GEMCO Excess Water Disposal Project

Marine Discharge Modelling Report

GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited)

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Executive Summary

Groote Eylandt Mining Company Pty Ltd (GEMCO) is investigating alternative disposal options for discharging surplus mine dewater, which is currently discharged to bushland. One of the options being considered is marine discharge via a proposed new ocean outfall located near GEMCO's port facility on the western coast of Groote Eylandt, approximately 10 km north of the mining operations (the Project).

GEMCO engaged GHD Pty Ltd to undertake hydrodynamic modelling of the proposed marine discharge to predict the extent of the marine mixing zone.

The following scope has been undertaken:

– Near-field modelling of a range of outfall configurations was undertaken to recommend an appropriate diffuser concept design for the marine discharge. The concept design selected is a ~150 m long diffuser of 30 alternating 150 mm ports discharging north-westward and south-eastward at the seabed with an average depth of ~8.5 m.
– Marine trigger values were adopted that were derived from available site-specific water quality data and literature, and dilution targets were defined for a range of parameters within the discharge.
– A three-dimensional (3D) far-field hydrodynamic model was developed, calibrated and validated for the south-western region of the Gulf of Carpentaria with refined resolution in the vicinity of Groote Eylandt and the proposed marine outfall site.
– The diffuser concept design was incorporated into the 3D far-field model and an operational discharge flowrates of 80 GL/a was simulated over a one-year period to account for seasonally varying met-ocean conditions at the site.

Based on conservative assumptions of discharge quality, dilution targets of 42-fold for the mixing zone of **potential indirect effects** related to nitrate enrichment, and 35-fold for the mixing zone for **potential direct effects** related to salinity reduction have been defined for this study. The indirect effects are only likely to represent a risk if the receiving marine environment is not flushed rapidly enough, with algal blooms potentially arising in stagnant zones (though this was not predicted for this site). Further, potential direct effects related to salinity reduction are only expected to yield ecological impacts when occurring at the seabed in the presence of benthic primary producers (seagrass or corals) that are unable to escape the plume.

The far-field simulations yielded the following predictions:

– The outer extent of the surface mixing zone for **potential indirect effects** (42-fold dilution target related to nitrate enrichment) is predicted to extend ~650 m north and ~550 m southeast from the diffuser.
– The outer extent of the surface mixing zone for **potential direct effects** (35-fold dilution target related to salinity reduction) is predicted to extend ~400 m north-northwest and ~350 m southeast from the diffuser.
– There was no predicted mixing zone at the seabed due to the buoyant nature of the plume.
– Predicted flushing rates of the near-shore receiving waters encompassing the mixing zone are rapid, with e-folding timescales (the time to exchange ~67% of the volume with surrounding ambient waters) averaging 16 hours, and ranging from 6 hours at a minimum to 35 hours maximum. The PIANC (2008) standard for marinas states e-folding times of less than four days represent good flushing.

The risks of negative ecological impacts related to nitrate enrichment (potential indirect impacts) are reduced by the rapid flushing rates. Additionally, the risks of direct impacts to benthic primary producers at the seabed related to salinity reductions are negated by the buoyancy of the plume which yields a mixing zone that is vertically constrained to the surface waters. The discharge scenario assessed in this study are considered to pose a suitably low level of environmental risk.

The predictions presented in this study are considered conservative for the following reasons:

– The discharge of 80 GL/a defined by GEMCO represents the assumed peak flow. The discharge rate in the model was held constant over a one-year duration simulation and therefore overestimates the likely discharge volumes on an annual timescale, which during operations are expected to average 60 GL/a.

– Concentrations of analytes within the discharge were generally defined as the 95th percentile of historical measurements from the site and therefore are over-estimates of loads for the majority of the time.
– Though the hydrodynamic model was verified with measured currents that were well reproduced, current speeds are marginally under-estimated. This resultant reduced simulated flushing of the nearshore environment relative to actual conditions therefore likely represents an over-prediction of the mixing zone spatial extent in general due to less volumetric dilution.
– All water quality analytes (with the exception of pH, which was evaluated with a separate model that accounts for pH buffering processes) were treated as numerically conservative tracers, neglecting transformative processes (degradation, decay, biological uptake) that may otherwise occur for some analytes and will lead to lower concentrations during operations than those simulated here. In general, this assumption will over-estimate the spatial extent of the mixing zone.

This report is subject to, and must be read in conjunction with, the limitations set out in section 1.2 and the assumptions and qualifications contained throughout the Report.

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1. Introduction

Groote Eylandt Mining Company Pty Ltd (GEMCO) operates a manganese mine on Groote Eylandt, located within the Gulf of Carpentaria approximately 650 km south east of Darwin and 50 km off the Arnhem Land coast. The open pit mining operations intercept groundwater and rainwater within the mine pits, which is subsequently dewatered and partially utilised for operational needs (manganese ore processing, dust suppression and washdown facilities). Excess dewater surplus to operational needs is currently released to the surrounding bushland. The discharge to bushland is subject to the water quality falling within an acceptable range of water quality limits (trigger values).

Recent years have seen increases in dewatering volumes driven by increased mine production, greater depths of mining and closer proximity of mine pits to the coast. Additionally, GEMCO is predicting a deterioration in water quality, primarily related to marginal increases in salinity and turbidity, that may yield the water unfit for disposal to bushland under the current water quality limits. GEMCO is therefore investigating alternative options for excess water disposal. One of the options being considered is marine discharge via a proposed new ocean outfall located near GEMCO's port facility on the western coast of Groote Eylandt, approximately 10 km north of the mining operations (the Project).

1.1 Purpose of this report

GEMCO engaged GHD Pty Ltd to undertake hydrodynamic modelling of the proposed marine discharge to predict the extent of the marine mixing zone. This report presents the inputs, methodology and outcomes of the hydrodynamic modelling undertaken.

1.2 Scope and limitations

The following scope has been undertaken:

– Near-field modelling of a range of outfall configurations was undertaken to recommend an appropriate diffuser concept design for the marine discharge.
– On the basis of marine trigger values that were derived from available site-specific water quality data and literature, dilution targets were defined for a range of parameters within the discharge.
– A three-dimensional (3D) far-field hydrodynamic model was developed, calibrated and validated for the south-western region of the Gulf of Carpentaria with refined resolution in the vicinity of Groote Eylandt and the proposed marine outfall site.

  The preliminary diffuser configuration that was developed via near-field modelling was incorporated into the 3D far-field model. The proposed discharge of 80 GL/a of excess mine dewater was simulated in the far-field model over a one-year period to account for seasonally varying met-ocean conditions at the site. The discharge rate represents the likely peak daily flow rate of future operations, which is estimated by GEMCO to be ~25% greater than average daily discharge rates. Nevertheless, as a conservative measure, the peak flow rates are adopted throughout the entire year-long simulation for this modelling assessment.
– The far-field modelling scenario was used to define the spatial extent of the mixing zone beyond which all parameters are predicted to be diluted to a sufficient degree to satisfy the adopted marine trigger values.

This report has been prepared by GHD for GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited) and may only be used and relied on by GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited) for the purpose agreed between GHD and GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited) as set out in section 1.1 of this report.

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The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared the MIKE model and PHREEQC Model (collectively referred to as the "Model") for, and for the benefit and sole use of, GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited) to support the assessment of the environmental mixing zone and must not be used for any other purpose or by any other person.

The Model is a representation only and does not reflect reality in every aspect. The Model contains simplified assumptions to derive a modelled outcome. The actual variables will inevitably be different to those used to prepare the Model. Accordingly, the outputs of the Model cannot be relied upon to represent actual conditions without due consideration of the inherent and expected inaccuracies. Such considerations are beyond GHD's scope.

The information, data and assumptions ("Inputs") used as inputs into the Model are from publicly available sources or provided by or on behalf of the GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited), (including possibly through stakeholder engagements). GHD has not independently verified or checked Inputs beyond its agreed scope of work. GHD's scope of work does not include review or update of the Model as further Inputs becomes available.

The Model is limited by the mathematical rules and assumptions that are set out in the Report or included in the Model and by the software environment in which the Model is developed.

The Model is a customised model and not intended to be amended in any form or extracted to other software for amending. Any change made to the Model, other than by GHD, is undertaken on the express understanding that GHD is not responsible, and has no liability, for the changed Model including any outputs.

GHD has prepared this report on the basis of information provided by GEMCO Pty Ltd (Groote Eylandt Mining Company Proprietary Limited) and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

2. Site Context

The Project site is situated in the vicinity of GEMCO's port operations on the northwestern coast of Groote Eylandt (Figure 1). The region is populated with many islands (of which Groote Eylandt is the largest), with Connexion Island being the nearest at approximately 4.2 km west of the Groote Eylandt coast. The narrow span between Connexion Island and Groote Eylandt results in elevated current speeds through the contraction.

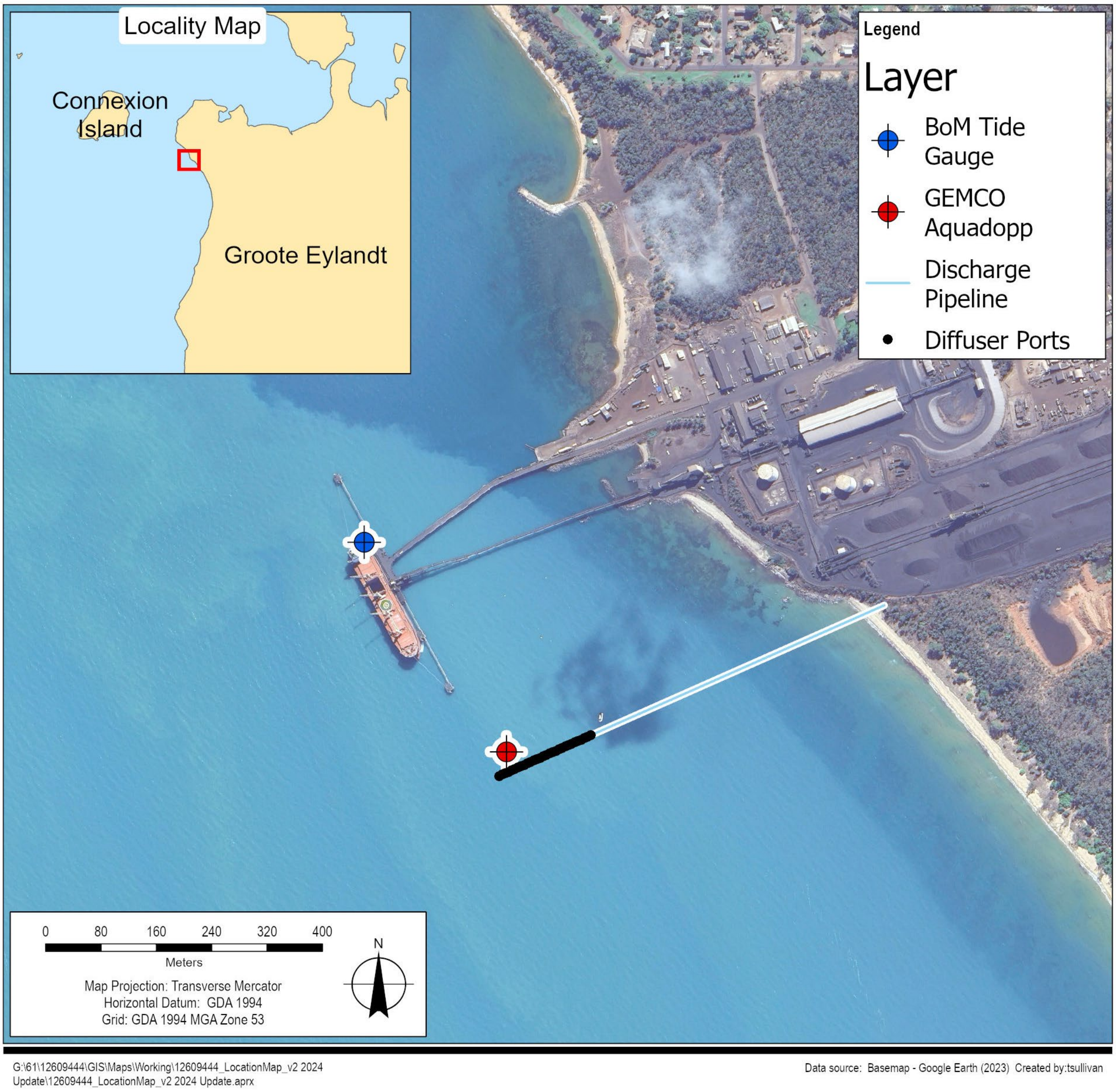


Figure 1 ***Site location including proposed discharge pipeline, diffuser and oceanographic monitoring stations.***

2.1 Tides

Tides near the Project site are measured by the Bureau of Meteorology's (BoM's) tide gauge located at Milner Bay (depicted in Figure 1). The tide gauge has been operational since 1993. Tidal characteristics for Milner Bay are summarised in Table 1.

