Model while retaining the dominant processes relevant to the sensitivity analysis.

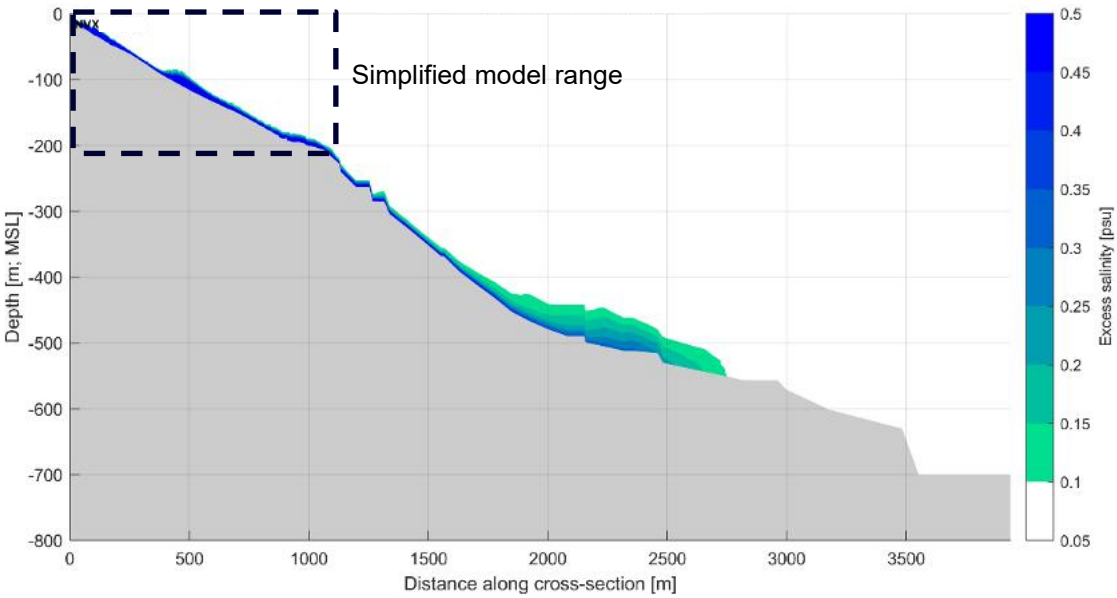

Figure 5.3 Demonstration of the limited influence of ambient stratification on plume behaviour within the upper part of the canyon (up to approximately -200 m MSL), which forms the focus area of the sensitivity analysis.

5.2.3 No tidal boundary conditions and no wind forcing

Tidal boundary conditions and wind forcing were excluded from the Simplified Model to isolate the density-driven behaviour of the brine plume. In the Full Model, tidal water-level variations and the corresponding near-bed current velocities are shown in Figure 5.4 for the simulated wind conditions. The near-bed tidal and wind-driven current velocities are generally approximately 0.05 m/s, whereas the plume-driven currents reach approximately 1 m/s. The ambient currents are therefore small compared with the currents generated by the effluent plume.

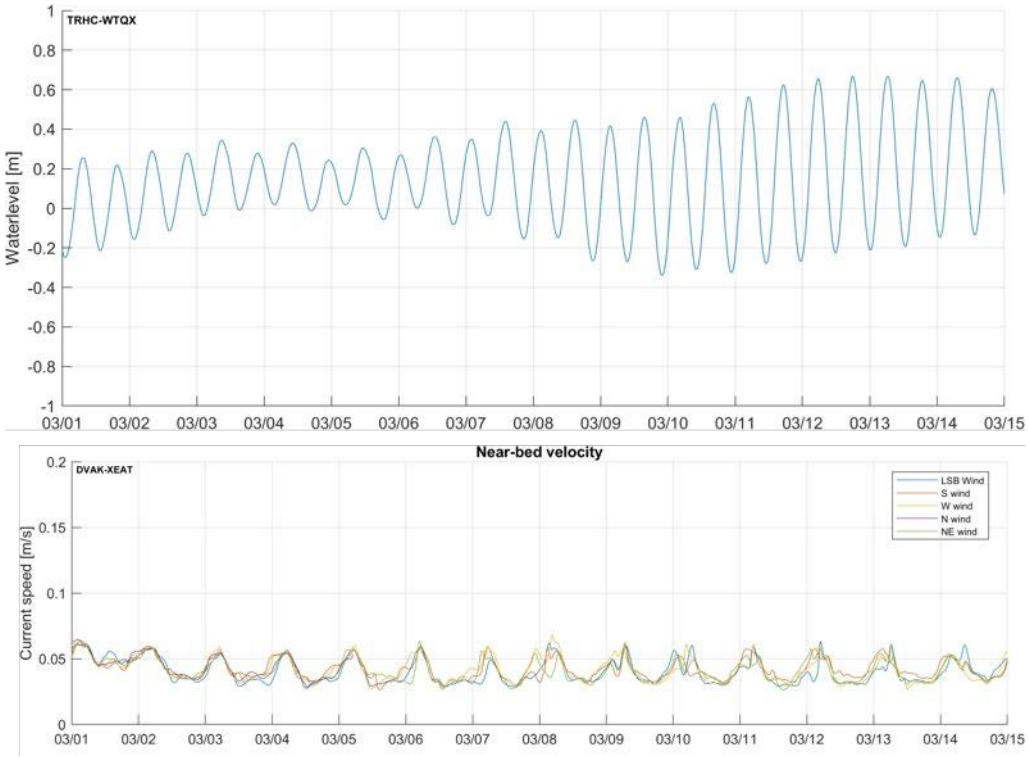

Figure 5.4 Modelled water-level variation (top) and near-bed current velocity under the simulated wind conditions (bottom) in the Full Model.

5.2.4 Simulation duration

The Simplified Model simulations were run for a total duration of 5 hours, starting from an initial condition without any brine discharge. This duration was selected to ensure that the plume reached a steady-state condition. Analysis of the model results showed that the plume footprint develops rapidly during the first hours after the start of the discharge and that only minor changes occur after approximately 3 hours of simulation (see Figure 5.5). Based on this observation, the period between 4 and 5 hours after the start of the simulation was used for the sensitivity analysis, thereby avoiding any influence of initial transient effects.

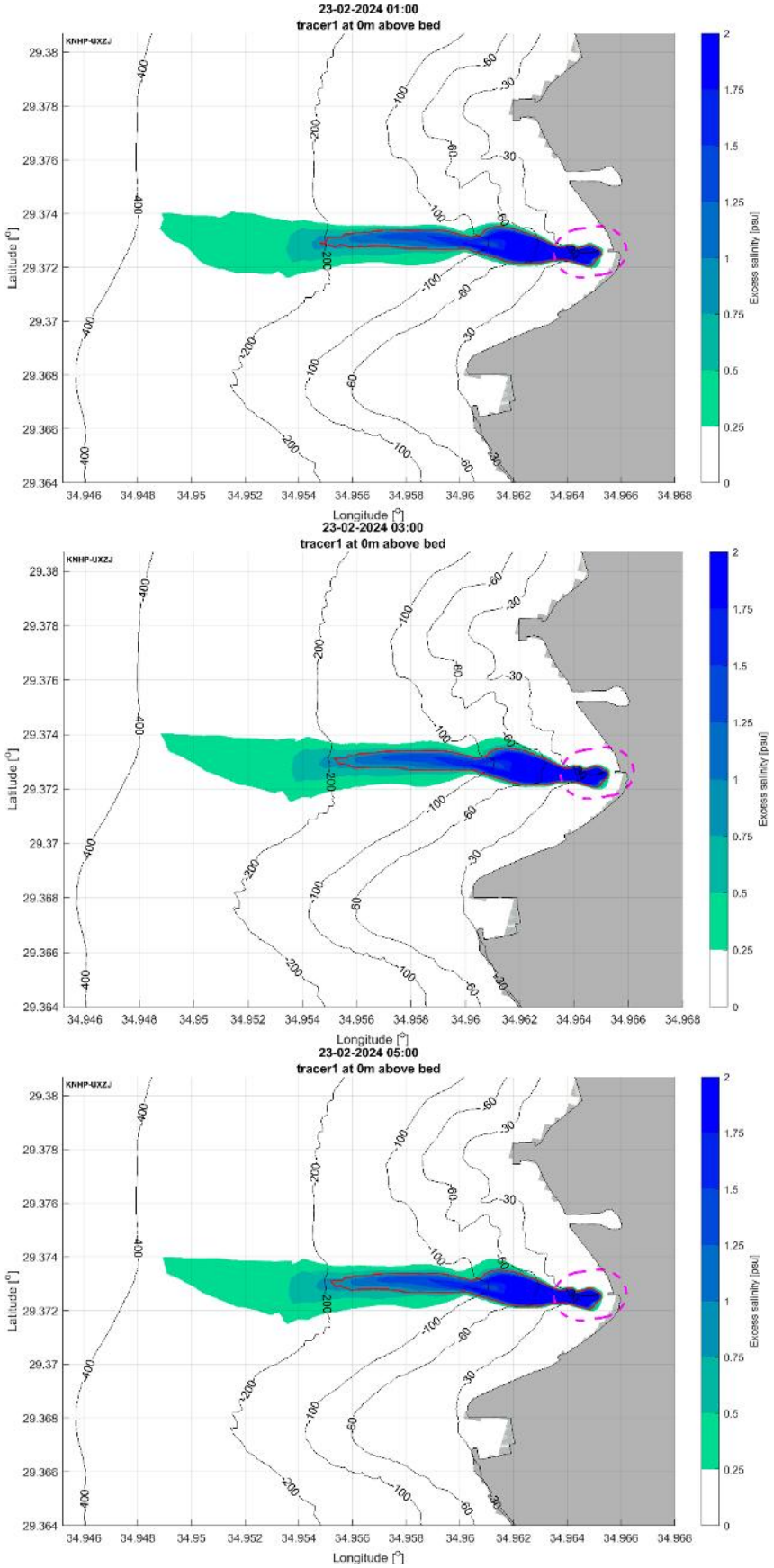

Figure 5.5 Evolution of the near-bed excess-salinity footprint after 1, 3 and 5 hours of continuous discharge. The plume rapidly approaches a stable configuration, with only limited changes in footprint extent occurring after approximately 3 hours of simulation.

5.3 Comparison of Simplified Model to Full Model

To verify whether the Simplified Model is suitable for the sensitivity analysis, its results were compared with those of the Full Model. The Full Model includes ambient stratification, tidal forcing and wind forcing and was run for a longer simulation period, whereas these processes were omitted from the Simplified Model. The comparison focused on the predicted extent of the plume in the Transition Zone, which is the primary area of interest for the sensitivity analysis.

The figure below illustrates the spatial definition of the three analysis zones used to interpret the model results and to compare the Simplified Model with the Full Model. It also shows the predicted 2% excess-salinity contour from both model configurations. The Immediate Outfall Zone covers the area directly surrounding the diffuser, extending over the first several tens of metres from the outfall and approximately up to the first narrowing of the canyon. In this zone, plume behaviour is governed mainly by jet momentum, negative buoyancy and entrainment. These processes are most appropriately represented by the detailed CFD modelling carried out by ATM, which is therefore considered the most reliable source of information for the immediate vicinity of the diffuser.

Downstream of the Immediate Outfall Zone, the plume progressively transitions from a momentum-driven jet plume into a gravity-driven density current that follows the canyon geometry and bathymetry. This part of the plume pathway is referred to as the Transition Zone and is located approximately between the first and second canyon narrowing. Within this zone, both the Delft3D-FM and CFD results can provide useful information, although neither model should be interpreted as an exact validation reference for the other. The comparison in this zone is therefore used to assess the overall consistency of both (vastly different) modelling approaches and to support the interpretation of plume extent, side-slope intrusion and dilution behaviour.

Further offshore, beyond the Transition Zone, the plume behaviour is increasingly controlled by larger-scale hydrodynamic processes, seabed slope, density-current spreading and interaction with the wider canyon bathymetry. This area is defined as the Offshore Zone. The Offshore Zone lies beyond the practical extent and main applicability of the CFD model. Delft3D-FM is reliable for assessing offshore plume transport and dispersion in this part of the domain. The close agreement between the Simplified Model and the Full Model within the Transition Zone supports the use of the Simplified Model for the subsequent sensitivity analysis, while the Full Model remains the basis for the final assessment of plume behaviour under realistic ambient forcing conditions.

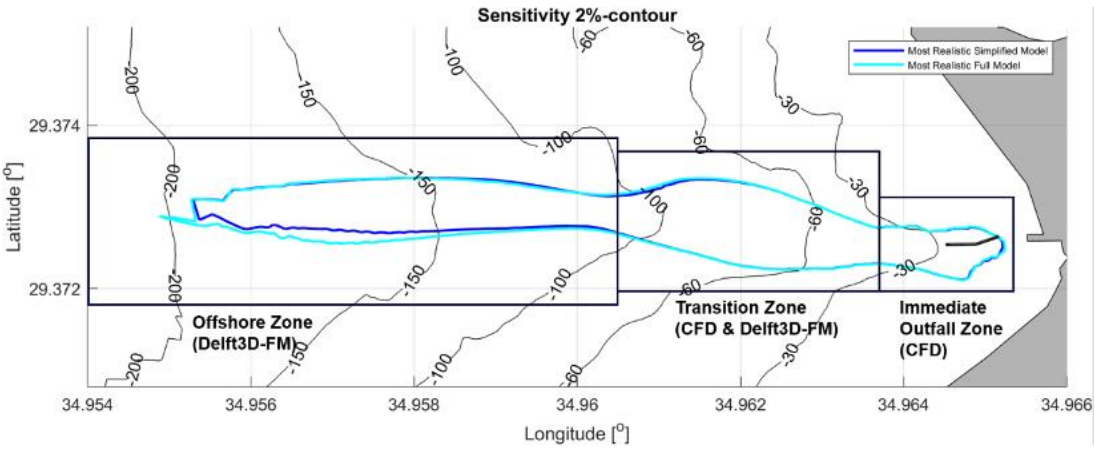

Figure 5.6 Definition of the different zones of the outfall plume trajectory

Figure 5.7 compares the excess-salinity contour lines predicted by the Simplified Model and the Full Model for salinity increases of 2%, 3% and 5% above background salinity. The contour lines show a similar overall plume shape and spatial extent in both model configurations. The agreement is particularly good within the Transition Zone, where the sensitivity analysis is focused. Based on this comparison, it was concluded that the Simplified Model provides a sufficiently representative approximation of the Full Model for evaluating the relative influence of individual model parameters and schematisations. The Simplified Model was therefore used for the sensitivity analysis presented in Chapter 6.

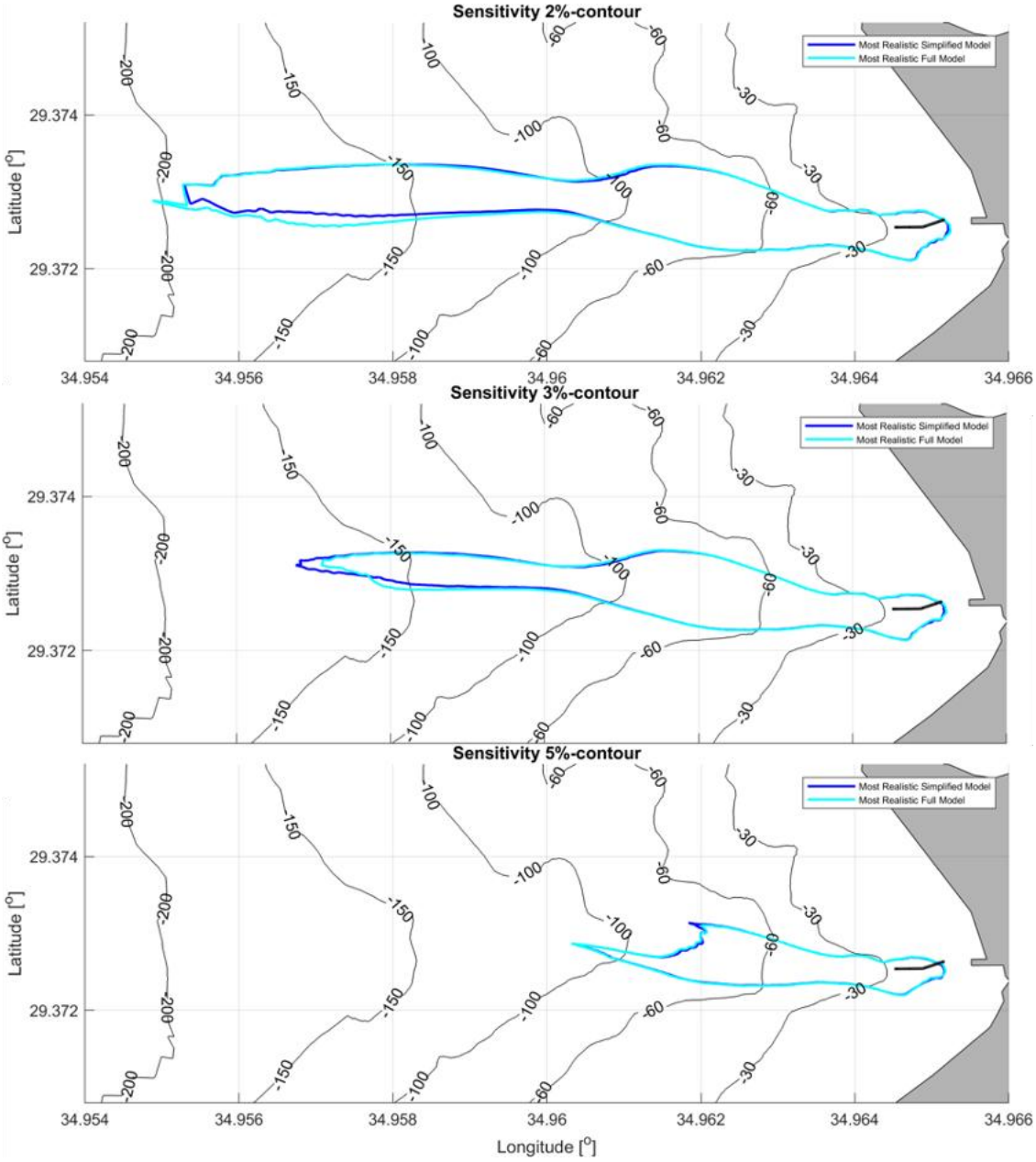

Figure 5.7 Comparison of the 2%, 3% and 5% excess-salinity contour lines predicted by the Full Model and the Simplified Model. The comparison demonstrates that the Simplified Model reproduces the plume extent in the Transition Zone sufficiently well for use in the sensitivity analysis.

6 Sensitivity analysis

A comprehensive sensitivity analysis was performed to assess the influence of selected numerical and physical model parameters on the predicted dispersion of the AAWDCP brine plume. The analysis was carried out using the Simplified Delft3D-FM model described in Chapter 5, which enabled a large number of simulations to be performed efficiently.

The sensitivity of the model results was evaluated primarily by comparing the predicted near-bed 2% and 5% excess-salinity contours. These contours were used to assess changes in both the offshore extent of the plume and its extent along the canyon side slopes.

Each sensitivity simulation was compared with a Reference Run based on the original model settings. The Reference Run was used only as a consistent basis for evaluating the effect of individual parameters. It does not represent the most realistic model configuration, which was eventually defined based on the combined results of the sensitivity analysis and comparison with the ATM CFD results in the Transition Zone.

The tested parameters comprise vertical layering, the sigma-correction settings, horizontal diffusivity, horizontal viscosity, bed roughness, near-field dilution, horizontal grid resolution, inclusion of the KEMAPCO outfall, vertical diffusivity and vertical viscosity. The settings examined for each parameter are summarised in Section 6.1, followed by the detailed results in Section 6.2

6.1 Simulated parameter sets in the sensitivity analysis

For each tested parameter category, simulations were performed by varying the applicable parameter or model setting relative to a Reference Run while retaining the remaining settings. The tested settings are summarised in Table 6.1.

In addition to these parameter-specific simulations, the possible influence of ambient stratification, tides, wind-driven currents and simulation duration was assessed through comparison of the Simplified and Full Models, as described in Chapter 5. These environmental processes were therefore not tested individually within the parameter matrix presented in this chapter. Their collective influence on plume behaviour in the Transition Zone was found to be limited for the modelled conditions.

Table 6.1 Settings evaluated in the sensitivity analysis

Parameter or condition	Reference setting	Tested settings or assessment method
Sigma-layer thickness near bed [in % of total depth]	2%	0.5%, 1% and 2%
Sigma correction[8]	Off	On and off
Z-layer thickness	Not applicable	0.75, 1.0, 1.6 and 5.0 m
Horizontal diffusivity	0.1 m²/s	0.05–0.2 m²/s
Horizontal viscosity	0.1 m²/s; Smagorinsky 0.2	0.05–0.2 m²/s; Smagorinsky 0.1–0.4
Bed roughness	Manning 0.028 $s/m^{1/3}$	Manning 0.020–0.032 $s/m^{1/3}$
Near-field dilution	100%	50%, 100% and 200%
Horizontal grid resolution	8 × 8 m	4 × 4, 8 × 8 and 20 × 20 m
KEMAPCO outfall	Excluded	Included and excluded
Vertical diffusivity	5×10^{-6} m²/s	0–1×10^{-5} m²/s
Vertical viscosity	5×10^{-5} m²/s	1×10^{-6}–1×10^{-4} m²/s
Ambient stratification	Excluded from Simplified Model	Assessed through Simplified/Full Model comparison
Tidal and wind forcing	Excluded from Simplified Model	Assessed through Simplified/Full Model comparison

6.2 Sensitivity analysis results

The sensitivity-analysis results are presented in the following sections for each tested parameter category. The influence of each parameter was assessed primarily by comparing the predicted near-bed 2% and 5% excess-salinity contour lines with those of the Reference Run. The comparison considers both the offshore extent of the plume along the canyon axis and its lateral extent along the canyon side slopes. The results are used in Section 6.3 to identify the model parameters that most strongly affect plume dispersion and to support the selection of the Most Realistic and Conservative model settings used in the subsequent Full Model simulations (See Chapter 7).

6.2.1 Vertical layering

Vertical layering determines how the water column is represented in the three-dimensional Delft3D-FM model and influences the numerical representation of the near-bed density current. The sensitivity analysis assessed sigma-layer configurations with different near-bed layer thicknesses, use of the sigma-correction setting, and several z-layer configurations. Vertical layering was found to have a large influence on both the offshore extent of the plume and its intrusion along the canyon side slopes.

In a sigma-layer configuration, the computational layers follow the seabed and water surface, and their thickness varies with the local water depth. The Reference Run used a near-bed sigma-layer thickness equal to 2% of the local water depth. Additional simulations were

[8] This is a numerical setting that affects how density gradients are treated on steep slopes in the the bathymetry in sigma-layer models

performed using near-bed thicknesses of 1% and 0.5%. At -40 m MSL, these configurations correspond to near-bed layer thicknesses of 0.8, 0.4 and 0.2 m, respectively. At -80 m MSL, the corresponding thicknesses are 1.6, 0.8 and 0.4 m. A separate simulation was performed using the 2% sigma-layer configuration with the alternative sigma-correction setting.

The z-layer simulations used nominal vertical layer thicknesses of 0.75, 1.0, 1.6 and 5.0 m. In contrast to the terrain-following sigma layers, the z-layer configurations use fixed vertical levels.

Figure 6.1 compares the predicted near-bed 2% excess-salinity contours for the tested vertical-layer configurations. The sigma-layer simulations generally predict a greater offshore extent than the z-layer simulations. In the plotted results, the sigma configurations with finer near-bed layers extend furthest offshore, whereas the z-layer configurations produce shorter and more compact footprints. The smaller offshore extent of the z-layer simulations is caused by the fact that it results in a more (numerical) diffusive behaviour of the density current.

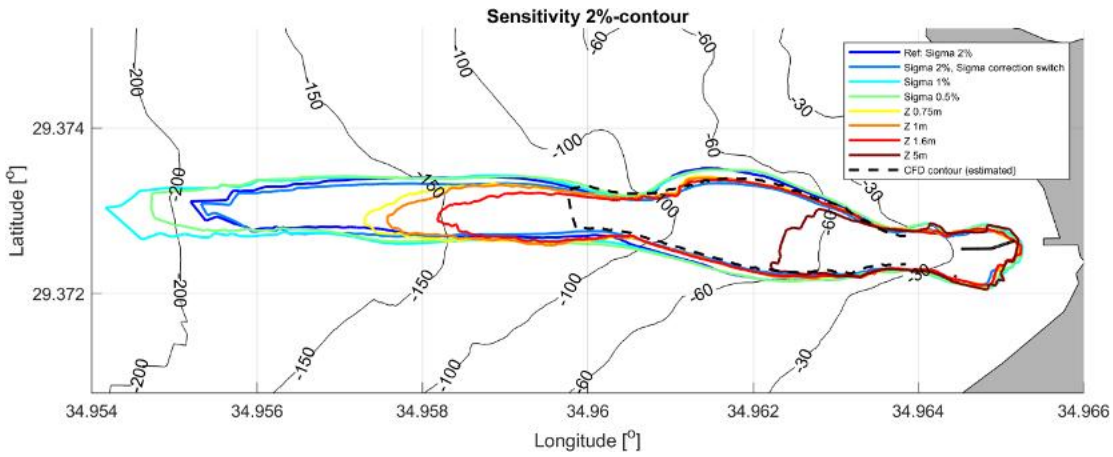

Figure 6.1 Predicted near-bed 2% excess-salinity contours for the tested sigma-layer and z-layer configurations, including the ATM CFD contour (dashed line) in the Transition Zone .