The tidal range at Milner Bay is reasonably large at 2.4 m (difference between HAT and LAT). Tides have mixed semidiurnal variations, with typically two high tides and two low tides each day. The greater diurnal range (the difference between MHHW and MLLW) is moderate at 1.3 m.

Table 1 Tidal data for Milner Bay

Tidal Datum	Tide Level (m relative to LAT)
Highest Astronomical Tide (HAT)	2.4
Mean Higher High Water (MHHW)	1.9
Mean Lower High Water (MLHW)	1.7
Mean Sea Level (MSL)	1.21
Mean Higher Low Water (MHLW)	0.7
Mean Lower Low Water (MLLW)	0.6
Lowest Astronomical Tide (LAT)	0.0

Source: Australian Government Department of Defence (2017)

2.2 Currents

Currents were measured continuously via an Aquadopp current profiler that was deployed at the GEMCO port facility (Figure 1). Time-series plots of measured current speeds and directions since January 2022 are presented in Figure 2. The current pattern demonstrates a strong tidal influence, with speeds reaching peaks of 0.5-0.6 m/s during spring tides and 0.3-0.4 m/s during neap tides. Directions typically alternate south-easterly and north-westerly, which is aligned to the orientation of the coastline at the Project site. Onshore currents (northerly to easterly) occur infrequently, while offshore currents directed towards the west are also rare in the measured data.

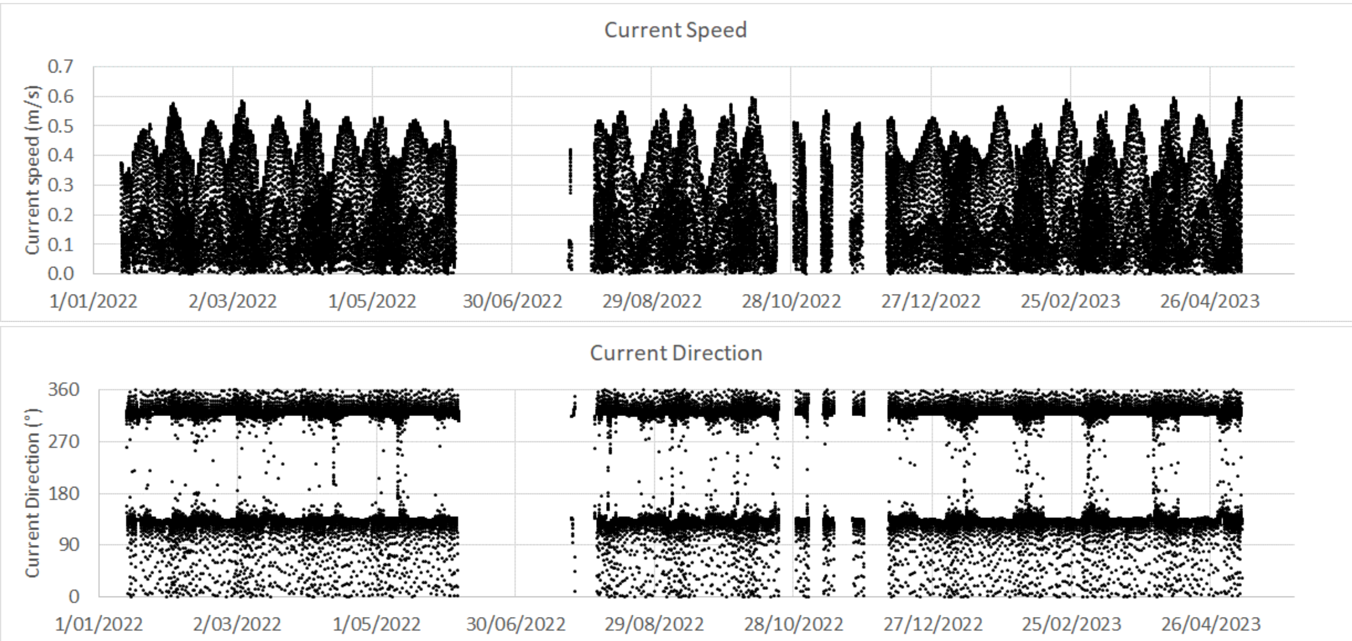


Figure 2 Measured current speeds (top) and directions (bottom) at GEMCO port. [1]

North-westerly currents are dominant within the dataset, occurring 65% of the time, while south-easterly currents occur 30% of the time. North-westerly currents are also generally faster as demonstrated by the statistical distribution of current speeds in Figure 3, with a median current speed of 0.3 m/s compared to 0.13 m/s for south-easterly currents.

[1] Note: Convention for current directions is the direction the current is going 'to'

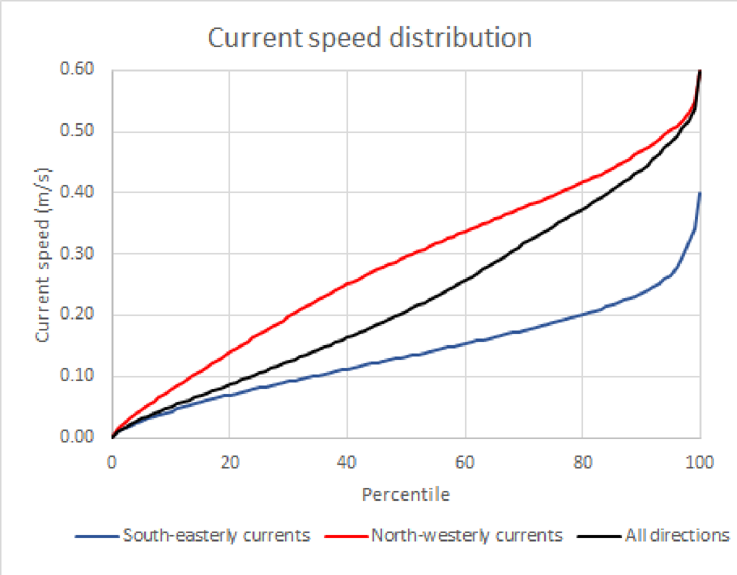


Figure 3 ***Statistical distribution of all currents (black), south-easterly currents (blue) and north-westerly currents (red).***

2.3 Waves

The Project site, located on the northwest coast of Groote Eylandt, is sheltered from offshore swells that penetrate into the Gulf of Carpentaria from the north. Further, it is protected from more locally generated swells that may form within the Gulf of Carpentaria and approach Groote Eylandt from the east or south. Any swells approaching the site from the west will be greatly fetch-limited, as there is less than 50 km of ocean between the Project Site and the Arnhem Land coast for swells to form. An example snapshot of simulated waves in the Gulf of Carpentaria from the Centre for Australian Weather and Climate Research (CAWCR) wave hindcast aggregated collection dataset (Durrant *et al*., 2019) is presented in Figure 4.

Due to the high degree of wave sheltering at the project site, waves have been excluded from this modelling assessment.

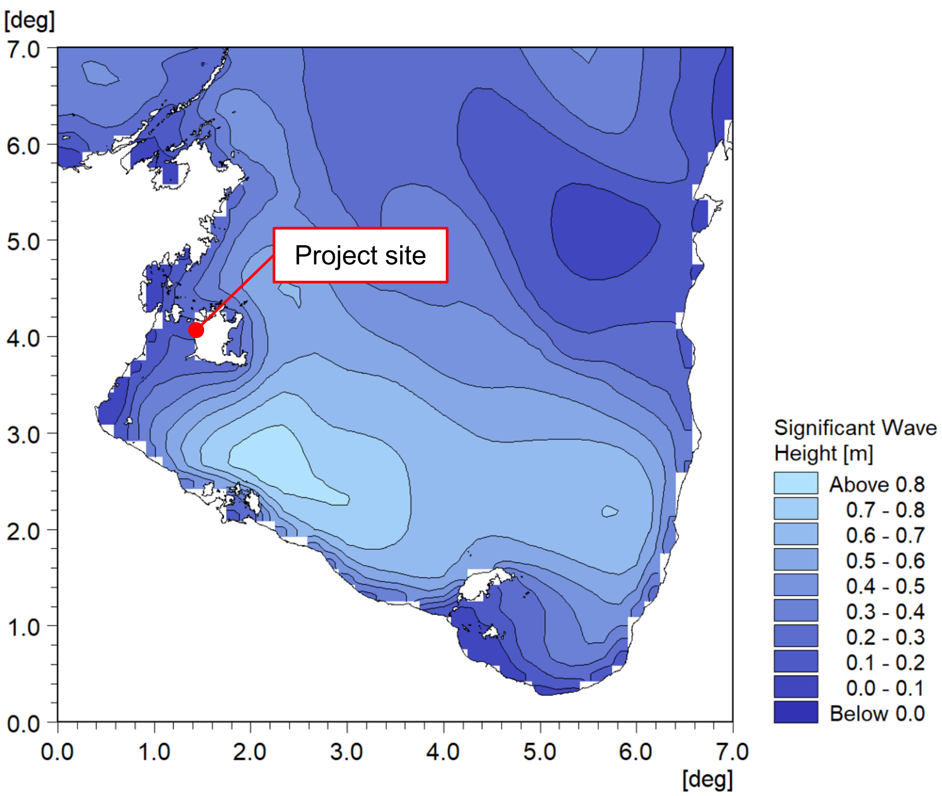
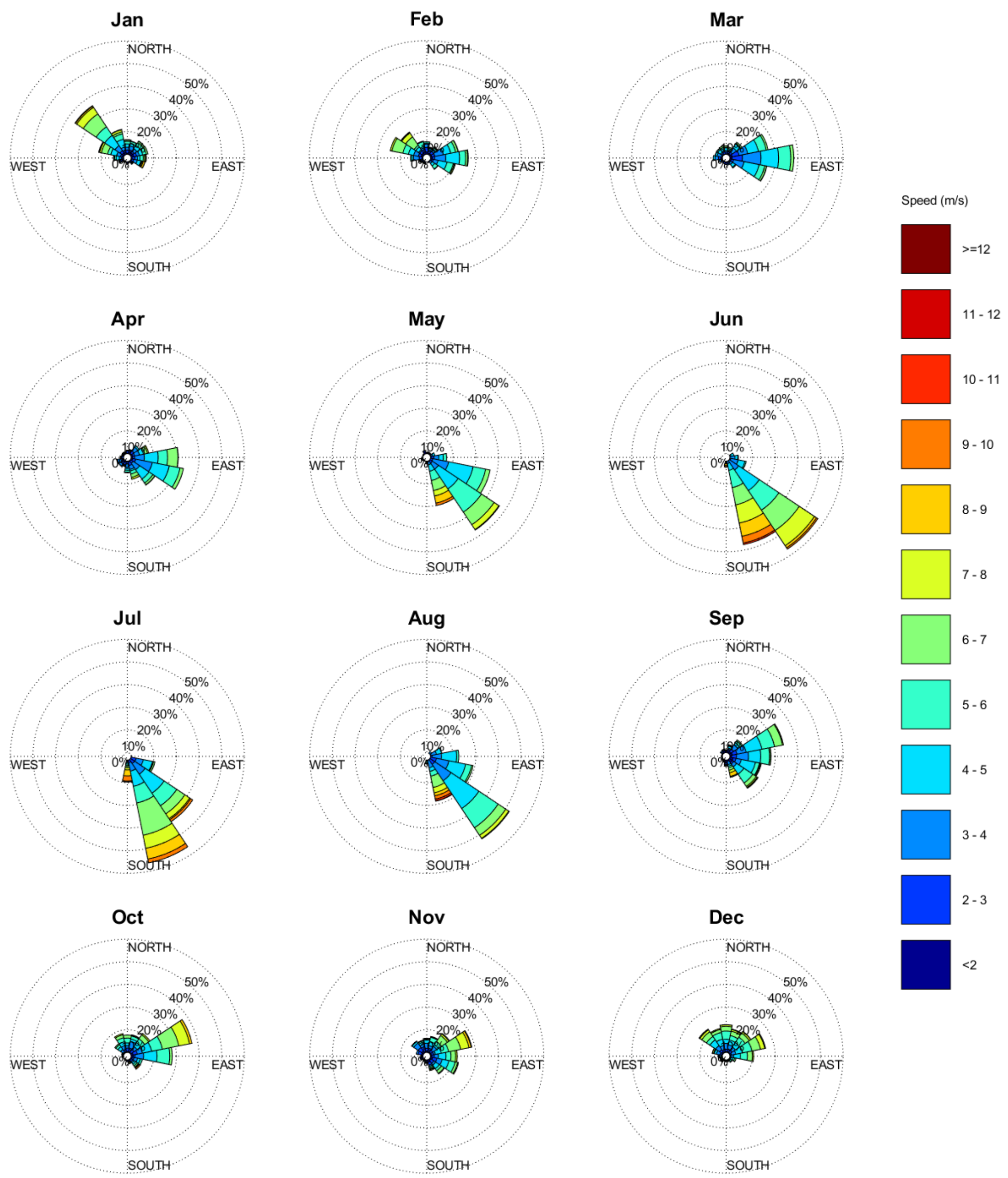


Figure 4 ***Snapshot of wave field from CAWCR wave hindcast model demonstrating sheltering at the Project site.***

2.4 Winds

The National Centers for Environmental Prediction (NCEP) Climate Forecasting System version 2 (CFSv2) winds (Kalnay *et al*., 1996; Kistler *et al*., 2001) served as temporally (hourly) and spatially (0.2°) varying inputs for the modelling. CFSv2 monthly wind roses from three years of wind data extracted for the CFSv2 node nearest to the Project Site are presented in Figure 5.

The wind regime is characterised primarily by generally moderate wind speeds 3-8 m/s. Wind directions vary seasonally with the dry season (April to August) being characterised by prevailing easterly and south-easterly winds, with more varied wind directions generally ranging from north-westerly to easterly during the wet season October to February). March and September are transitional periods with a mixture of the wet and dry season wind regimes.



Wind roses from 01/12/2021 to 01/02/2023 at -13.79898 , 136.32500

Figure 5 ***Monthly wind roses from CFSv2 dataset at Groote Eylandt over the period of 2021-2023*** [2]

[2] Note: Convention for wind directions is the direction the wind is 'from'

Hourly filtered wind measurements from BoM station 14518 at Groote Eylandt Airport are highly variable compared to the hourly modelled CFSv2 data (Figure 6) indicating significant wind gusts and potential measurement noise in the BoM dataset. However, daily filtered BoM measurements compare well with CFSv2 data (Figure 7) at Groote Eylandt. This provides confidence that the CFSv2 inputs are a reasonable representation of the underlying trend in wind speeds and directions and, while short-period gusts are not captured, the data represents winds for the purposes of a long-term mixing zone assessment with reasonable accuracy.

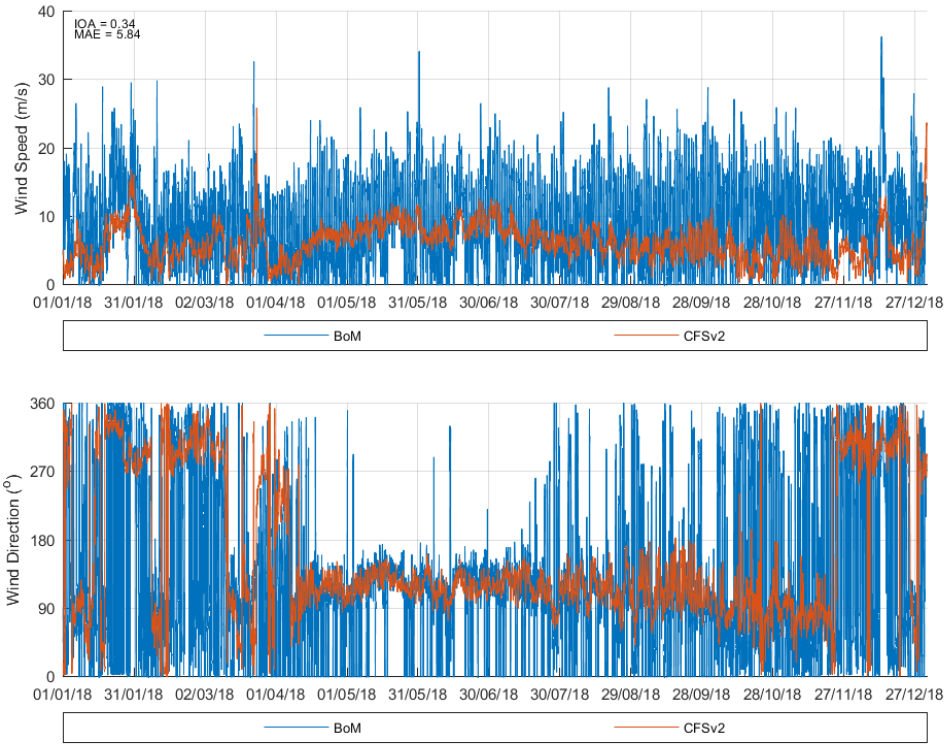


Figure 6 ***Comparison of hourly CFSv2 simulated data and hourly filtered BoM measurements at Groote Eylandt during 2018.***

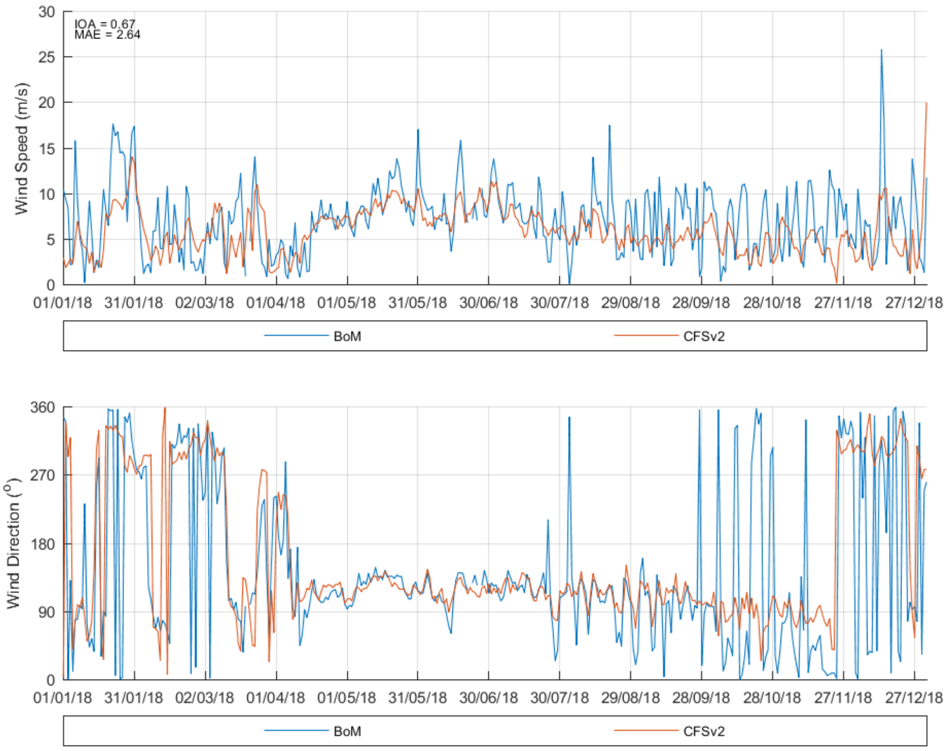


Figure 7 ***Comparison of daily filtered CFSv2 simulated data and daily filtered BoM measurements at Groote Eylandt during 2018.***

3. Methodology

3.1 Overview of modelling approach

Modelling for this study was undertaken in two phases, namely:

- **Near-field modelling** (Section 3.2). The primary purpose of this modelling was to determine an appropriate diffuser concept design that would yield elevated levels of dilution in close proximity to the outlet over a range of discharge flowrates (allowing for potential future increase in mine production beyond 80 GL/a).
- **Far-field modelling** (Sections 3.6-3.6.9). The adopted outlet concept design from the near-field modelling assessment was incorporated into the 3D far-field model. The 3D far-field model was the primary tool to predict dilution of the excess mine water discharge in the marine environment for the nominated flowrate, tidal and wind conditions.

3.2 Near-field modelling

3.2.1 Near-field concept

The near-field region refers to the immediate area around the outlet/diffuser where the discharged water undergoes momentum-driven or buoyancy-driven transport and enhanced mixing along its trajectory through the water column (i.e. prior to surfacing, impinging on the seafloor, or achieving neutral buoyancy). The highest rates of mixing and dilution typically occur through these near-field mixing processes relative to natural background levels of mixing via dispersion by ambient currents (i.e. far-field dilution).

In the case of a discharge of excess mine water of lower density (due to lower salinity) than the seawater (due to higher salinity), the buoyant plume will rise toward the sea surface and the near-field region terminates at the point where the plume surfaces, ceases to rise in the water column due to interaction with a density layer (stratification), or loses its upward buoyancy because it has undergone sufficient dilution to have the same density as the ambient the waters.

3.2.2 Modelling approach

Near-field modelling was carried out with the industry standard Updated Merge 3 (UM3) model of the Visual Plumes software suite by the United States Environmental Protection Agency (US EPA) (Frick et al. 2001). In this setting, the near-field simulation of the excess mine water discharge with UM3 terminates when the buoyant plume intersects the sea surface. At this point, the near-field jet and/or plume mixing processes are no longer simulated with UM3.

Several concept designs of the outlet were evaluated with UM3 to determine a submerged outlet configuration with adequate rates of near-field dilution. The outlet concept design was determined through an iterative approach that is detailed in Section 3.3. The following three discharge rates were considered in the near-field analysis to determine the outlet concept design:

- **Scenario 1**: 60 GL/a.
- **Scenario 2**: 112.5 GL/a.
- **Scenario 3**: 150 GL/a.

Scenario 1 corresponds to the far-field scenario (80 GL/a), which adopted a higher discharge rate in the 3D hydrodynamic modelling. The discharge rate for Scenario 1 is based GEMCO's estimate of likely average daily flows of 60 GL/a and a peak discharge of 80 GL/a. For the purposes of near-field modelling to evaluate an adequate outlet concept design, the 60 GL/a flow rate was used as a lower bound to assess the diffuser performance for this typical condition. The far-field modelling of Scenario 3 adopts the 80 GL/a peak flow as a conservative measure to predict the spatial extent of the environmental mixing zone.

Scenarios 2 and 3 are conservatively higher estimates provided by GEMCO to inform the diffuser design, to ensure it performs adequately in the event that future mining operations require an increase in discharge above the 80 GL/a estimate, for which approval is currently being sought.

Ambient current speeds for the near-field modelling inputs were defined as 0.13 m/s, which is moderately low for the site (30^{th} percentile of all measured current speeds, Figure 3).

3.3 Outfall concept design

Concept design elements of the outfall on the basis of UM3 near-field modelling are tabulated in Table 2. One preliminary concept design of a multi-port diffuser has been developed to achieve adequate environmental performance in terms of near-field dilution across the three defined flow scenarios. Further commentary on the design elements is provided in Table 2.