The vertical-layer configuration also influences the lateral extent of the plume along the canyon side slopes. The z-layer simulations and the 2% sigma-layer simulation using the alternative sigma-correction setting produce contours that are closer to the estimated ATM CFD contour in the Transition Zone than the other sigma-layer simulations. This indicates that offshore plume propagation and side-slope intrusion respond differently to the selected vertical discretisation.

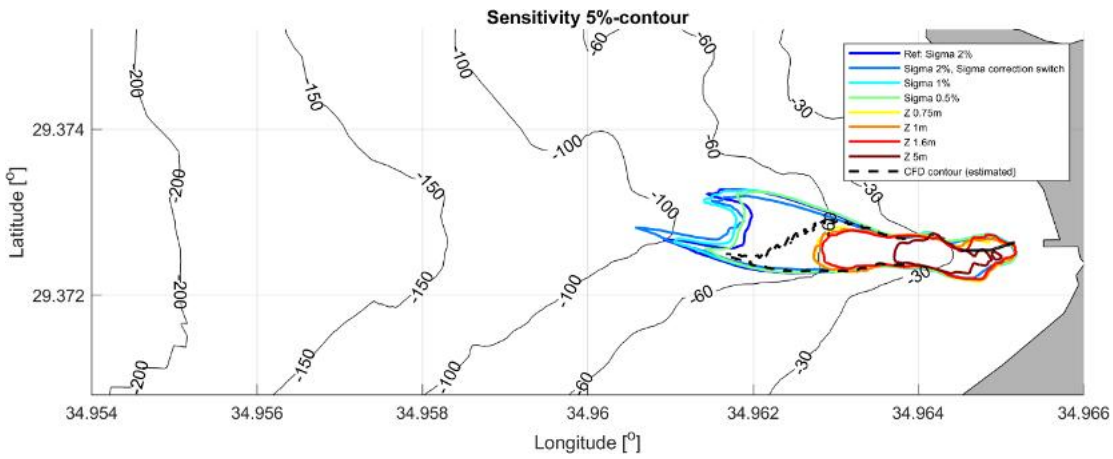

Figure 6.2 Predicted near-bed 5% excess-salinity contours for the tested sigma-layer and z-layer configurations, including the estimated ATM CFD contour (dashed line) in the Transition Zone.

Figure 6.2 presents the equivalent comparison for the 5% excess-salinity contour. As observed for the 2% contour, the sigma-layer simulations generally produce a larger offshore extent, whereas the z-layer simulations produce a smaller offshore footprint. The smaller offshore extent in the z-layer simulations is attributed to greater numerical diffusion. Since the diffusion in the z-layer simulations is clearly numerical and the sigma-layers are known to better and more realistically reproduce density currents, the larger offshore extent predicted by the sigma-layers is considered more realistic and reliable.

For the 5% contour, the comparison along the canyon side slopes is particularly relevant. The z-layer simulations show side-slope behaviour similar to the estimated CFD contour in the Transition Zone. A comparable side-slope extent is obtained with the 2% sigma-layer configuration using the selected sigma-correction setting. This consistency with the z-layer and CFD results in the Transition Zone was used when identifying the Most Realistic Delft3D-FM settings.

The ATM CFD contour provides an independent reference in the Transition Zone. The CFD is the recommended source of information in the Immediate Outfall Zone because it represents the near-field jet processes. In the Transition Zone, CFD and Delft3D-FM produce similar side-slope extents for the 5% contour. Further offshore and below approximately -60 m MSL, the CFD plume appears more diffusive, and Delft3D-FM is considered the more appropriate source for predicting offshore transport.

Vertical layering and the sigma-correction setting have a large influence on the predicted 2% and 5% excess-salinity footprints. The sigma-layer simulations generally produce a greater offshore extent, which is considered more realistic, whereas the z-layer simulations produce more numerical diffusion and a smaller offshore footprint. The 2% sigma-layer configuration using the selected sigma-correction setting give a side-slope extent similar to the ATM CFD result in the Transition Zone. These findings resulted in the use of sigma-layers with sigma-correction settings in the Most Realistic and Conservative Full Model configurations.

6.2.2 Horizontal diffusivity

Horizontal diffusivity controls the lateral spreading of salinity due to unresolved turbulent mixing processes. To assess its influence on the predicted plume footprint, simulations were performed using horizontal diffusivities between 0.05 and 0.2 m²/s. The resulting 2% and 5% excess-salinity contours are compared in Figure 6.3.

The results show that increasing the horizontal diffusivity enhances lateral mixing of the discharged effluent. This results in a slightly larger side-slope intrusion of the plume and a somewhat smaller offshore extent along the canyon axis. However, the overall influence on the footprint remains limited, and the resulting contour lines remain relatively similar for all tested values. The sensitivity analysis therefore classifies horizontal diffusivity as having a medium influence on the predicted plume extent.

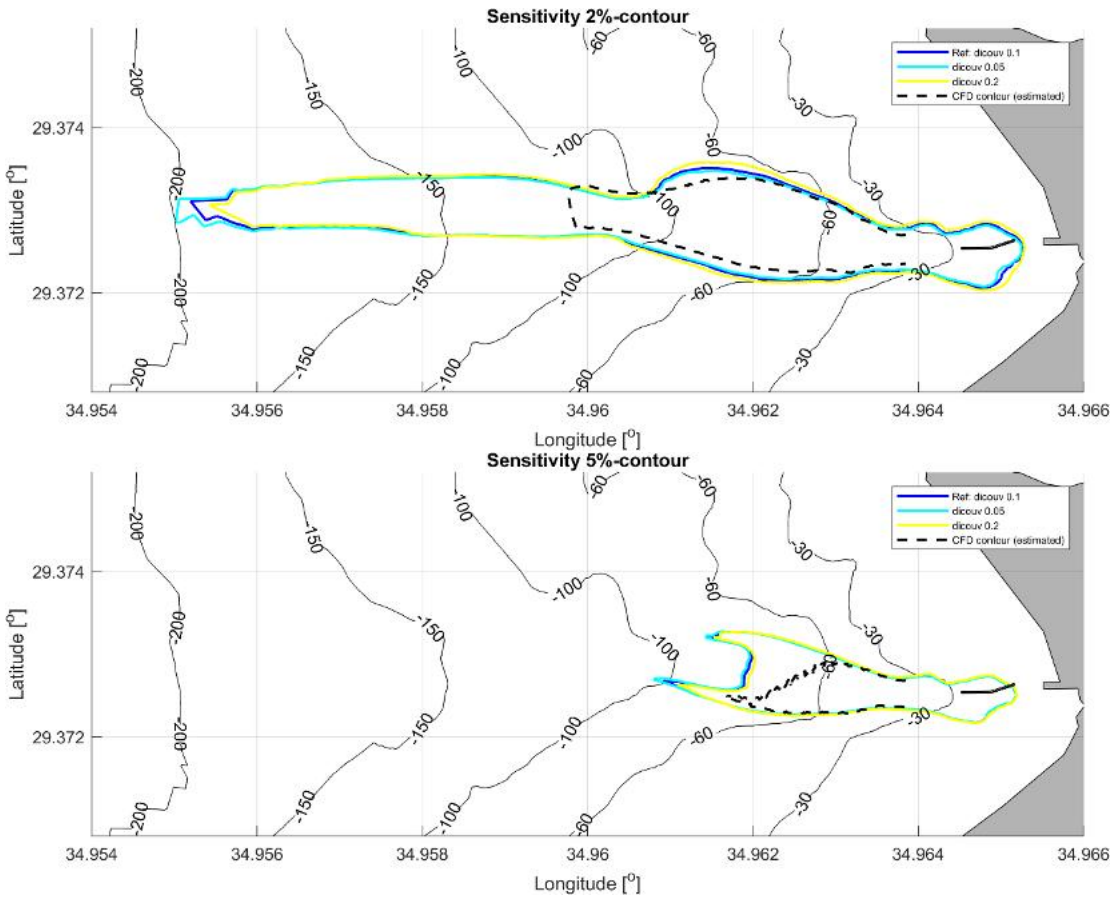

Figure 6.3 Comparison of the 2% and 5% excess-salinity contours for different horizontal diffusivity values.

6.2.3 Horizontal viscosity

Horizontal viscosity controls the exchange of momentum between neighbouring computational cells and therefore influences turbulent mixing and plume spreading. Sensitivity simulations were performed using both constant horizontal-viscosity values and different Smagorinsky coefficients.

The results indicate that increasing horizontal viscosity leads to enhanced turbulent mixing and subsequently a slightly larger lateral spreading of the plume. Similar to horizontal diffusivity, the increased mixing results in a limited increase in side-slope extent and a slight reduction in offshore extent. The influence is classified as medium because the effect is systematic but relatively limited compared to the vertical-layering sensitivity.

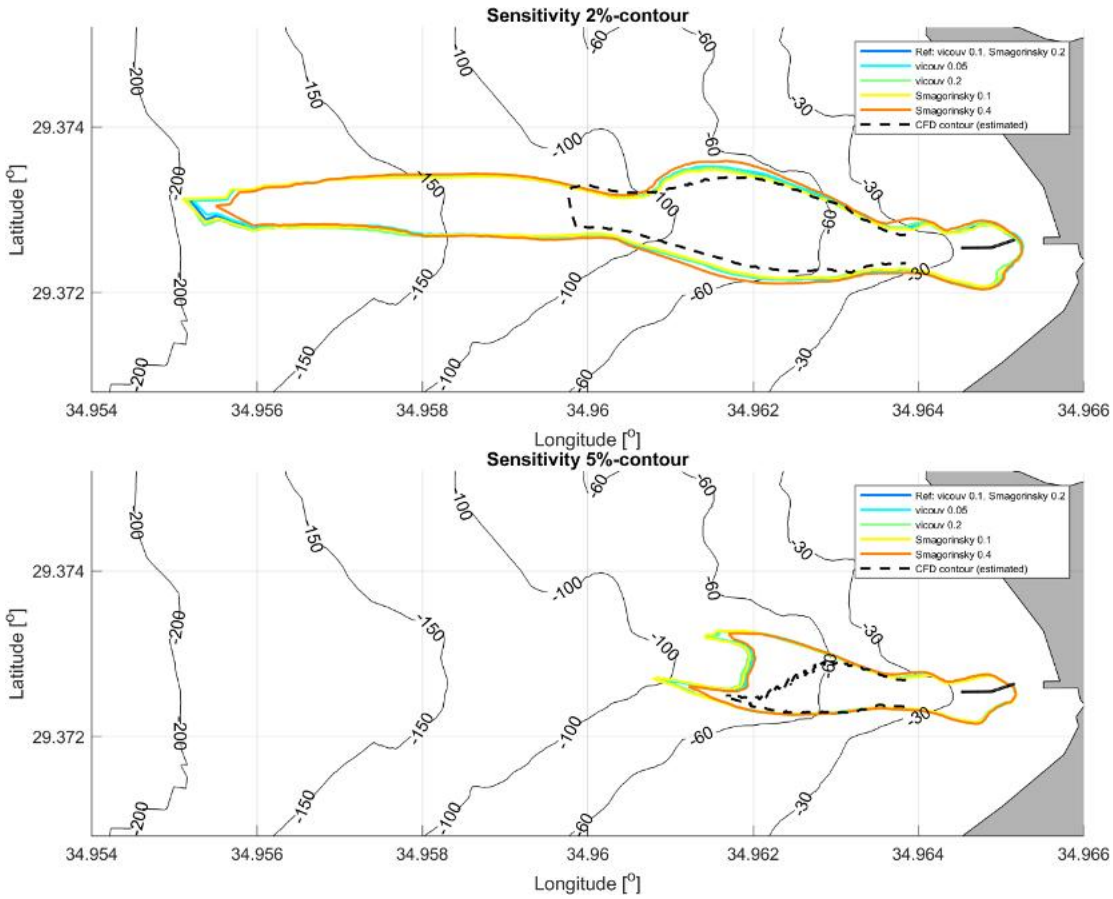

Figure 6.4 Comparison of the 2% and 5% excess-salinity contours for different horizontal-viscosity settings.