Table 2 Conceptual outfall details

Parameter	Scenario 1	Scenario 2	Scenario 3	Comment
Flow rate (GL/a)	60	112.5	150	Scenarios for assessment defined by GEMCO
Flow rate (m^3/s)	1.90	3.57	4.76	
Number of ports	30			Port sizing and spacing designed to minimise merging of plumes from neighbouring ports. Number of ports and diffuser length selected to fit within available spatial constraints (i.e. multi-port diffuser not extending past 10 m contour). Outlet diameters selected to give exit velocities that promote momentum (velocity) induced near-field mixing in the immediate vicinity of the outlet.
Diffuser length (m)	145			
Port spacing (m)	5			
Port Diameter (m)	0.15			
Multi-Port Diffuser Depth Range (m)	7.5-9.5 (8.5 average)			Diffuser located on seafloor between 8-10 m depth contour, with 0.5 m port elevation above seabed
Diffuser height above seabed (m)	0.5			
Port Discharge Vertical Angle	10°			Slightly upward discharge angle to avoid interaction of the plume with seabed, but yet maintain sufficient water depth above the plume when it transitions from momentum (velocity) induced mixing to buoyancy (rising plume to surface) driven mixing.
Port Discharge Horizontal Angles	315°/135° alternating			Alternating north-west/south-east discharge angles that are aligned with the prevailing site current directions to minimise plumes emanating from different ports interacting and merging (plume merging reduces near-field mixing efficiency).
Port Exit Velocity (m/s)	3.6	6.7	9.0	Elevated exit velocities achieved through selection of port diameters to maximise turbulent dilution near diffuser for near-field dilution

3.4 Water quality objectives

The Water Quality Objectives (WQOs) to be achieved at the edge of the mixing zone for key parameters of concern in the excess mine water discharge have been developed in consideration of the following data:

– Ambient water quality data:
  - Available water quality data of the marine receiving environment from GEMCO's marine monitoring program as reported by Indo-Pacific Environmental (IPE, 2023a). The 50^{th} percentile (median) of IPE (2023a) data has been adopted as the ambient marine water quality concentration for each analyte.
  - Additional monthly marine water quality data for nutrients and salinity at a marine reference site ~800 m south of the port facility was available from GEMCO's wastewater discharge monitoring program. These

nutrient and salinity data span from March 2015 to July 2023 and September 2022 to July 2023, respectively.

  - It is noted that the median nitrate and phosphate measurements from the GEMCO wastewater discharge monitoring data at the reference site were below the Limit of Reporting (LOR), as were the majority of all measurements. In these cases, half of the LOR was assumed to represent the ambient concentration.

- Discharge water quality data:
  - Discharge water quality was largely defined by IPE (2023b) to be the 95th percentile of the volume-weighted mixed analyte concentrations on the basis of long-term monthly monitoring by GEMCO at a range of mine pits. This is considered a high (conservative) estimate of the discharge water quality, particularly in the context of the 3D far-field modelling approach that evaluated a continuous discharge at these 95th percentile concentrations for a whole year. Clearly, excess mine water discharge concentrations are likely to be lower than the 95th percentile concentration for the vast majority of the time.
  - For salinity, the discharge water quality was estimated to be 0 PSU (Practical Salinity Units) based on the very low electrical conductivity (EC) measurements.
  - For pH, the volume-weighted approach employed by IPE (2023b) is not suitable due to complex chemical interactions of various factors that occur when mixing solutions of differing pH. An alternative approach for developing pH WQOs was applied as detailed in Section 3.5.
- Marine trigger values (or WQOs) were:
  - Primarily defined by IPE (2023a) as either:
    - The 80th percentile of marine water quality data;
    - Trigger values suggested in the published literature; or
    - Default Guideline Values (DGVs) reported in ANZG (2018) or ANZECC & ARMCANZ (2000).
  - For ammoniacal nitrogen, the 80th percentile of measured data from GEMCO's wastewater discharge monitoring program (reference site) was adopted in lieu of the trigger value reported in IPE (2023a), which did not have this dataset available at the time of reporting.
  - For salinity, the trigger value was selected on the basis of a maximum allowable salinity reduction of 1 PSU below ambient conditions. This was derived as the difference between median and 20th percentile salinity from the CSIRO Atlas of Regional Seas (CARS, 2009), which is a modelling dataset adopted by ANZG (2018) in the derivation of some guideline values for mesoscale marine bioregions. The data from the CARS (2009) node nearest to the Project site was extracted to calculate the salinity reduction.

The WQOs are expressed as a required dilution factor of the discharge by the ambient marine waters to meet the relevant water quality trigger values. The dilution of the discharged excess mine water by the ambient marine waters is simulated in the 3D far-field modelling assessment to predict the spatial extent of the mixing zone during operation. The dilution factors to define the edge of the mixing zone are calculated as:

$$D_T = \frac{C_O - C_A}{C_T - C_A}$$

where:

- D_T = Target dilution factor.
- C_O = Outlet concentration.
- C_T = Target concentration to achieve the WQO.
- C_A = Ambient concentration.

The calculated dilution targets are summarised in Table 3. The most stringent dilution target is **42-fold** for nitrate, Therefore, achieving a 42-fold dilution of the mine water plume will ensure adequate dilution of all other parameters to meet the respective WQOs. It is noted however the trigger value for nitrate is not based on marine toxicity, but rather as a nutrient that acts to stimulate ecosystem productivity (e.g. higher algal biomass). Elevated nitrate within the mixing zone is therefore not likely to have direct impacts to marine biota, by may lead to indirect impacts such as higher phytoplankton concentrations. However, this is only likely if the receiving marine environment is poorly flushed and algae remain in the mixing zone with elevated nutrient concentrations for extended periods of time.

The next most stringent dilution target is that of salinity at **35-fold**. Salinity is a more traditional analyte for defining a mixing zone, as it may lead to direct ecological effects when marine biota, particularly benthic primary producers, are exposed to reduced salinity concentrations beyond the natural range of the environment that they are adapted to survive in.

The mixing zone for 42-fold dilution is therefore described in this study as the zone of **potential indirect effects**, whereas the mixing zone for 35-fold dilution is described as the zone of **potential direct effects**.

Table 3 Summary of water quality data and dilution calculations with bold dilution targets indicating those that are assessed in further detail with the far-field modelling.

Analyte	Units	C_A [3]	C_O [4]	C_T [5]	D_T
Aluminium	µg/L	2.5	325.35	24	14.0
Antimony	µg/L	0.25	0.52	270	No dilution required [6]
Arsenic	µg/L	1.5	0.68	12	No dilution required [6]
Cadmium	µg/L	0.1	0.06	0.7	No dilution required [6]
Chromium (Cr VI)	µg/L	0.25	0.59	4.4	No dilution required [6]
Cobalt	µg/L	0.1	0.92	1.0	No dilution required [6]
Copper	µg/L	0.5	1.81	1.3	No dilution required [6]
Iron	µg/L	2.5	44.28	5.4	13.4
Lead	µg/L	No data	0.5	4.4	No dilution required [6]
Manganese	µg/L	1.8	292.08	300	No dilution required [6]
Mercury	µg/L	No data	0.05	0.1	No dilution required [6]
Nickel	µg/L	0.25	2.02	6	No dilution required [6]
Silver	µg/L	0.05	0.5	1.4	No dilution required [6]
Thallium	µg/L	No data	0.5	17	No dilution required [6]
Tin	µg/L	2.5	0.73	10	No dilution required [6]
Vanadium	µg/L	No data	5	100	No dilution required [6]
Zinc	µg/L	2.5	20.16	8	2.2
Rare-earth elements	µg/L	0 [7]	4.25	0.5	7.5
>C10 – C40 Fraction (sum)	µg/L	0 [7]	52.37	50	No dilution required [6]
Ammoniacal Nitrogen	µg/L	50 [8]	457.54	142 [9]	3.4
Nitrate Nitrogen	µg/L	5 [10]	308.25	12.15	**41.4**
Total Nitrogen	µg/L	500 [8]	317.18	1,000 [9]	No dilution required [6]
Phosphate	µg/L	5 [10]	2.87	9.31	No dilution required [6]
Total Phosphorus	µg/L	60 [8]	5.34	100 [9]	No dilution required [6]
Salinity	PSU	35.62 [8]	0	34.62 [11]	**34.6**
Turbidity	NTU	3.55	119.93	20	6.1

[3] Ambient concentration C_A is defined by IPE (2023a) unless otherwise specified by subsequent footnotes.
[4] Outlet concentration C_O is defined by IPE (2023b) unless otherwise specified by subsequent footnotes.
[5] Trigger value C_T is defined by IPE (2023a) unless otherwise specified by subsequent footnotes.
[6] No dilution require when outlet concentration C_O is already below the trigger value C_T
[7] Assumed zero concentration of rare earth elements and hydrocarbons in ambient environment.
[8] Calculated as 50th percentile of GEMCO wastewater discharge monitoring reference site data.
[9] Calculated as 80th percentile of GEMCO wastewater discharge monitoring reference site data.
[10] All ambient measurements from GEMCO wastewater discharge monitoring reference site data were below LOR (10 µg/L). Adopted half LOR for C_A.
[11] Using salinity reduction of 1 PSU from ambient on basis of difference between median and 20th percentile salinity from CARS (2009)

3.5 WQO for pH

Development of WQOs for pH required additional data (namely alkalinity) to predict the pH of mine dewater when mixed from various stand-alone storages within the mine site.

GEMCO supplied additional pH and alkalinity data to GHD and Indo-Pacific Environmental (IPE). IPE (2023) produced a memorandum summarising the statistical spread of pH readings collected in the marine environment throughout multiple GEMCO monitoring campaigns, as well as a statistical summary of mine dewater pH.

GHD has utilised the updated pH data (IPE, 2023c), along with recent alkalinity measurements to determine the number of dilutions of discharged mine dewater required to achieve the adopted pH water quality trigger.

3.5.1 Summary of pH and alkalinity data

IPE (2023c) provides a summary of the pH data collected by GEMCO, including 111 *in situ* readings taken across 20 mine quarries and 283 *in situ* readings compiled from GEMCO's marine monitoring programs for the port and wastewater discharge.

The following values were adopted for the pH mixing zone assessment:

- The median pH of the marine monitoring data (**pH 8.05**) was adopted for the ambient marine environment.
- The discharge pH was calculated by IPE (2023c) as the volume-weighted 5th percentile pH values from the mine quarry measurements. The approach used projected dewatering flow rates from each quarry provided by GEMCO for financial years 2025-2031 to determine volume-weighted (or flow-weighted) pH values for the mixed discharge from all mine quarries. A 5th percentile pH was produced for each year of 2025-2031. The average of the 5th percentile volume-weighted pH data for each year (**pH 5.37**) was adopted as a conservative value to represent mine dewater discharge for this assessment. The average was calculated by first converting the pH values for each year to hydrogen ion concentrations, taking the average, then converting back to pH. This approach is necessary to account for the logarithmic pH scale.
- The marine water quality trigger for pH was defined as the 20th percentile of marine water quality data (**pH 8.00**), as aligned with the approach adopted for salinity and recommended in ANZG (2018). The relatively low pH of the mine dewater discharge (pH 5.37) must be increased through dilution and buffering processes with ambient seawater (pH 8.05) to at least pH 8.00 in order to satisfy this water quality objective.

Alkalinity data provided by GEMCO to GHD included the following:

- Monthly marine monitoring data from the wastewater discharge monitoring program (reference site in the receiving environment) totalling 24 measurements spanning January 2022 to November 2023.
- Measurements taken during October 2023 from the marine monitoring program across 41 locations.
- 89 measurements from 24 mine quarries spanning July to November 2023.

Representative alkalinity values were defined as follows:

- Mine dewater discharge was defined as the average alkalinity from quarry measurements (**3 mg/L** as $CaCO_3$).
- The alkalinity of the receiving marine environment was defined as **119 mg/L** (as $CaCO_3$) on the basis of the average from the wastewater discharge monitoring program data, which spanned almost two complete years. The data from the marine monitoring program for the port, which contained a large number of measurements spanning a short period in October 2023, was excluded so as not to introduce a seasonal bias to the data.