6.2.4 Bed roughness

Bed roughness controls the momentum losses resulting from bottom friction and therefore affects the near-bed velocity field governing plume transport. Manning coefficients between 0.020 and 0.032 s/m$^{1/3}$ were evaluated.

The simulations show that lower Manning coefficients result in lower friction losses and higher near-bed current velocities. The increased current speeds enhance turbulent mixing and lead to a slightly reduced offshore plume extent. The influence on side-slope intrusion is relatively small, although local differences occur within sections of the Transition Zone where the canyon geometry changes. Overall, bed roughness is classified as having a medium influence on the predicted plume footprint.

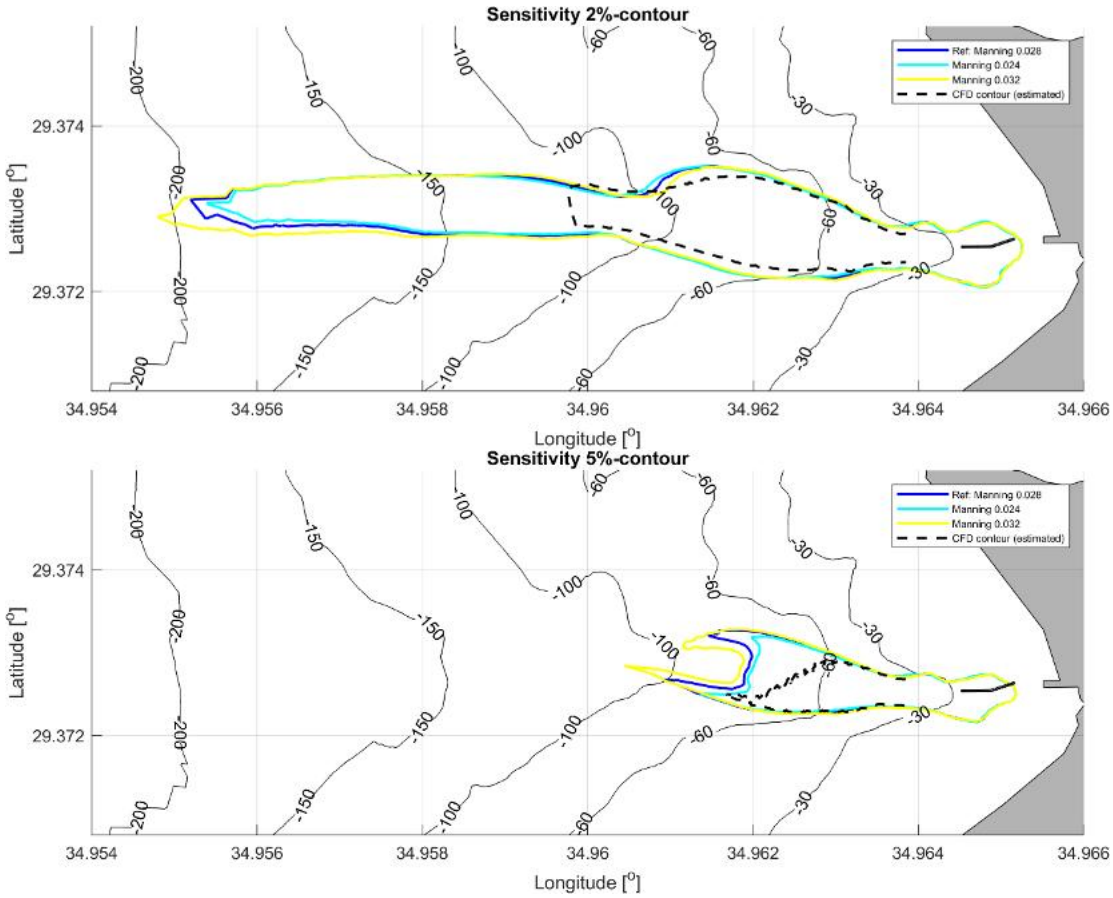

Figure 6.5 Comparison of the 2% and 5% excess-salinity contours for the tested Manning roughness coefficients.

6.2.5 Near-field dilution

Near-field dilution defines the concentration of the plume entering the far-field model following the initial diffuser-induced mixing. Sensitivity simulations were performed using dilution factors corresponding to 50%, 100% and 200% of the reference value.

As expected, higher near-field dilution results in lower initial salinity concentrations entering the far-field domain. Consequently, both the 2% and 5% excess-salinity contours become smaller. The effect is mainly visible in the offshore extent of the plume, whereas the side-slope extent is only weakly affected. The influence of near-field dilution on the footprint is therefore classified as small.

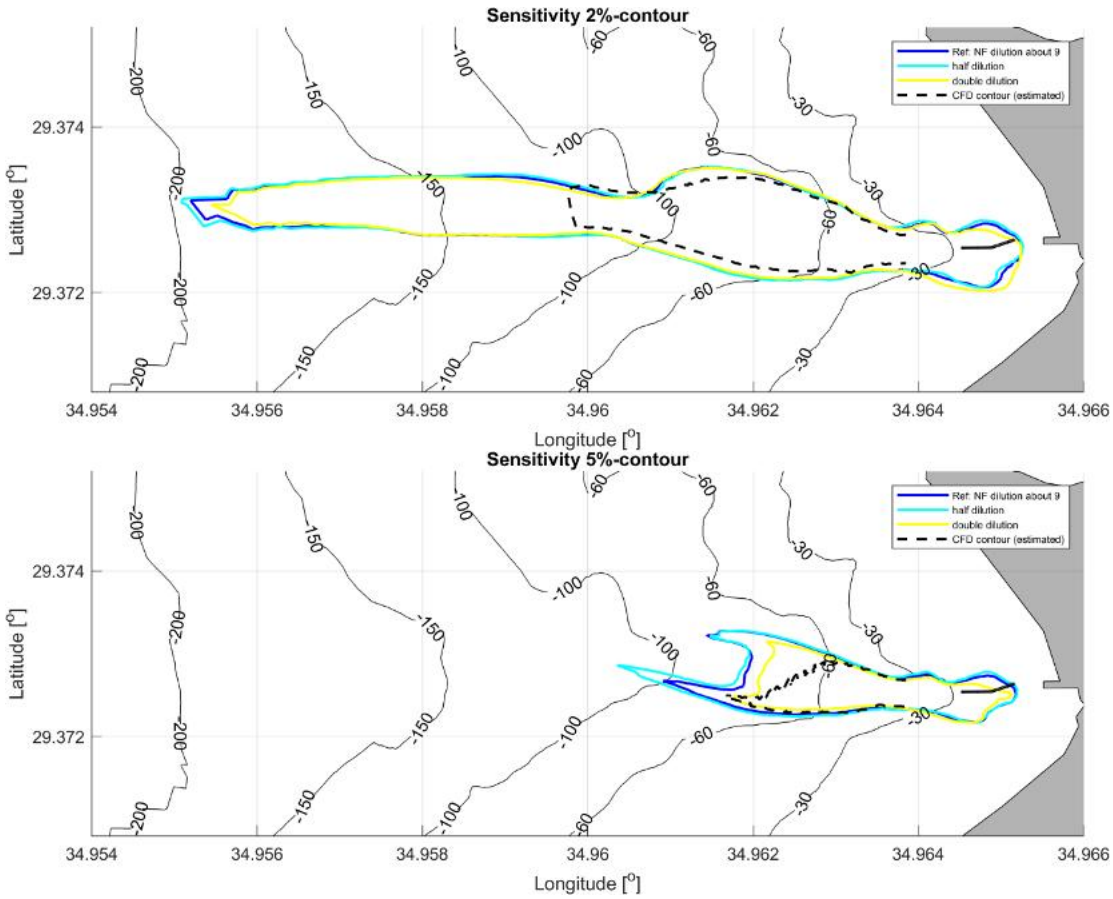

Figure 6.6 Comparison of the 2% and 5% excess-salinity contours for different near-field dilution assumptions.

6.2.6 Horizontal resolution

The influence of horizontal grid resolution was assessed using computational-cell sizes of 4 × 4 m, 8 × 8 m and 20 × 20 m.

The results indicate that the coarsest grid resolution underrepresents plume spreading within the canyon, particularly for the 5% contour. The 8 × 8 m resolution provides results very similar to the finer-grid simulations while requiring substantially lower computational effort. Based on these findings, an 8 × 8 m horizontal resolution was considered sufficient for the sensitivity analysis and subsequent model simulations. The influence of horizontal resolution is therefore classified as small (except for low resolutions like 20 x 20 m).

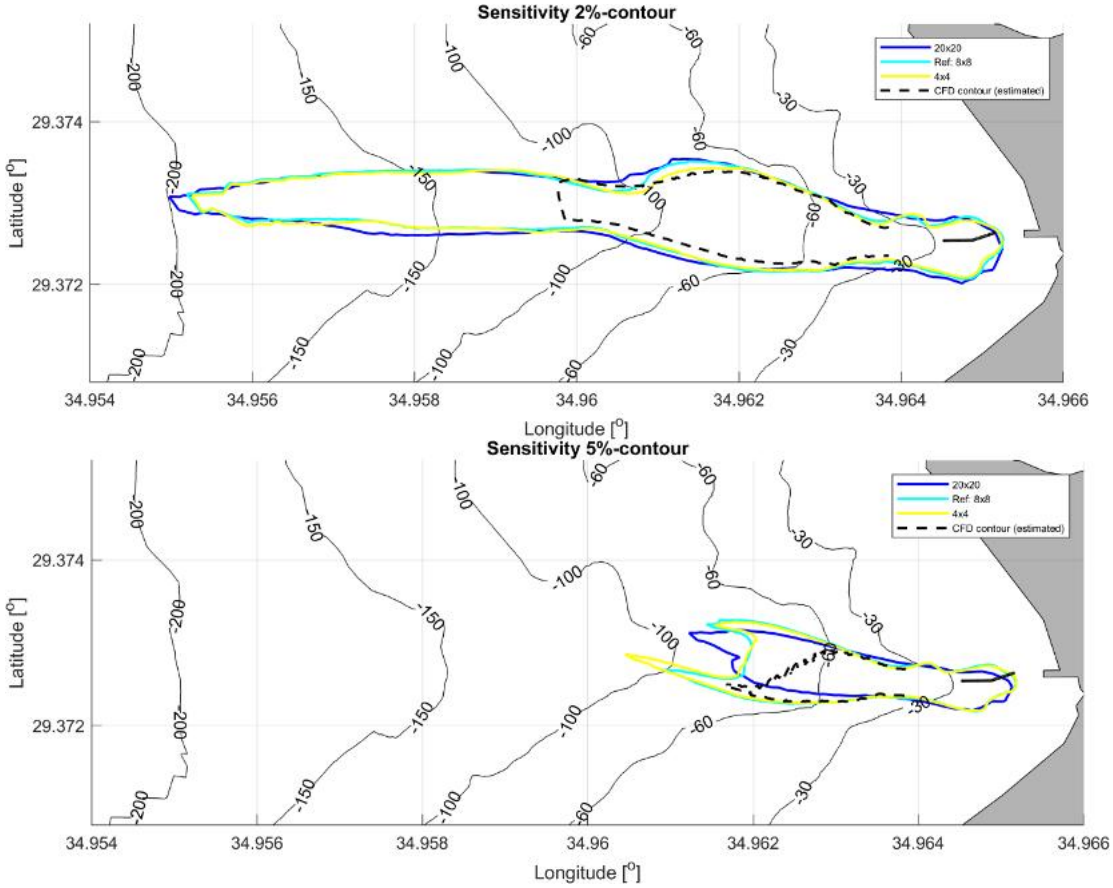

Figure 6.7 Comparison of the 2% and 5% excess-salinity contours for different horizontal-grid resolutions.

6.2.7 KEMAPCO outfall

To assess possible interactions with neighbouring discharges, simulations were performed both with and without inclusion of the KEMAPCO outfall. The resulting plume footprints show negligible differences between the two model configurations. The KEMAPCO discharge therefore does not significantly affect the plume behaviour of the AAWDCP outfall in the investigated area. The effect is classified as insignificant.