3.5.2 pH modelling

Adopting the pH and alkalinity conditions described in Section 3.5.1, water quality modelling was undertaken using the PHREEQC software, version 3.7.3 (Parkhurst and Appelo, 2013). PHREEQC is an industry standard software for simulating chemical reactions and transport processes in natural or polluted water, in laboratory experiments, or in industrial processes. Importantly, PHREEQC includes algorithms for calculating the water quality resulting from the mixing of two pre-defined solutions, with sufficient complexity in the model to account for pH transformations, including pH buffering, when mixing two solutions.

The key inputs to PHREEQC are summarised in Table 4. Other properties defined for ambient marine water adopted the default values for seawater outlined in the PHREEQC user manual. Where inputs are not specifically defined, PHREEQC calculates an extensive set of ionic compositions of each solution.

Table 4 Summary of key inputs to PHREEQC

Parameter	Mine dewater discharge	Ambient marine water	Basis
pH	5.37	8.05	Section 3.5.1
Alkalinity (mg/L as $CaCO_3$)	3	119	Section 3.5.1
Temperature (°C)	28	28	Typical air temperature (for mine dewater) and average ocean temperature at Groote Eylandt from CARS (2009)
Density (kg/m^3)	1,000	1,023	Calculated on basis of salinity and temperature

PHREEQC was used to assess various mixing ratios of mine dewater and ambient seawater to determine the minimum dilution required to achieve the pH water quality objective (pH ≥ 8.00). For the adopted input conditions, a minimum **dilution ratio of 28** results in a mixed pH of 8.001, marginally higher than the pH water quality objective. This dilution target is below the calculated targets for nitrate (dilution target of 42 for potential indirect effects) and salinity (dilution target of 35 for potential direct effects), thereby indicating that any potential environmental effects related to pH will be abated (via dilution) closer to the point of discharge compared to those related to nitrate and salinity.

3.6 Far-field model development

3.6.1 Far-field concept

The far-field describes the region beyond the near-field whereby plume transport is driven by ambient currents (generated by tides and winds) and vertical circulation (generated by waves). As a conservative approach, only tidal and wind-induced currents are included within the modelling framework, while the influence of waves is excluded (as described in Section 2.3).

3.6.2 Model platform

Far-field modelling was undertaken with the three-dimensional (3D) MIKE3 FM (flexible mesh) hydrodynamic model to simulate wind and tide-induced currents. MIKE 3 FM was developed by the Danish Hydraulic Institute (DHI) and is an industry standard for 3D hydrodynamic (HD) modelling. The model domain in MIKE 3 FM is defined horizontally by an irregular network of triangles (the model 'cells') that are split into vertical layers by a sigma coordinate (fixed number of vertical layers throughout the model domain that vary in thickness according to the depth) or a combined sigma and z-level (allows inclusion of layers with fixed widths) configuration. For each model cell, MIKE 3 FM simulates a range of hydrodynamic properties including, but not limited to, current speed, current direction, water level and salinity. MIKE 3 FM is driven by user-defined environmental inputs (e.g. variations in water levels and currents at the open boundaries, winds acting on the sea surface, heat exchange across the model domain and point sources including outfalls/diffusers).

3.6.3 Model domain

The model mesh and bathymetry are presented in Figure 8 (entire domain), Figure 9 (high resolution area surrounding the Project site) and Figure 10 (Milner Bay Wharf and post-dredge survey data locality).

The resolution of the hydrodynamic model mesh ranges from ~15 km at the offshore model boundaries to ~30 m in the proposed area of the diffuser. The bathymetry was developed with the following data:

- Neptune 0.25 m resolution survey of the Milner Bay Wharf area.
- September 2022 0.25 m resolution post-dredge bathymetry survey of the GEMCO Tug Berth.
- DHI's MIKE C-Map nautical chart information in all areas where no other data was available.

The vertical domain in the 3D model was configured as follows:

- Sigma coordinate system of the 4 layers in the upper section of the water column extending to a depth of 12 m below MSL. These layers expand and contract in response to tidal and non-tidal water level variations.
- At depths greater than the sigma domain (i.e. depths greater than 12 m below MSL), a fixed coordinate (z-level) system of 7 lower layers is used. Layer thicknesses in the z-level domain, from top to bottom, are 3 m, 5 m, 5 m, 5 m, 10 m, 10 m and 20 m thick.

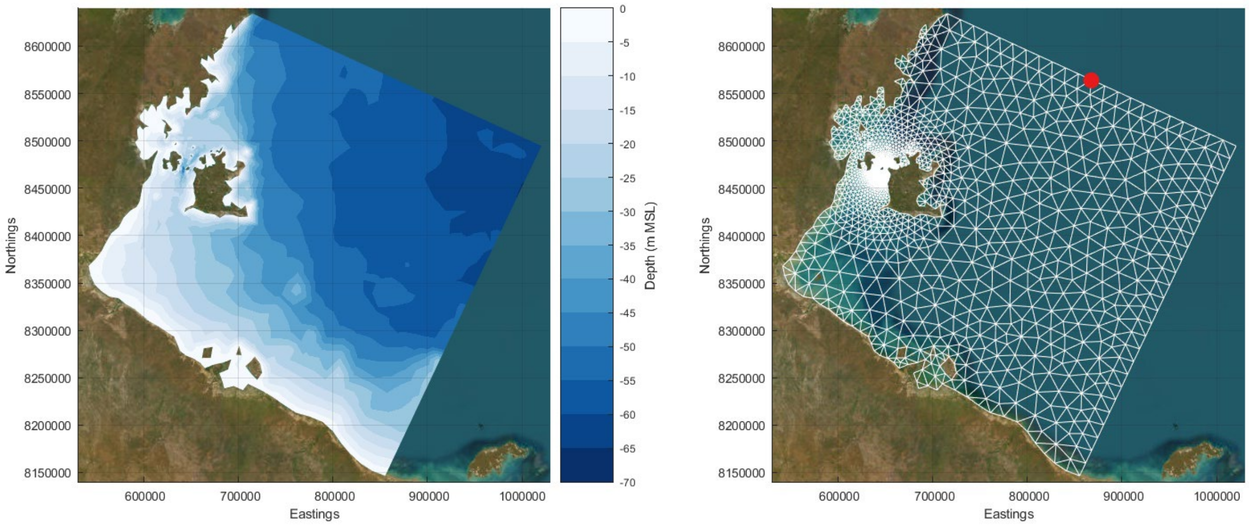


Figure 8 ***Model bathymetry (left) and mesh (right) of the entire model domain with red dot demarking location of open ocean boundary inputs presented in Section 3.6.4.***

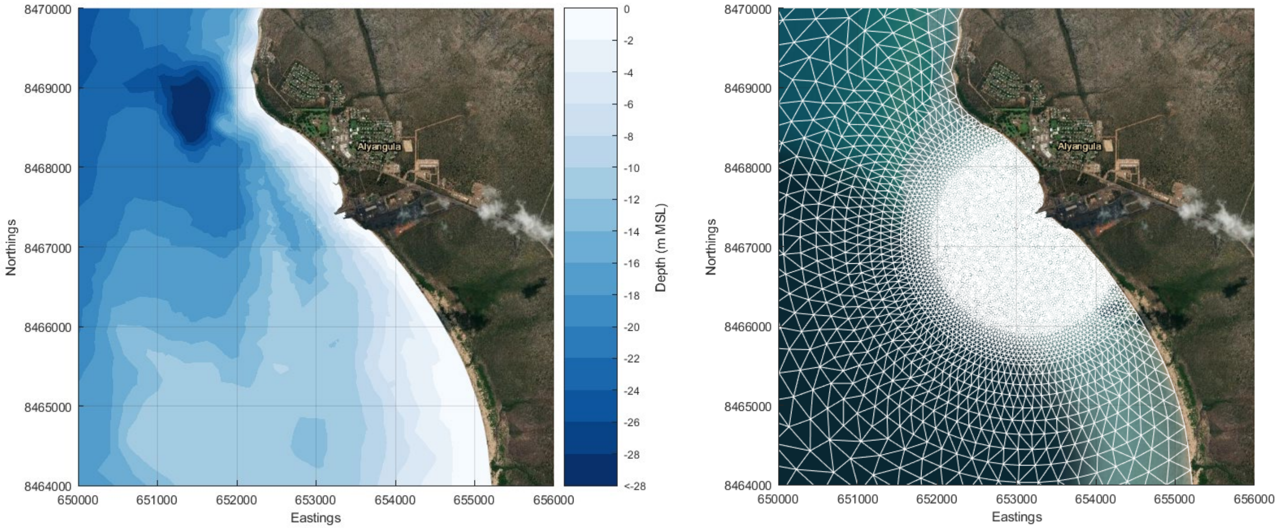


Figure 9 ***Model bathymetry (left) and mesh (right) in the diffuser locality.***

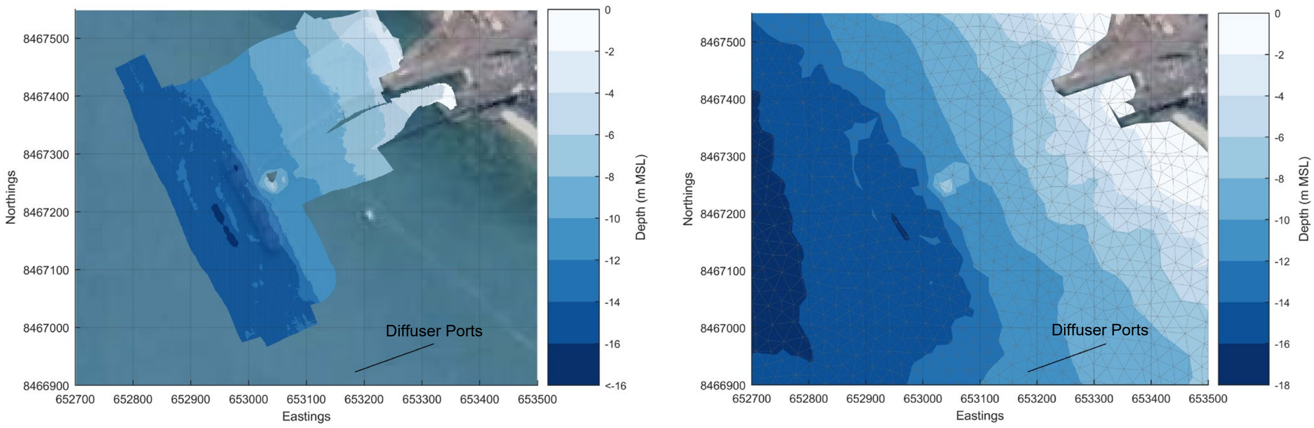


Figure 10 ***Survey data (left) and model mesh/bathymetry (right) at the Milner Bay Wharf locality.***

3.6.4 Open ocean boundary inputs

Model inputs of spatially varying water levels were from a combination of astronomical tides from the global tide model TPXO9 (Egbert and Erofeeva, 2002) and non-astronomical water levels from the Hybrid Coordinate Ocean Model (HYCOM) at 1/12° horizontal resolution and 3-hourly temporal resolution (Chassignet *et al*., 2007). Further, horizontally, vertically and temporally varying currents applied at the model open boundaries were from the combined oceanographic HYCOM and tidal TPXO9 currents.

Examples of the model's offshore inputs at the middle of the northern open boundary (point shown in Figure 8) are illustrated for water levels in Figure 11, v-currents (north-south) and u-currents (east-west currents) in Figure 12 and temperatures and salinities in Figure 13.

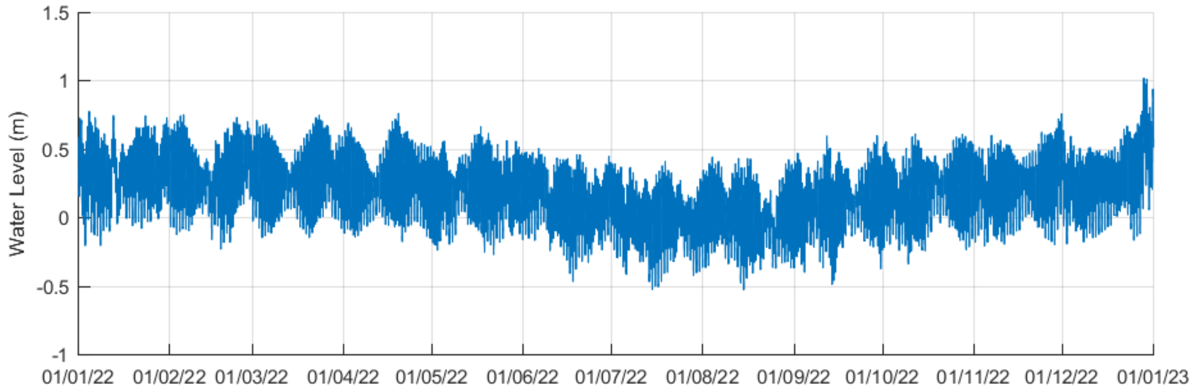


Figure 11 Water levels at a middle location along the northern open ocean boundary from 1 January 2022 through 1 January 2023

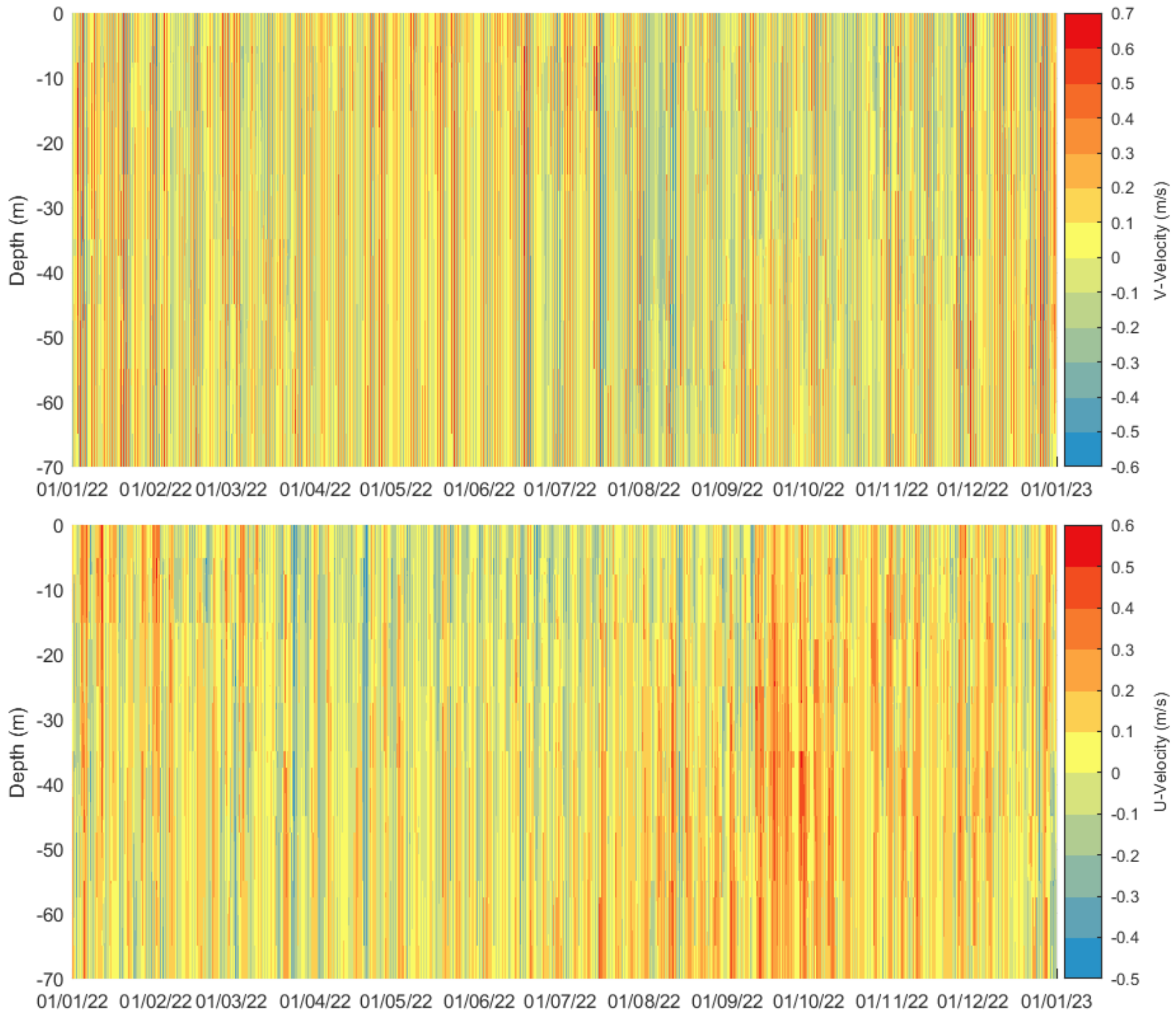


Figure 12 V- (upper) and U- (lower) currents at a middle location along the northern open ocean boundary from 1 January 2022 through 1 January 2023

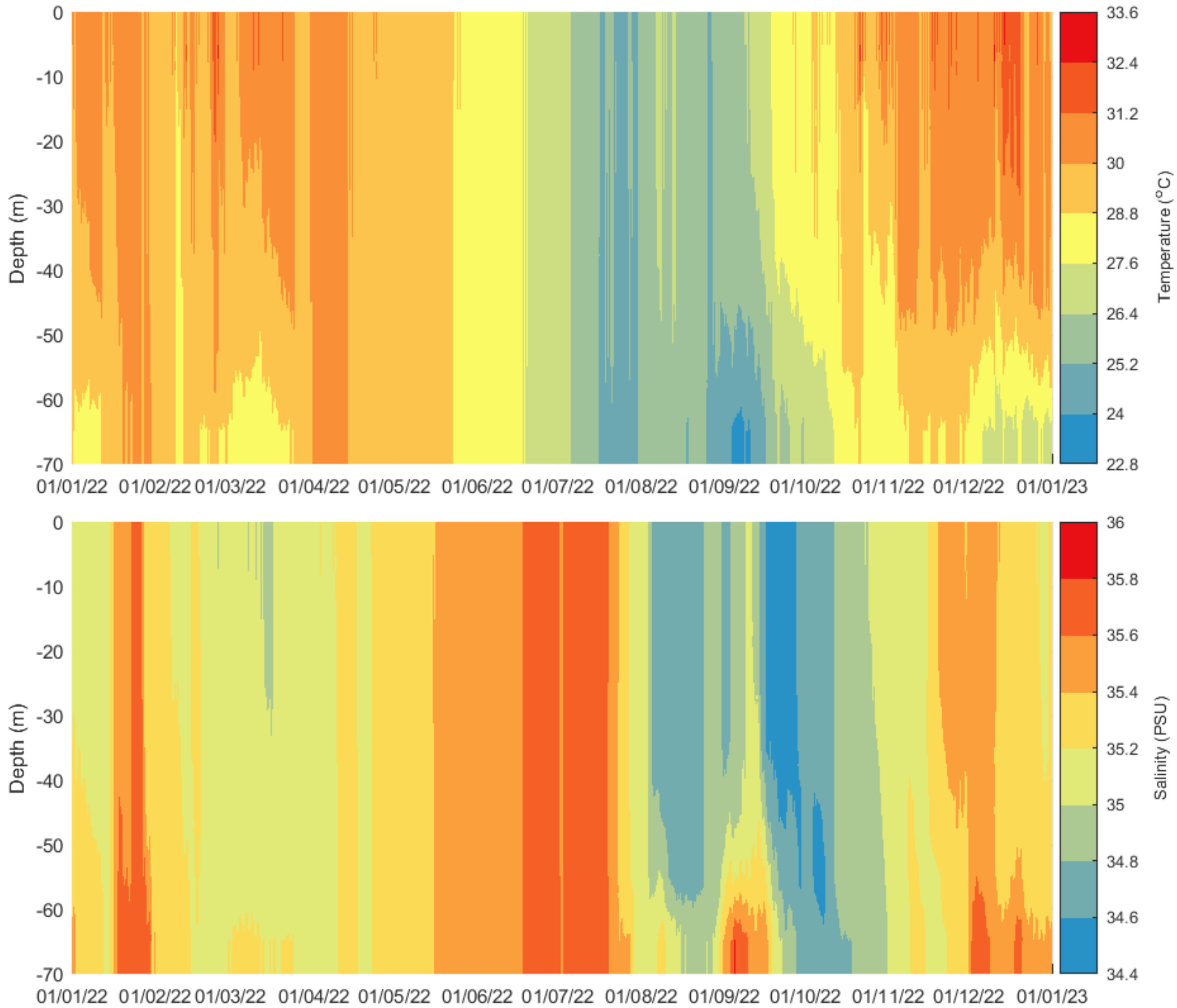


Figure 13 ***Temperatures (upper) and salinities (lower) at a middle location along the northern open ocean boundary from 1 January 2022 through 1 January 2023***

3.6.5 Wind forcing

Spatially varying CFSv2 wind forcing was applied to the sea surface of the model. Wind speeds and directions from the CFSv2 dataset at Groote Eylandt are illustrated in Figure 14 for the year of 2022 (representative year selected for this study).

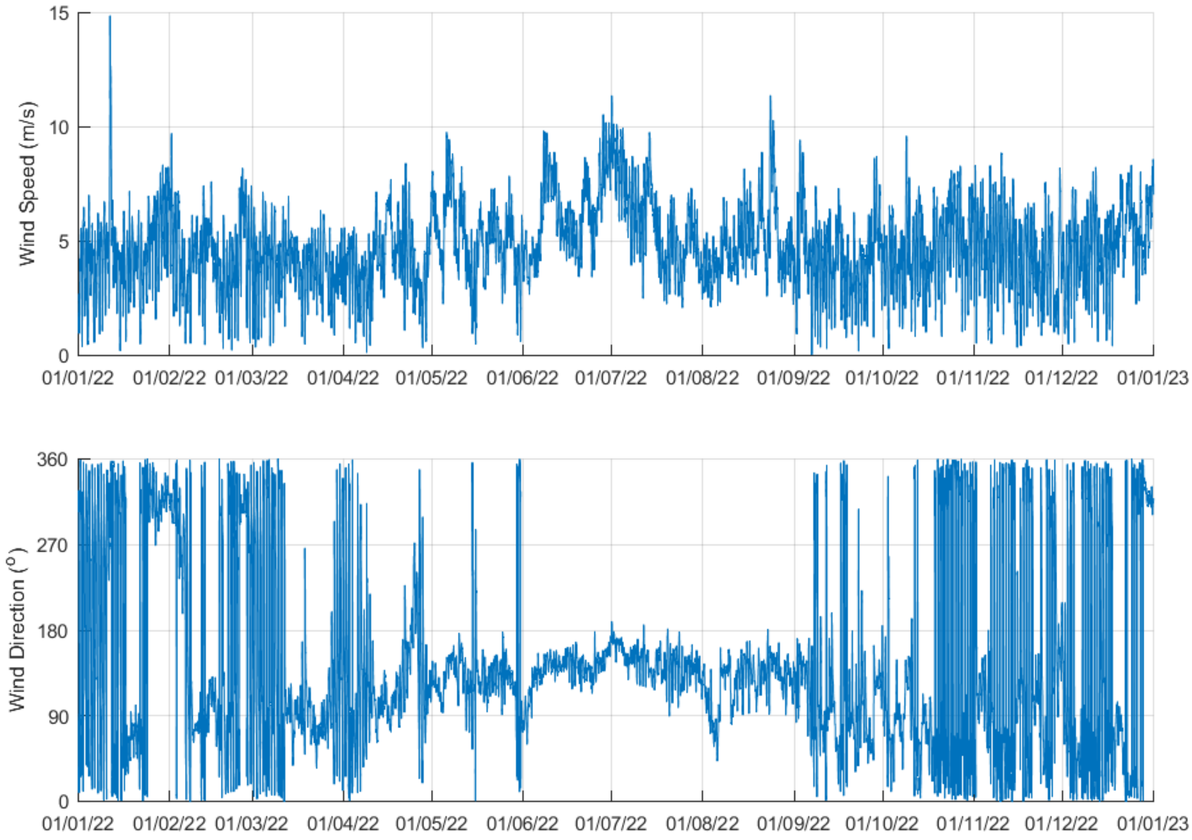


Figure 14 ***CFSv2 simulated wind data at Groote Eylandt from 1 January 2022 to 1 January 2023 (upper- wind speed, lower- wind direction).***

3.6.6 Heat exchange processes

Heat exchange was included in the model configuration to account for the transfer of heat between the water surface and atmosphere via evaporation, convection and solar radiation (longwave and shortwave). The inputs for the heat exchange module were derived from CFSv2 and included the shortwave radiation flux, air temperature, relative humidity and clearness coefficient (a measure of the proportion of cloud cover).