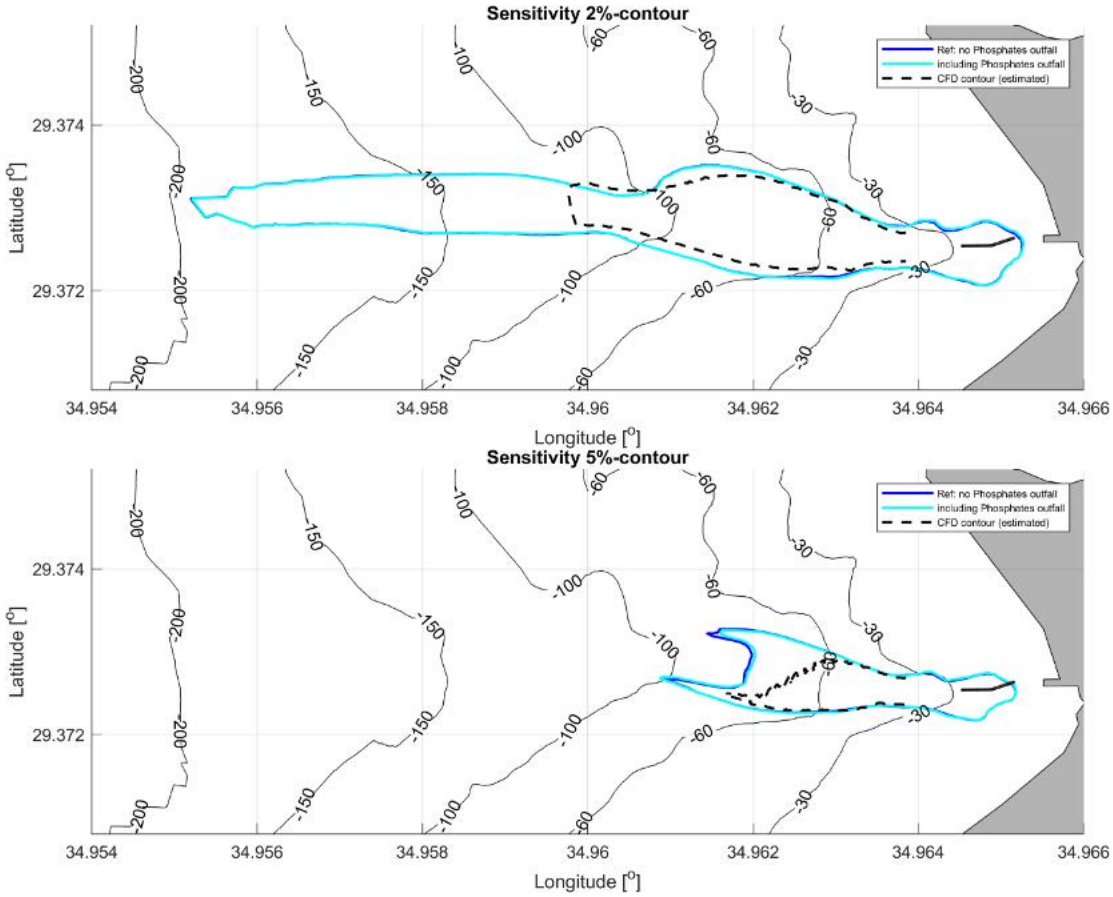

Figure 6.8 Comparison of the 2% and 5% excess-salinity contours with and without inclusion of the KEMAPCO outfall.

6.2.8 Vertical diffusivity

Vertical diffusivity controls vertical mixing of salinity between adjacent model layers. Values ranging from 0 to 1 × 10^{-5} m²/s were tested.

The resulting contour comparisons show virtually no change in the predicted 2% and 5% plume footprints. Within the tested range, vertical diffusivity therefore has a negligible influence on the plume extent and is classified as insignificant.

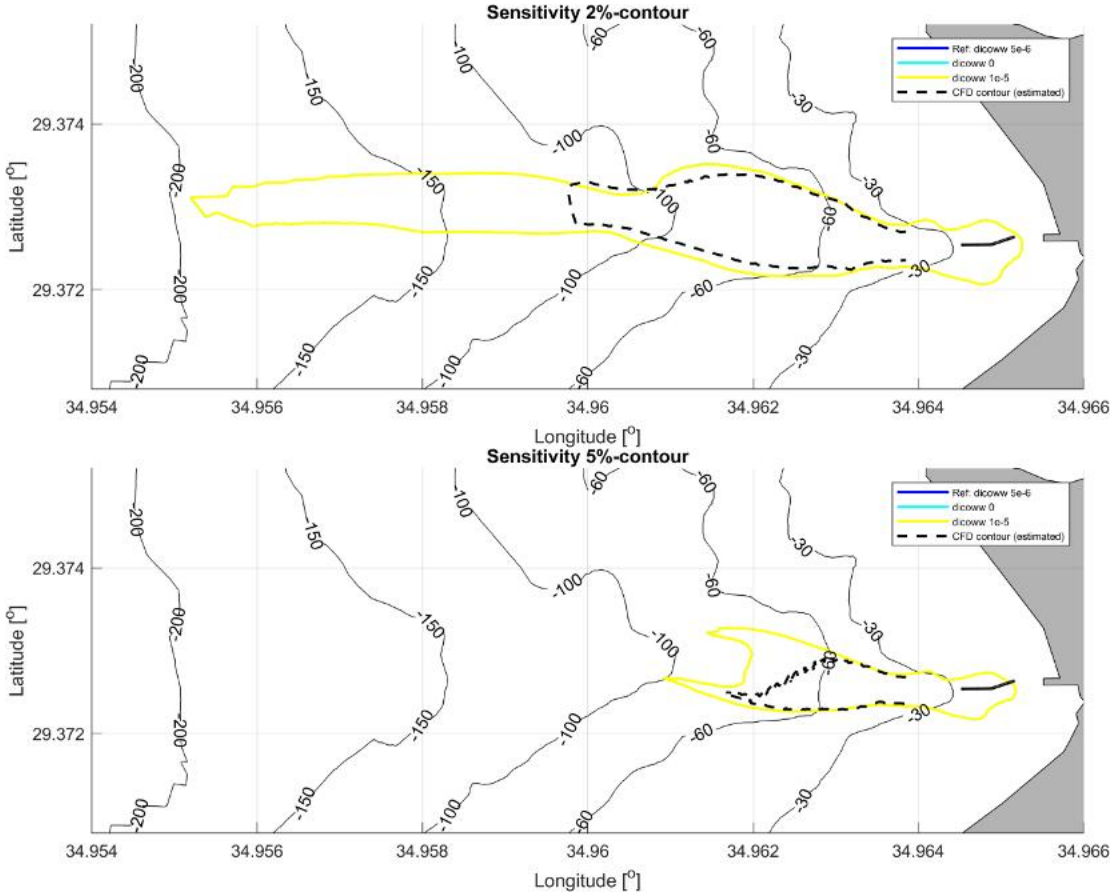

Figure 6.9 Comparison of the 2% and 5% excess-salinity contours for the tested vertical diffusivity values.

6.2.9 Vertical viscosity

Vertical viscosity controls vertical momentum exchange between neighbouring model layers. Values between 1×10^{-6} and 1×10^{-4} m²/s were evaluated.

The simulations show that the predicted plume footprint is largely insensitive to the selected vertical-viscosity value. Virtually no differences are observed in either the 2% or 5% contour lines. Vertical viscosity is therefore classified as having an insignificant influence on the predicted plume extent within the tested parameter range.

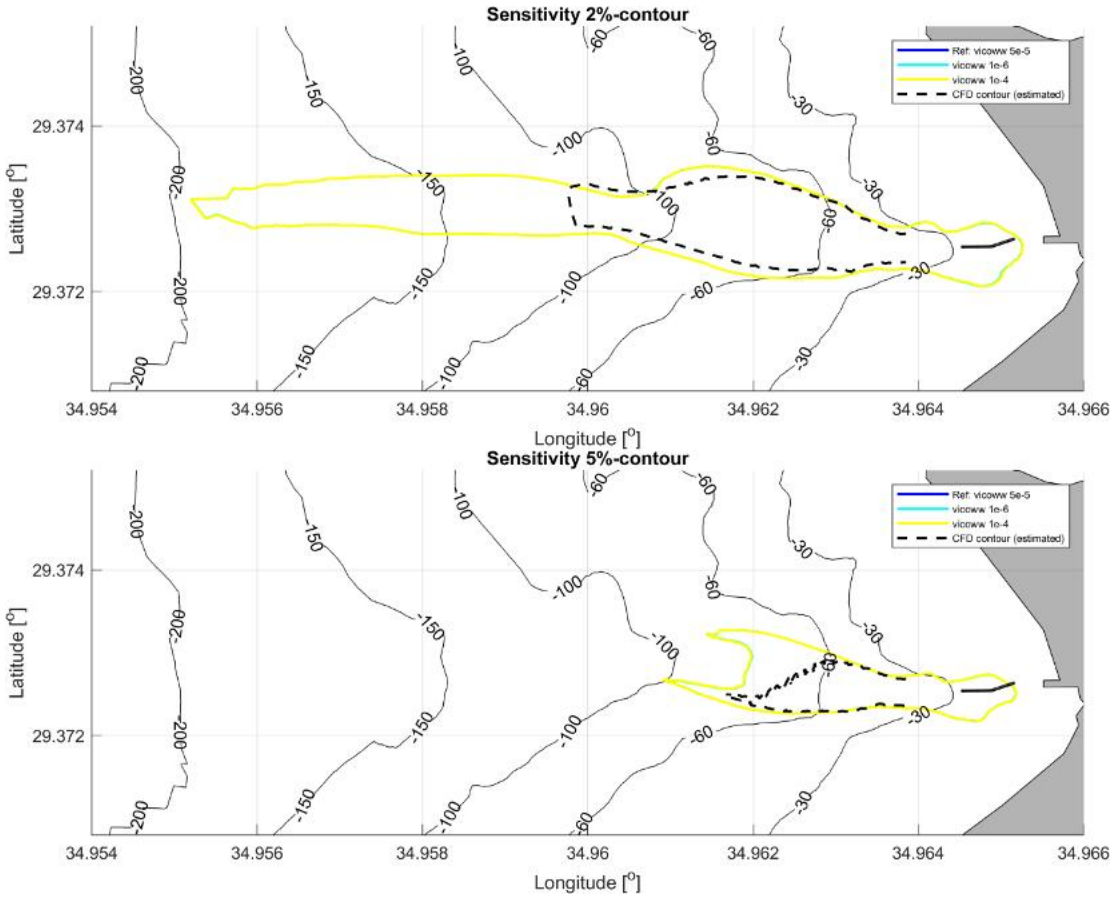

Figure 6.10 Comparison of the 2% and 5% excess-salinity contours for the tested vertical-viscosity values.

6.2.10 Physical and operational conditions

In addition to the numerical and physical model parameters tested explicitly, the importance of ambient conditions and operational discharge conditions was considered. Ambient stratification, tides and wind forcing were excluded from the Simplified Model but included in the Full Model. Their combined influence was assessed through the Simplified Model to Full Model comparison presented in Section 5.3. Variations in discharge flow rate, excess salinity, stopping and starting of the plant operations were not included in the sensitivity simulations as these variations are out of scope of the present study.

Ambient stratification and density profile

Ambient stratification was excluded from the Simplified Model because the sensitivity analysis focuses on density-current behaviour up to approximately -200 m MSL. Full Model results indicate that ambient stratification primarily affects plume trapping at greater depths, estimated in the presentation at approximately -300 to -600 m MSL depending on the ambient stratification. Upstream of the trapping region, stratification was considered to have negligible influence on effluent behaviour. Comparison of the Simplified and Full Models showed very similar 2%, 3% and 5% contours in the Transition Zone for the modelled conditions.

Ambient currents and forcing conditions

Tidal boundary conditions and wind forcing were excluded from the Simplified Model. The presentation indicates near-bed tidal and wind-driven currents of approximately 0.05 m/s, compared with plume-driven currents of approximately 1 m/s in the density-current part of the plume trajectory. On this basis, tide and wind were considered secondary within the sensitivity-analysis area up to plume trapping. Their combined influence is addressed through the Full Model comparison, not through separate current-speed, current-direction or tidal-state sensitivity simulations.

6.3 Conclusions of sensitivity analysis

The sensitivity analysis assessed the influence of the selected numerical and physical model parameters on the predicted 2% and 5% excess-salinity contours. The strongest sensitivity was observed for vertical layering and the sigma-correction setting, which affect both offshore plume propagation and side-slope intrusion. Horizontal diffusivity, horizontal viscosity and bed roughness had a moderate influence, while near-field dilution and horizontal resolution had a smaller influence within the tested ranges. Inclusion of the KEMAPCO outfall and variations in vertical diffusivity and vertical viscosity had an insignificant influence on the predicted plume footprint.