3.6.7 Discharge

The concept design of the multi-port diffuser from the near-field modelling assessment was configured into the 3D far-field model. The discharge scenario of 80 GL/a was simulated spanning the entire year of 2022 as summarised in Table 2. As noted in Section 3.2.2, Scenario 1 for the far-field assessment has an increased discharge (80 GL/a) relative to the near-field assessment to conservatively account for likely shorter-term peak flow rates that may occur throughout the year.

Table 5 Diffuser configuration and flow rates incorporated into the 3D far-field model.

Parameter	Far-field Scenario 1
Flow rate (GL/a)	80
Flow rate (m^3/s)	2.54
Number of ports	30
Diffuser length (m)	145
Port spacing (m)	5
Outlet Diameter (m)	0.15
Outlet Depth (m)	7.5-9.5 (8.5 average)
Outlet height above seabed (m)	0.5
Discharge Vertical Angle	10°
Discharge Horizontal Angle	315°/135° alternating
Exit Velocity (m/s)	4.8

3.6.8 Far-field model verification

Verification of the model performance utilised the following quantitative indices to compare the simulation with the measurements:

– **Percentile probability distributions** of simulated and measured data. This is a graphical comparison of the statistical spread of the data for a parameter at a particular location (e.g. current speed range at the ADCP site) between the simulation and measurements. This comparison enables quantification of the percentage of time that the model is under- or over-predicting the measured data.

– **Mean Absolute Error (MAE).** A quantitative measure of the absolute differences between the simulation and measurements. Low values of MAE represent good model performance. This metric is easily interpreted and a more natural measure than the commonly used root-mean-squared error, as it is less influenced by extreme values (i.e. outliers or 'noise' in the measured data) (Willmott 1982).

  The **MAE** is calculated as:

$$\boldsymbol{MAE} = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n}$$

  where:

  - P_i = Predicted value at comparison time i
  - O_i = Observed value at comparison time i
  - n = Number of comparison measurements

– **Index of Agreement (IOA).** IOA is a quantitative measure of the average differences between predicted and observed values relative to the range of values in the observation data (Willmott 1982). It is bounded between the values of 0 and 1, with values close to 0 describing large relative differences (i.e. poor validation) and values close to 1 describing small relative differences (i.e. good validation). Willmott et al. (1985) suggests that IOA values meaningfully greater than 0.5 represent good model validation, with values approaching 1 representing excellent validation. The **IOA** is calculated as:

$$\boldsymbol{IOA} = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

  where, further to the definitions for MAE:

  - $\bar{O}$ = Mean of the observations during the comparison period.

The quantitative model skill measures of MAE and IOA are not applicable to directional parameters (e.g. current direction) as these equations are not designed for data defined on a circular scale.

3.6.9 Modelling scenarios

3.6.9.1 Far-field modelling scenarios

A total of two simulations were evaluated in this modelling assessment as summarised in Table 6, which include a baseline simulation for model verification and the operational discharge scenario of 80 GL/a.

Each simulation period included a one-week simulation spin-up time to allow the models with static starting conditions to reach a representative dynamic state.

Table 6 Simulation scenarios

Scenario	Simulation Period
Baseline simulation (for model verification)	January 2022 to December 2022
Scenario 1: Estimate of likely short to medium-term discharge rates based on current operations (80 GL/a to account for peak flows)	January 2022 to December 2022

3.6.9.2 Flushing simulations

As an additional assessment to contextualise the mixing zone predictions, simulations were carried out to determine the flushing rate of the nearshore receiving waters. The flushing rate is evaluated through calculation of the e-folding flushing time. The e-folding flushing time is the duration for ~63% of a water body's volume to exchange with adjacent ambient waters until ~37% (1/e) of the original volume remains. Numerically, this is estimated by fitting an exponential curve of the form $C_t=e^{-kt}$ to a conservative tracer concentration (C_t) over time (t). The inverse of the fitted exponent (1/k) is the e-folding flushing time scale.

The e-folding time was determined for the 'control volume' of the near-shore waters encompassing the predicted mixing zones, which was defined as an area extending approximately to the 12 m depth contour, and ~5 km northward and southward from the Project site, as depicted in Figure 15. This control volume is 'seeded' with a numerical tracer at the start of the flushing assessment in order to track the exchange of waters between the control volume and surrounding marine environment.

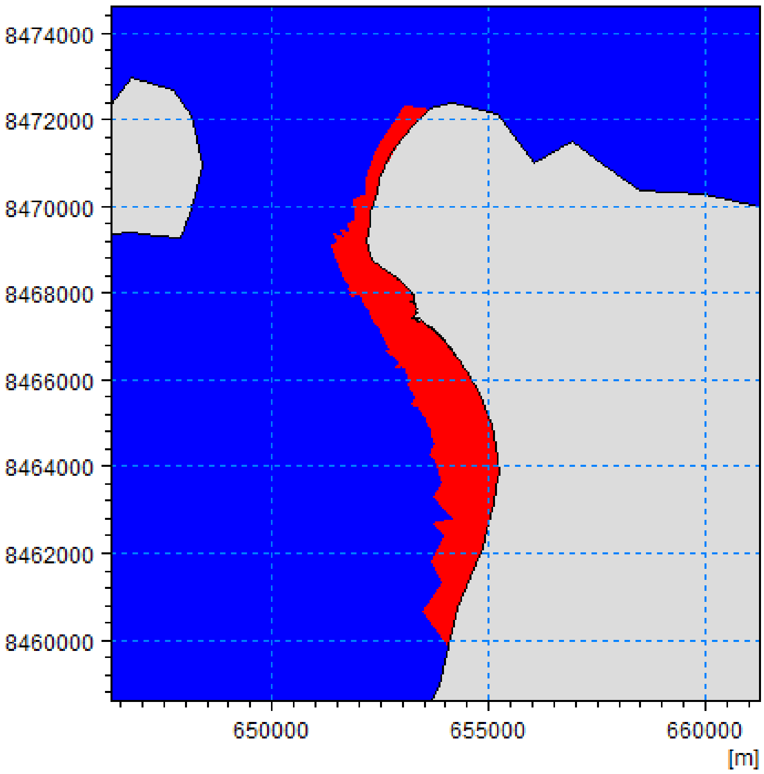


Figure 15 Control volume (red area) assessed for flushing simulations.

The e-folding time is presented in two ways, namely:

– A 'bulk' volumetric e-folding flushing time for ~63% of the volume to exchange with adjacent waters.
– Spatial e-folding flushing times are presented by calculated the individual e-folding time for each model cell, yielding contours of flushing times demonstrating the spatial variability in localised flushing rates within the control volume.

An example depicting the calculation of the bulk volumetric e-folding time is shown graphically in Figure 16 for a control volume that flushes in 1.44 days.

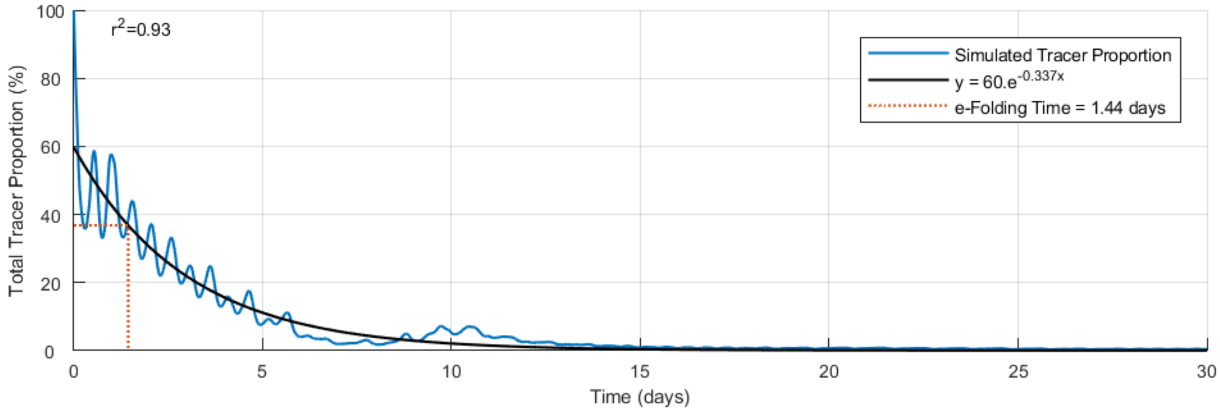


Figure 16 ***Example calculation of the bulk e-folding flushing time***

To contextualise the results of the flushing assessment, the e-folding time estimates are compared with the PIANC (2008) guidance for marinas, which states an e-folding time of four days (eight tidal cycles) to represent "good" flushing, with flushing between four and ten days classified as "fair" and "poor" for flushing times exceeding ten days. The purpose of the evaluation for marinas is to avoid water quality issues related to stagnation (e.g. eutrophication).

Since flushing can typically be approximated as an exponential reduction, whereby the majority of exchange from the control volume occurs rapidly, the e-folding flushing rate can be highly sensitive to the met-ocean conditions encountered at the start of the assessment. In order to incorporate a range of conditions in the flushing assessment, ten flushing simulations were run with start dates targeting a range of tidal states and wind conditions as summarised in Table 7. The met-ocean conditions during the start dates of the flushing scenarios are further depicted in Figure 17.

Table 7 ***Flushing modelling simulations***

Simulation Number	Description of starting conditions	Start Date/time	End Date/time
1	Spring flooding tide under low wind	1/01/2022 6:00	31/01/2022 6:00
2	Neap low slack tide under low wind	6/02/2022 2:00	8/03/2022 2:00
3	Spring low slack tide under moderate wind	15/03/2022 21:00	14/04/2022 21:00
4	Spring flooding tide under moderate wind	23/04/2022 0:00	23/05/2022 0:00
5	Neap low slack tide under moderate wind	25/05/2022 7:30	24/06/2022 7:30
6	Neap ebbing tide under high wind	5/07/2022 7:30	4/08/2022 7:30
7	Spring flooding tide under moderate wind	8/08/2022 16:00	7/09/2022 16:00
8	Neap low slack tide under low wind	12/09/2022 0:00	12/10/2022 0:00
9	Neap low slack tide under high wind	24/10/2022 9:00	23/11/2022 9:00
10	Spring low slack tide under low wind	27/11/2022 3:30	27/12/2022 3:30