The horizontal-resolution assessment showed that the 20 × 20 m grid underrepresents plume dispersion within the canyon, particularly for the 5% contour, whereas the 8 × 8 m grid was considered sufficient to represent the principal plume characteristics.

The effects of ambient stratification, tidal forcing and wind forcing were not tested individually in the parameter matrix. Instead, their combined influence was evaluated through comparison of the Simplified and Full Models. For the modelled conditions, the comparison showed similar 2%, 3% and 5% contours within the Transition Zone, supporting the use of the Simplified Model for the parameter-specific sensitivity analysis.

The sensitivity analysis did not include separate variations in discharge flow rate, discharge excess salinity, turndown operation or upset conditions, as these are not within the scope of the present study. The conclusions therefore apply to the discharge characteristics used in the modelled scenario and should not be interpreted as demonstrating insensitivity to alternative operational conditions. Based on the completed sensitivity simulations and comparison with the ATM CFD results in the Transition Zone, Most Realistic and Conservative model settings were defined for the subsequent Full Model simulations (Chapter 7).

Table 6.2 Overview of parameters and their influence on the modelling results

Parameter	Influence on plume footprint
Vertical layering / sigma correction	Large
Horizontal diffusivity	Medium
Horizontal viscosity	Medium
Bed roughness	Medium
Near-field dilution	Small
Horizontal resolution	Small
KEMAPCO outfall	Insignificant
Vertical diffusivity	Insignificant
Vertical viscosity	Insignificant

7 Full Model runs with updated model settings

7.1 Introduction

Following completion of the sensitivity analysis described in Chapter 6, two representative Delft3D-FM model configurations were selected for application in the Full Model simulations: a Most Realistic configuration and a Conservative configuration. These parameter sets were derived from the sensitivity-analysis results and comparison with the ATM CFD simulations in the Transition Zone, and were selected to represent a realistic prediction of plume behaviour and a conservative estimate of side-slope intrusion, respectively.

The objective of the Full Model simulations is to evaluate the behaviour of the AAWDCP brine discharge using model configurations that account for the uncertainty identified during the sensitivity analysis. Unlike the Simplified Model used in Chapter 6, the Full Model includes the complete hydrodynamic forcing conditions and model setup adopted for the project assessment. The resulting simulations were used to assess the spatial extent of the plume, its vertical distribution in relation to the canyon side-slopes, transboundary effects and recirculation potential.

The parameter values defining the Most Realistic and Conservative model configurations are summarised in Table 7.1.

Table 7.1 Most Realistic and Conservative model settings applied in the Full Model simulations.

Parameter	Most Realistic	Conservative
Vertical layering	Sigma layering 2%	Sigma layering 1%
Sigma correction switch	0	1
Horizontal diffusivity	0.1	0.2
Horizontal viscosity (vicouv)	0.1	0.2
Horizontal viscosity (Smagorinsky)	0.2	0.4
Bed roughness (Manning)	0.024	0.020
Near-field dilution	100%	100%
Horizontal resolution	8 × 8 m	8 × 8 m
KEMAPCO outfall	Included	Included
Vertical diffusivity	1×10^{-6}	1×10^{-6}
Vertical viscosity	1×10^{-6}	1×10^{-6}

In this chapter, a selection of results is presented to facilitate readability of the report. However, all results have been provided in a digital format as an attachment to this report to the Client for further use in the preparation of the EIA.

7.2 Full Model simulation with Most Realistic settings

This section describes key characteristics of the modelling results for the simulation with the Most Realistic settings. This section presents the modelling results in the following ways:

- Salinity increase footprints
- 2DV excess-salinity cross-section along the canyon axis;
- 2DV excess-salinity cross-section perpendicular to the canyon axis;
- near-bed velocity.

Figure 7.1 shows that after discharge, the effluent initially flows southwest to west and then follows the slope of the submarine canyon. At 100 m from the diffuser, the maximum excess salinity is approximately +3.5 to +4 psu. This exceeds both the 2% and 5% excess-salinity criteria, corresponding to approximately +0.8 psu and +2 psu, respectively. The +5% contour descends to approximately -100 m depth and extends to a distance of about 300 m from the diffuser. The maximum height of the 5% excess-salinity contour up the canyon side slope is limited to approximately 1–2 m in the Transition Zone. Note that the excess salinity before the impact point is not shown in this figure, as Delft3D-FM only models the far-field dispersion after the near-field plume has been introduced into the model.

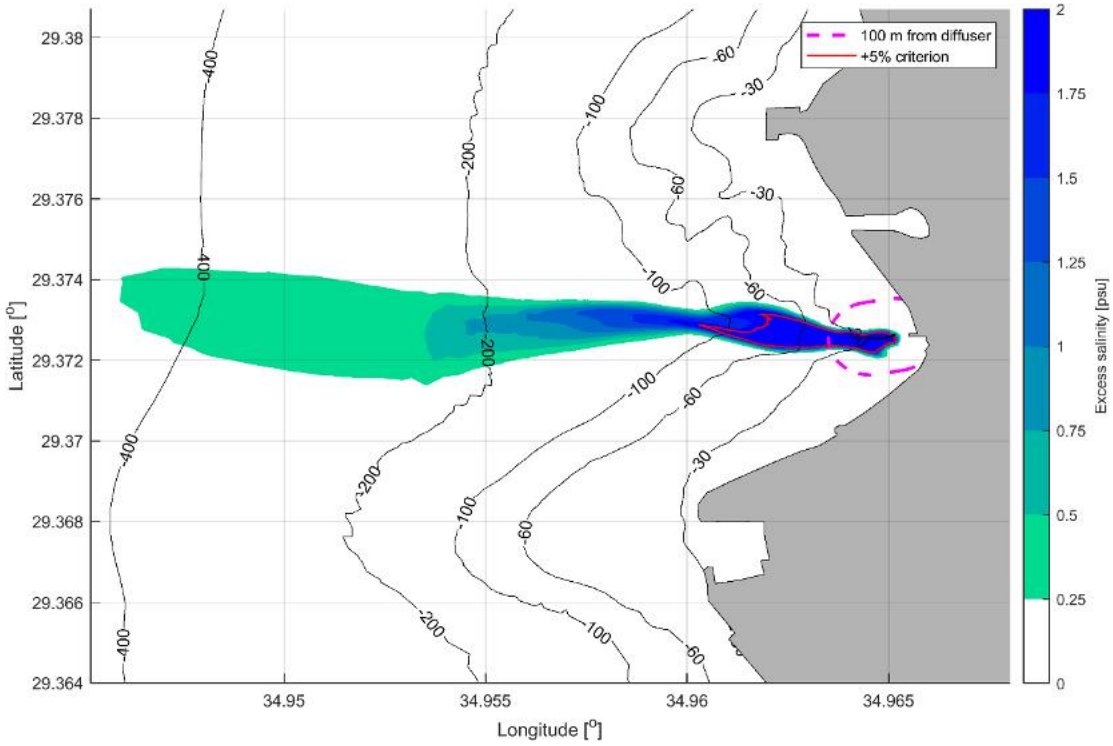

Figure 7.1 Computed excess salinity footprint for the most realistic model settings

Figure 7.2 shows the 2DV excess-salinity cross-section along the canyon axis. The figure indicates that the outfall plume propagates offshore close to the seabed. At locations where the canyon narrows, such as approximately 100 m and 400-600 m downstream of the diffuser, the plume reaches its largest thickness, reaching up to about 10 m for the 2% salinity increase contour. Between and beyond these canyon narrowings, plume thickness decreases to approximately 1-2 m for the 5% salinity increase contour and 2-5 m for the 2% salinity increase contour. The plume thickness values reported above apply to the plume centerline. Towards the canyon flanks, the bed elevation increases, resulting in a locally reduced plume thickness (see for example Figure 7.4). The figure also shows that the near-bed salinity increase caused

by the plume gradually decreases as the plume descends along the slope, due to mixing with the ambient water through entrainment.

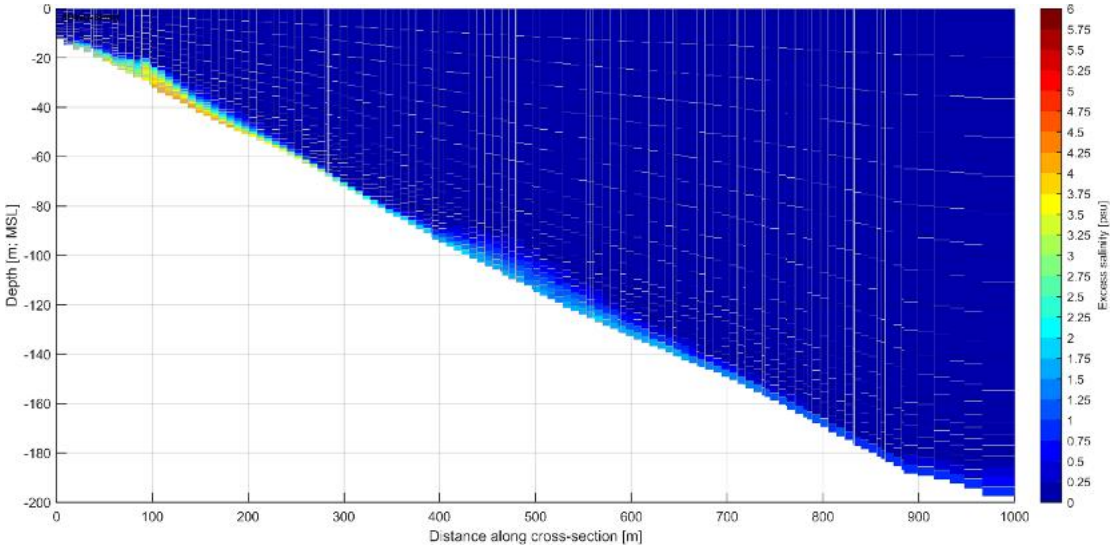

Figure 7.2 Computed 2DV excess salinity cross-section through canyon axis

Figure 7.3 shows the velocity along the same canyon axis. Computed near-bed velocities along the canyon axis are typically in the range of 0.8–1.1 m/s between approximately -60 m and -150 m MSL. Such density current velocities may mobilise bed material and this may result in changes in the bed morphology (like scour) and suspended sediments if the bed material is sufficiently fine. This is however not further assessed or quantified in the present study, but may be relevant to assess in more detail in relation to the environmental assessments.
As the velocity is driven by the excess salinity, and therefore the higher density, of the plume in combination with the seabed slope, the highest velocities are computed close to the bed, where the highest salinity increases are also expected.

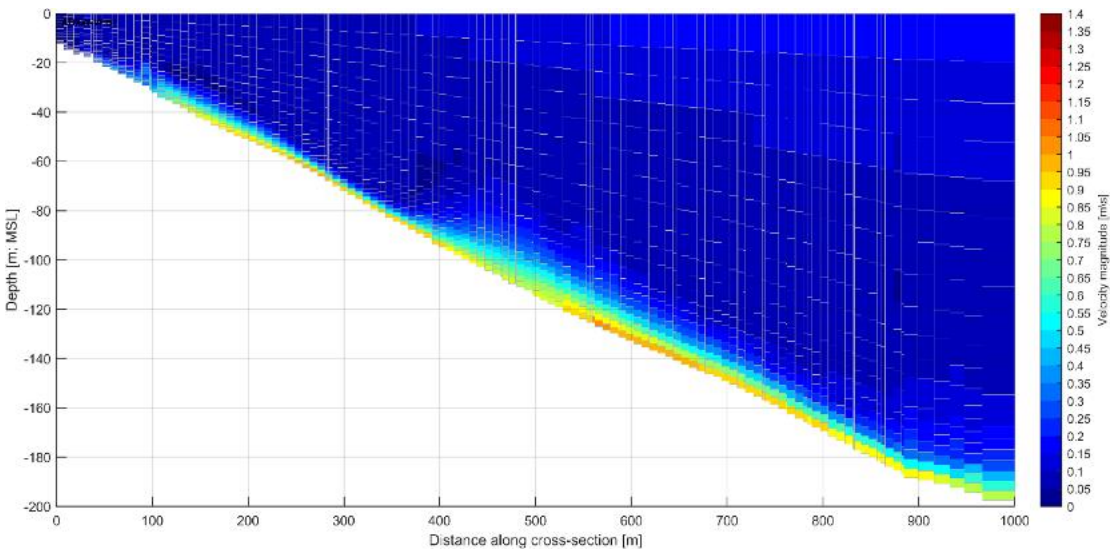

Figure 7.3 Computed 2DV velocity cross-section through canyon axis

Figure 7.4 and Figure 7.5 shows cross-section views of the computed excess salinity at two locations in the canyon downstream of the outfall. As above, the raw modelling results are presented, meaning that each computational grid cell and model layer is shown directly as computed by the model, without interpolation. This allows for a clear interpretation of the model resolution and of how the canyon geometry and plume dimensions are represented.

The first cross-section, located within the narrower part of the canyon, shows a relatively thick and more concentrated plume. Further downstream, as shown by the second cross-section, the plume has reduced both in thickness and in excess salinity.

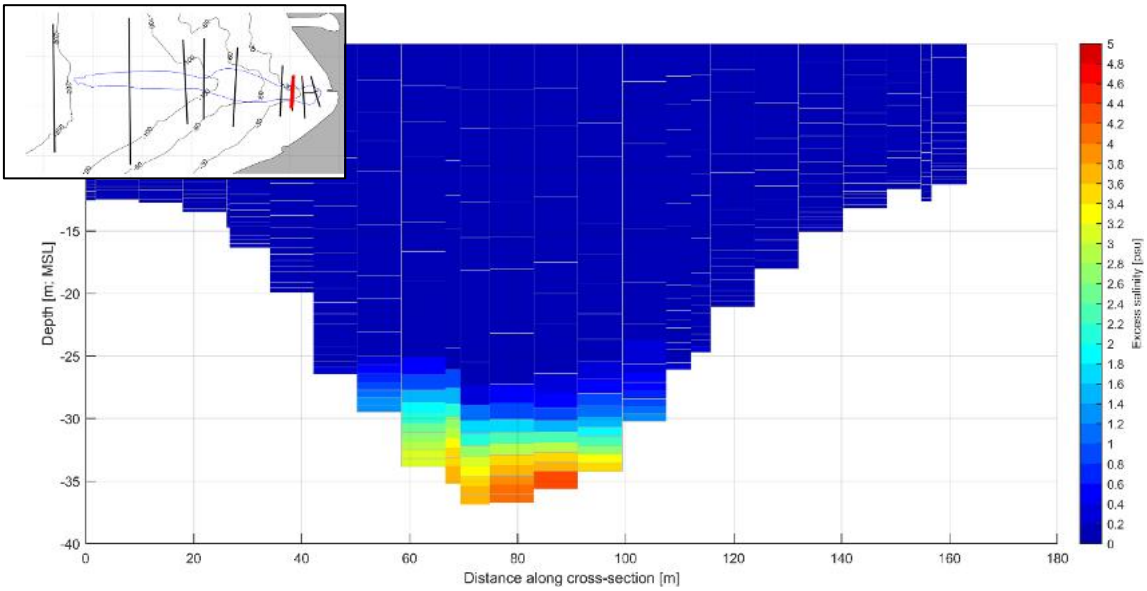

Figure 7.4 Cross section view of the computed excess salinity in the first narrowing of the canyon downstream of the outfall.

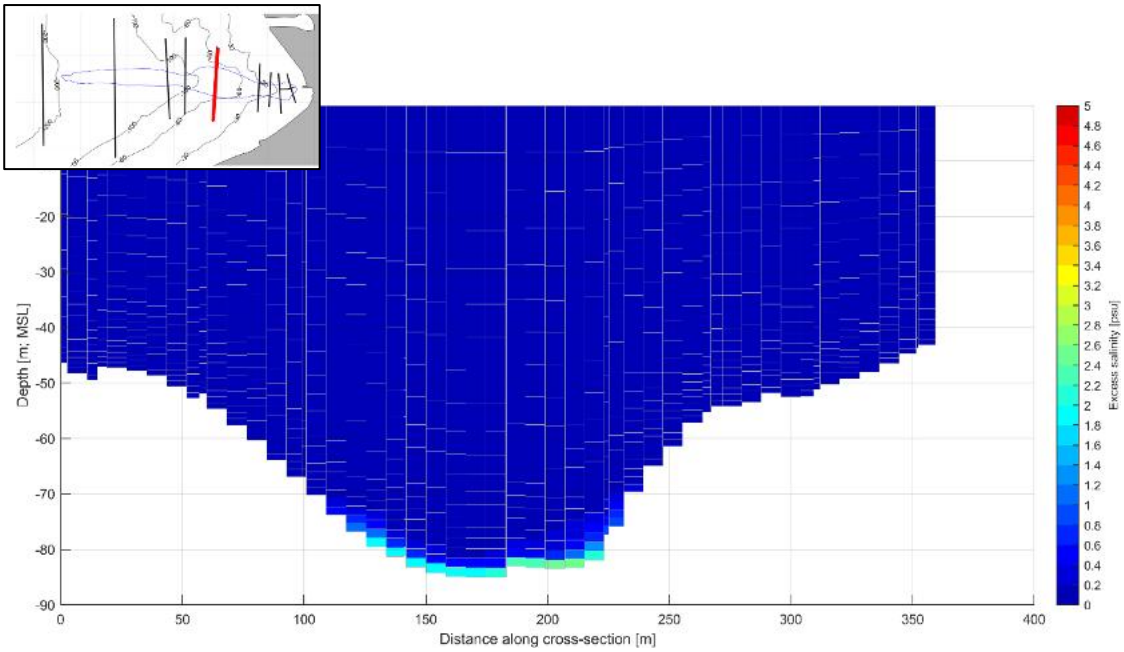

Figure 7.5 Cross section view of the computed excess salinity further downstream of the outfall (in the Transition zone).

7.3 Comparison of Most Realistic and Conservative simulations in relation to the CFD modelling results

The comparison of the sensitivity runs shows that the side-slope extent predicted with the Most Realistic configuration is very similar to the ATM CFD modelling results for both the 2% (i.e., +0.8 psu) and 5% (i.e., +2 psu) excess-salinity contour lines, see Figure 7.6. This agreement is an important finding, because the canyon side slopes form the main area where differences between modelling approaches can affect the interpretation of potential lateral plume spreading. The close correspondence indicates that the selected Delft3D-FM settings provide a realistic representation of plume intrusion along the canyon slopes within the Transition Zone.

In the Offshore zone, the Delft3D-FM sensitivity runs generally predict a larger extent than the CFD results. This difference is considered plausible and is related to the model formulations and numerical schematisations used in the two approaches. The sigma-layer approach used in the Delft3D-FM model is numerically less diffusive and better suited to realistically simulate the near-bed density current, allowing the plume to remain more concentrated and propagate farther downslope. In contrast, the CFD results appear to show stronger dilution and a therefore a shorter offshore extent, particularly farther away from the diffuser and outside the main zone for which the CFD model was originally developed.

Differences in the numerical mixing schemes used by CFD and Delft3D-FM may also contribute to the observed difference in offshore plume extent. The CFD model resolves local turbulence and jet behaviour in greater detail near the diffuser, but its scalar transport and turbulence closure settings may lead to different effective mixing rates when the plume evolves into a gravity-driven density current. Delft3D-FM, on the other hand, is specifically suited to represent the larger-scale downslope transport and interaction with the canyon bathymetry.

The spread between the contour lines obtained with on the one hand the Most Realistic and on the other hand the Conservative settings provides an indication of the range in predicted side-slope extent. The fact that the simulation with the Most Realistic settings lies close to the CFD-based side-slope extent supports the interpretation that the selected settings provide a balanced best estimate. At the same time, the difference between the contours for the Most Realistic and Conservative simulations is useful for defining a plausible range of side-slope intrusion that can be considered in the environmental assessment.

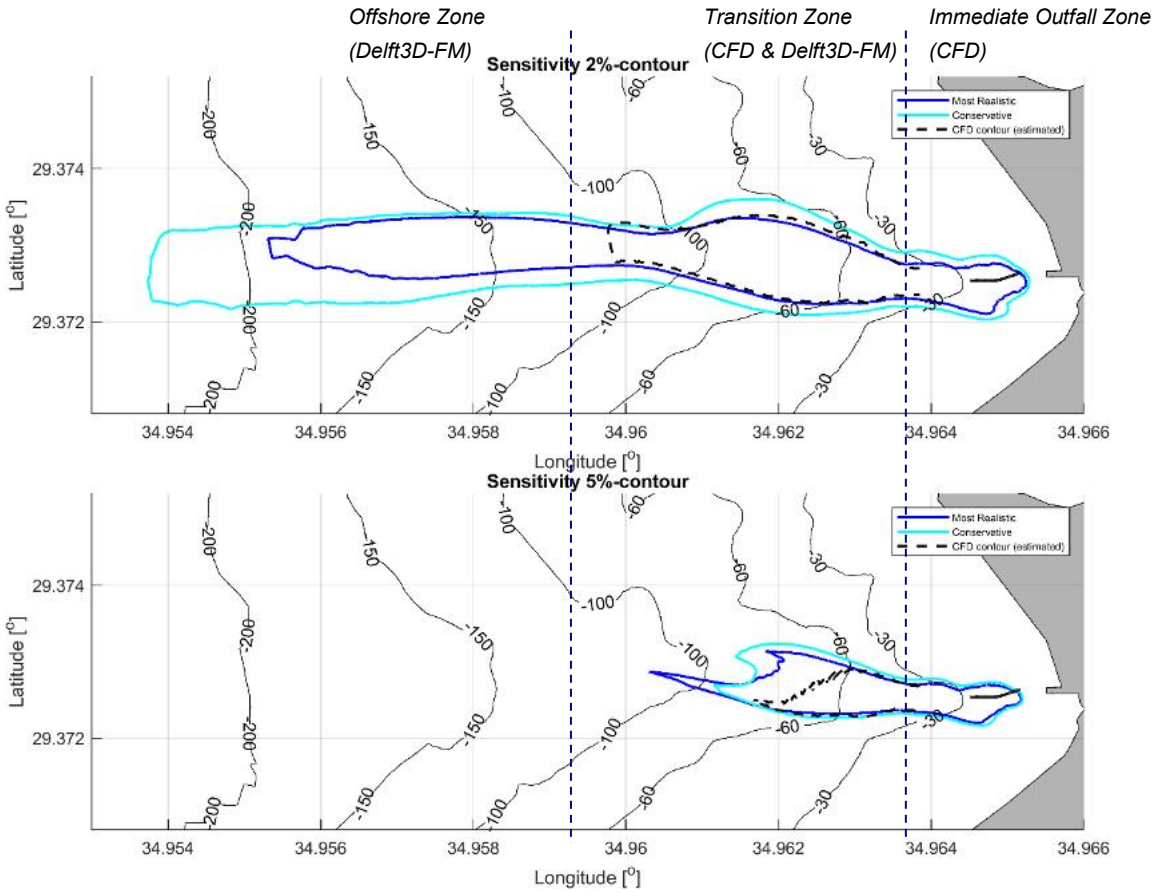

Figure 7.6 Predicted near-bed 2% and 5% excess-salinity contours for the Most realistic and Conservative modelling results.

7.4 Transboundary effects

As described in the Section 7.2, the discharged effluent initially behaves as a density current. Owing to its higher salinity and therefore higher density than the ambient water, the plume follows the seabed slope and is transported downslope towards deeper parts of the canyon. During this downslope transport, ambient seawater is entrained into the plume, which progressively reduces the excess salinity and density difference relative to the surrounding water.

At increasing distance from the outfall, the density contrast between the plume and the ambient water becomes very small. Once this occurs, the density-driven component of the transport becomes insignificant and the subsequent movement of the diluted plume is mainly governed by the weak ambient flow field. This causes the remaining low-concentration plume to be transported both northward and southward. By the time this stage is reached, the excess salinity is generally below 0.25 psu, and is therefore not visible in the salinity contour figure presented in this section.

At the border between Saudi Arabia and Jordan, the effluent plume is typically located at depths between approximately -100 m and -500 m MSL. Depending on the ambient density stratification and the local weak flow patterns, the plume may at times remain close to or in contact with the seabed, while at other times it may be detached from the bed. The local depth and offshore position of the plume are therefore mainly controlled by the ambient stratification and the prevailing weak circulation patterns, which can move the plume closer to or farther offshore.

The computed maximum excess salinity at the Saudi-Jordan border (see also Figure 7.7) is approximately 0.1 to 0.15 psu (i.e., a dilution factor of about 250 – 350). This corresponds to about 0.25% to 0.35% of the background salinity and is therefore very small compared with natural salinity levels in the Gulf of Aqaba of around 40.7 psu. At the borders with Israel and Egypt, the computed excess salinity is lower than 0.02 psu.

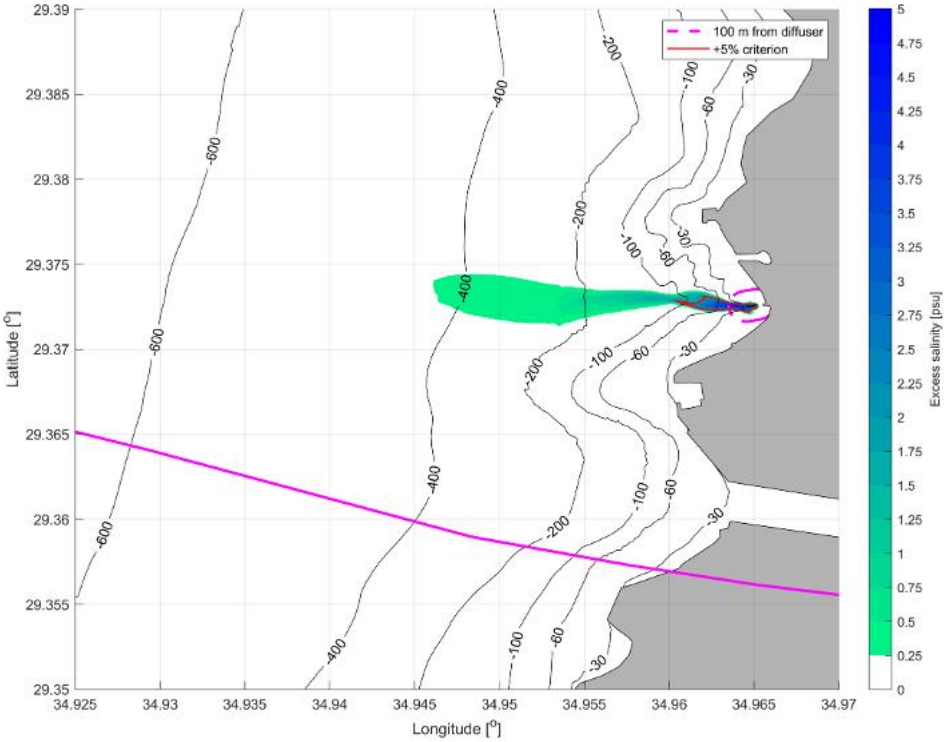

Figure 7.7 Computed outfall salinity footprint zoomed out to also show the Saudi Arabian border (purple line)

7.5 Recirculation

The Delft3D-FM modelling results show that the effluent is transported offshore down the seabed slope as a density current. Based on this plume behaviour, no recirculation towards the intake is computed and expected. The location of the effluent plume, canyon and intake are indicated in Figure 7.8. The maximum computed excess salinity at the intake is less than 0.1 psu, indicating that any potential recirculation effect is negligible. This is consistent with the CFD modelling results presented by the ATM study.

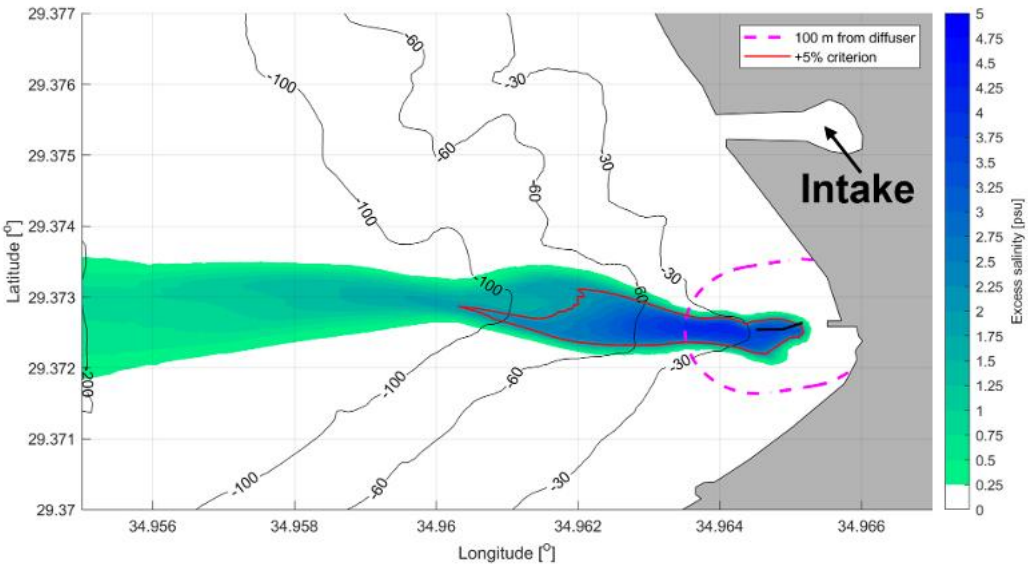

Figure 7.8 Computed outfall salinity footprint (near bed) and indication of the intake location

7.6 Long-term plume behaviour

The long-term behaviour of the AAWDCP brine plume was assessed based on the modelling results, supported by expert judgement on density-current behaviour, ambient stratification and far-field dispersion processes. The assessment focuses on whether continuous operation of the outfall could lead to progressive build-up of excess salinity in the receiving environment, or whether the plume is expected to reach a stable dynamic condition after discharge starts.

Based on time-series analysis of the modelling results, the density current and associated excess-salinity levels reach an equilibrium condition within a period ranging from minutes to several hours (or days at most), depending on the distance from the outfall. It is noted that the Full Model simulations have run for several weeks[9], so substantially longer than reaching the equilibrium condition.

Close to the diffuser and within the Immediate Outfall Zone, the plume responds rapidly to the start of the release because the local behaviour is dominated by jet momentum, negative buoyancy and initial entrainment. Further downstream in the Transition Zone and Offshore Zone, the adjustment time increases as the plume develops into a gravity-driven density current and propagates along the canyon bathymetry towards greater water depths.

No significant long-term accumulation of the discharge is expected in the vicinity of the outfall. The discharged brine has a higher density than the surrounding seawater and therefore sinks after release. After the initial diffuser-driven mixing phase, the plume continues downslope as a negatively buoyant density current. During this transport, entrainment and turbulent mixing with surrounding seawater progressively reduce the excess salinity and the density difference between the plume and the ambient water column.

The model results indicate that the plume will continue to descend along the submarine canyon until it reaches a depth where its density becomes comparable to the ambient density structure. This depth can be interpreted as the trapping depth of the diluted density current. Depending on the ambient stratification and discharge conditions, this trapping depth may occur at depths

[9] It is noted that the Simplified Model was run for 5 hours, which was demonstrated to be sufficient for the sensitivity analysis, but the Full Model simulations have been run for several weeks.

of several hundred metres below mean sea level. Once the plume has reached this depth range, vertical movement becomes limited and the remaining excess salinity is transported and dispersed by larger-scale ambient currents and mixing processes over a large offshore area.

The long-term plume behaviour should therefore be interpreted as a dynamic equilibrium rather than as a continuously expanding or accumulating plume. During continuous operation, a plume footprint will be maintained within the canyon and offshore receiving waters, but the model results do not indicate progressive build-up of excess salinity near the diffuser, along the canyon side slopes or within the Transition Zone. Instead, the plume is expected to remain largely confined to the density-current pathway, while gradual dilution and offshore dispersion reduce salinity increase with increasing distance from the outfall. This interpretation is also relevant for the assessment of transboundary effects and recirculation.

8 Conclusions

A rigorous sensitivity analysis was carried out to assess the robustness of the Delft3D-FM plume dispersion results and to identify the most realistic model settings for the final assessment in the absence of field data for model validation since the (future) SWRO plant is not present or operating yet. The analysis considered the influence of key numerical and physical model parameters, including vertical layering, mixing coefficients, bed roughness, horizontal resolution and near-field dilution. Based on this analysis, a set of most realistic model settings was selected to provide the best estimate of plume behaviour, side-slope intrusion and plume extent.

ATM's CFD model provides a detailed representation of the immediate outfall zone (in the first tens of metres around the outfall), where jet momentum, negative buoyancy, and entrainment dominate plume behaviour. Deltares' Delft3D-FM model provides the broader hydrodynamic and salinity-transport modelling approach needed to assess transport and dispersion beyond this immediate diffuser region. The comparison between both approaches focuses on the transition zone (the area between the first and second narrowing of the canyon, between about -30m and -100m MSL), where outputs from the CFD and Delft3D-FM models overlap and can be meaningfully compared.

For the Most Realistic Delft3D-FM model settings, the computed side-slope extent of the plume in the Transition Zone is very similar to the CFD results. The typical plume centreline thickness is about 1-2 m for the 5% excess-salinity contour and about 2 - 5 m for the 2% excess-salinity contour, reducing towards the plume margins depending on local canyon geometry. At certain locations, where the canyon narrows, the plume locally reaches a thickness of about 10 m (i.e. 2% salinity increase). Computed near-bed velocities along the canyon axis are typically in the range of 0.8–1.1 m/s between approximately -60 m and -150 m MSL. These velocities are associated with the downslope density-current behaviour of the plume and occur close to the seabed, where the highest excess salinities are also computed. Such density current velocities may mobilise bed material and this may result in changes in the bed morphology (like scour) and suspended sediments if the bed material is sufficiently fine. This is however not further assessed or quantified in the present study, but may be relevant to assess in more detail in relation to the environmental assessments.

The 5% excess-salinity contour extends offshore to a water depth of approximately -80 m to -100 m MSL in the Delft3D-FM results. This offshore extent is larger than indicated by the CFD results. The difference is likely related to differences in numerical schematisation, including the less diffusive vertical layering applied in the Delft3D-FM model through sigma layers, as well as differences between the CFD and Delft3D-FM models in terms of numerical mixing schemes. The numerical schematisation of the Delft3D-FM model is considered most suitable for a reliable representation of the outfall plume offshore extent (far-field).

For the Immediate Outfall Zone, the CFD modelling is considered the most appropriate source of information. In this area, plume behaviour is governed by near-field jet processes, initial momentum, negative buoyancy and rapid entrainment. These processes are explicitly represented in the CFD model, which was originally developed to assess local flow velocities around the diffuser. The CFD results should therefore be used as the preferred basis for interpreting conditions close to the diffuser, particularly where local flow velocities are relevant. Although CFD salinity data for this specific zone were not available for the present comparison, the Delft3D-FM results in the Immediate Outfall Zone are expected to be broadly consistent with the CFD results, particularly for the 5% excess-salinity contour. In this near-field area, the

Delft3D-FM results are likely to be slightly conservative. However, they remain suitable for use in the wider environmental assessment as part of the integrated Delft3D-FM modelling results. In the Transition Zone, the CFD and Delft3D-FM results are generally in good agreement with respect to the height of the 5% excess-salinity contour up the canyon side slopes. Both models show similar behaviour in the Transition Zone down to approximately -60 m MSL. Deeper than this, the CFD results appear more diffusive, while the Delft3D-FM model better preserves the effluent density current.

Based on these findings, the Delft3D-FM results are considered the recommended source of information below approximately -60 m MSL and farther offshore in the Offshore Zone. This recommendation reflects the suitability of Delft3D-FM for representing larger-scale density-current behaviour, bathymetric steering, ambient stratification and far-field transport, as well as the numerical limitations of the CFD modelling when applied beyond its primary near-field purpose.

The final Full Model simulations using the most realistic model settings obtained from the sensitivity analysis provide the basis for assessing the expected plume extent at excess-salinity levels of 2% and 5% above background salinity. Based on the modelling results, the assessment indicates that the plume is expected to remain primarily within the canyon pathway. These simulations also support evaluation of potential transboundary transport (approximately 0.1 to 0.15 psu increase (i.e., a dilution factor of about 250 – 350), corresponding to about 0.25% to 0.35% of the background salinity) and recirculation towards the intake (<0.1 psu increase).

Overall, the robustness of the modelling results has been demonstrated through a comprehensive sensitivity analysis of the Delft3D-FM model and an independent comparison with detailed CFD simulations undertaken by ATM. While direct validation against field measurements is not yet possible because the outfall has not been constructed or operated, the study benefits from a unique opportunity to compare two fundamentally different numerical modelling approaches. Such detailed inter-model comparisons are rarely available during the pre-construction phase of major infrastructure projects. The strong level of agreement between the Delft3D-FM and CFD predictions therefore provides a high degree of confidence in the reliability of the modelling results and the predicted behaviour of the brine plume, and for supporting the environmental assessment of the proposed discharge.

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