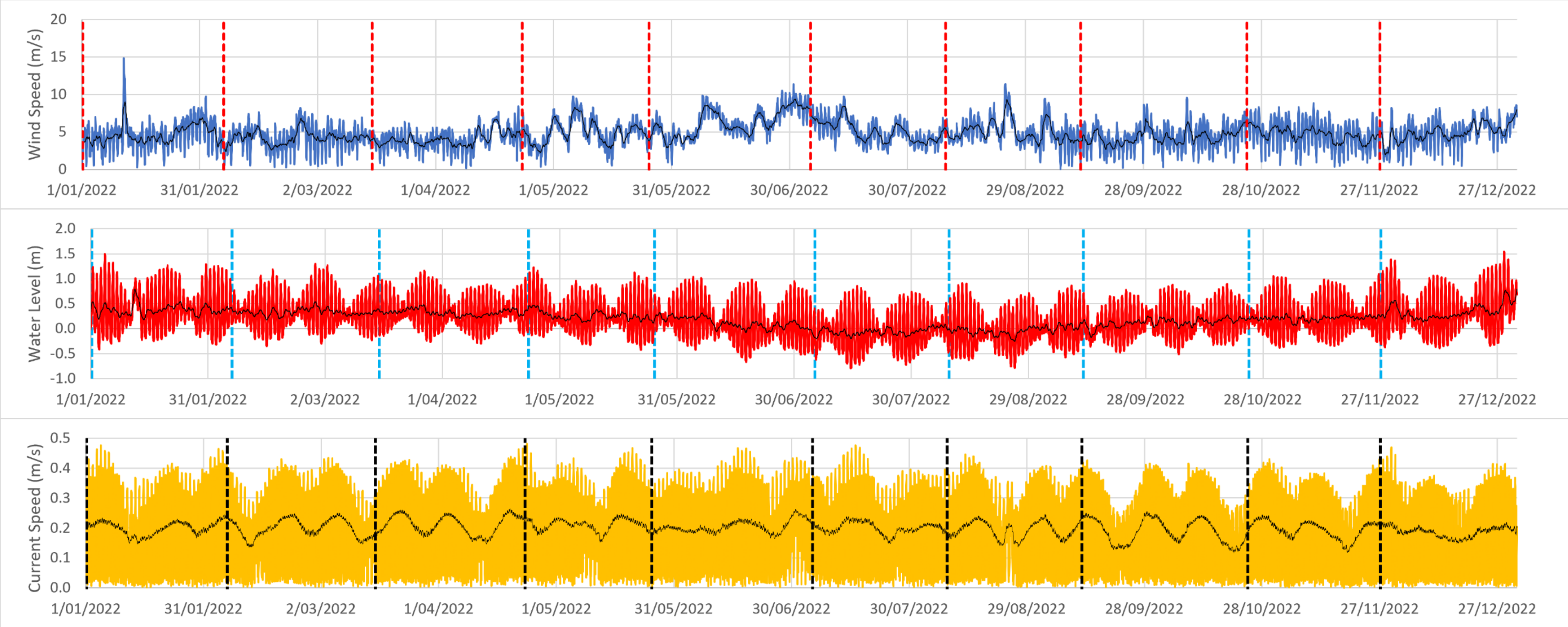


Figure 17 *Time series of wind speeds (top), water levels (middle) and current speeds (bottom) over the 1-year duration hydrodynamic simulation with the 24-hour running mean (black line) and vertical dashed lines representing the start date and time of the accompanying 10 flushing simulations.*

4. Results

4.1 Near-field modelling

The UM3 near-field modelling was undertaken for the scenarios outlined in Table 2 of Section 3.2 with ambient current speeds of 0.13 m/s. Predicted near-field plume trajectories and dilutions are displayed in Figure 18 and Figure 19, respectively.

The UM3 modelling indicates that the average plume dilutions (average dilution through a cross-section of the plume) are predicted to exceed the dilution targets of 42-fold (potential indirect effects) and 35-fold (potential direct effects). However, the plume centreline dilution (dilution in the centre of the plume) remains below these targets for all scenarios. This indicates that additional far-field mixing would be required to achieve the adopted dilution targets.

Furthermore, the UM3 assessment has the limitation of only assessing one steady-state condition (i.e. one ambient current speed) for each scenario. In this manner, the UM3 model is unable to account for the dynamic effects of long-term build-up of discharged mine waters within the receiving environment, which may reduce the dilution efficiency and further extend the mixing zone. Additional assessment of the mixing zone with the 3D far-field modelling was therefore required in order to provide higher confidence predictions of the mixing zone's spatial extent.

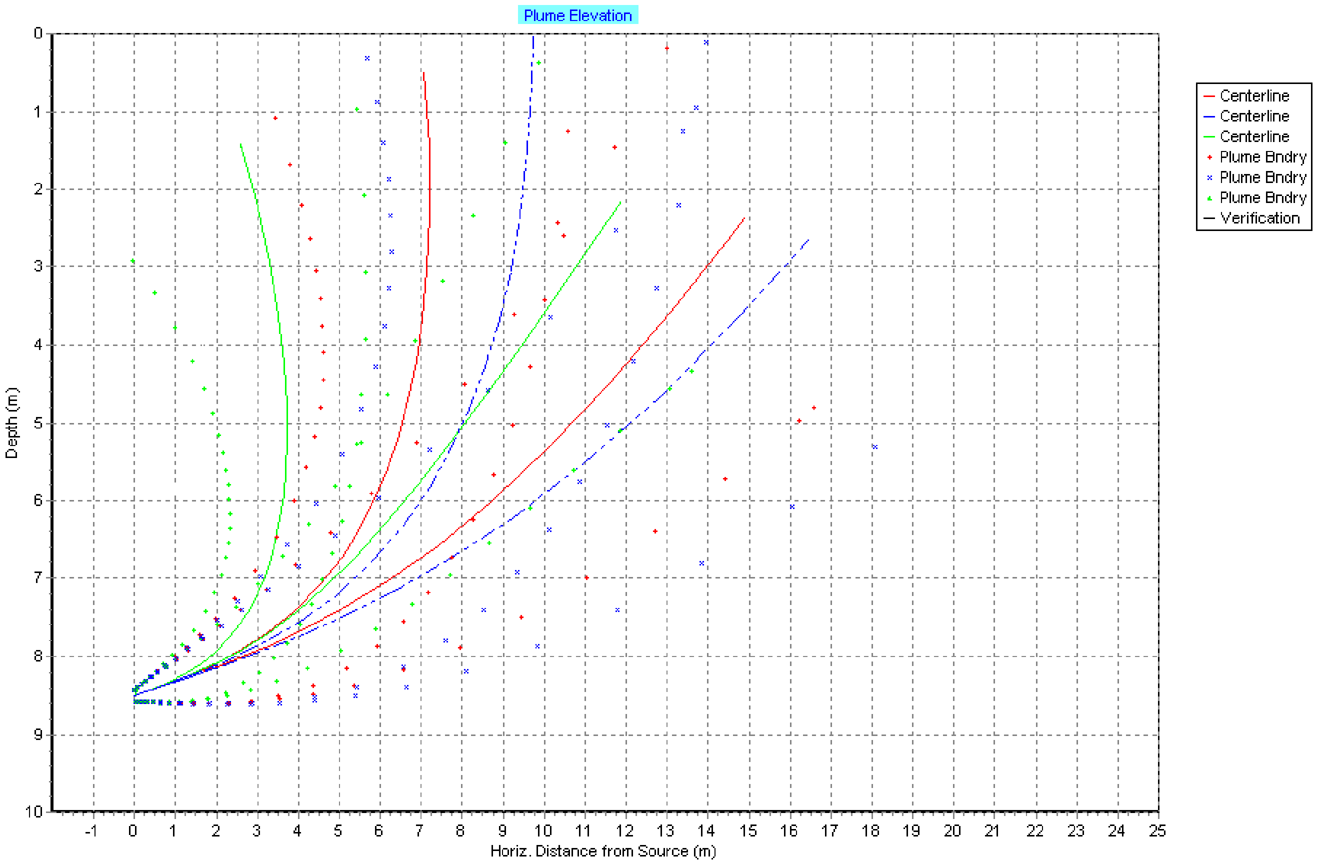


Figure 18 *UM3 prediction of near-field plume trajectory for near-field scenarios 1 (green), scenario 2 (red) and scenario 3 (blue). The two sets of lines for each scenario indicate the plumes from ports discharging with and into the currents.*

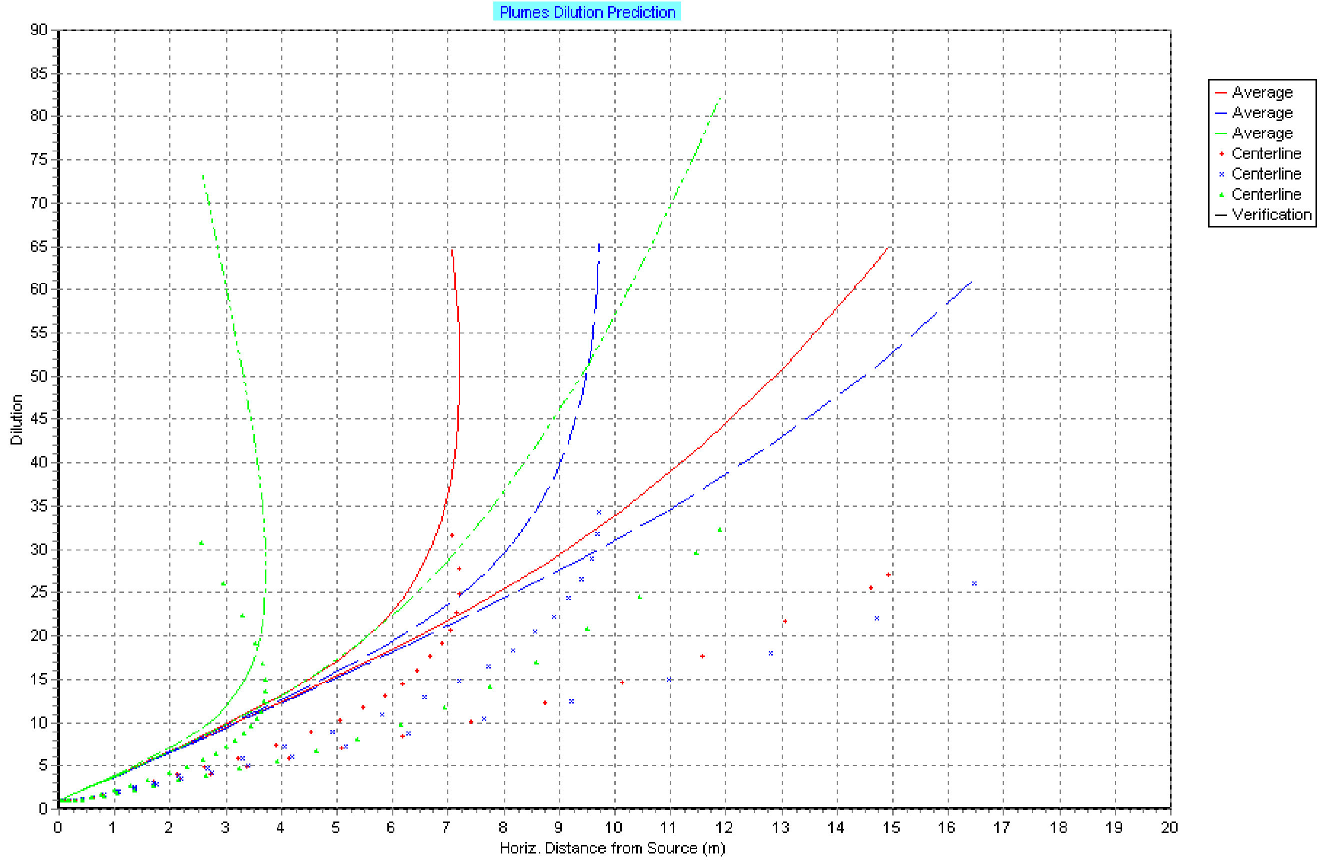


Figure 19 *UM3 prediction of near-field plume dilution for near-field scenarios 1 (green), scenario 2 (red) and scenario 3 (blue). The two sets of lines for each scenario indicate the plumes from ports discharging with and into the currents.*

4.2 Far-field model verification

The far-field model performance was verified via comparison of the model predictions to water levels downloaded from Bureau of Meteorology (BoM station 14406 – Groote Eylandt at 136.4158°E, 13.86°S) and current measurements supplied by GEMCO. The water level measurements span the entire year of 2022 at Groote Eylandt station, while the current speed measurements used for model verification ranged from 01 February 2022 to 01 June 2022 at the ADCP site (shown in Figure 1). It is noted that the ADCP data provided had only one current speed reported for each timestep. GEMCO was not able to ascertain the depth at which this measurement was recorded. Therefore, it was assumed to be a depth-averaged value, and the model results were depth-averaged accordingly for the comparison.

Quantitative measurements of model skill for water level and current speeds are presented in Table 8. The quantitative measurements include the index of agreement (IOA) and the mean absolute error (MAE) (Willmott, 1982). Willmott *et al.* (1985) suggests that IOA values meaningfully greater than 0.5 represent good model performance with values approaching 1 representing excellent performance.

Based on the quantitative indices, water levels are deemed to be extremely well represented by the model, achieving an excellent IOA score of 0.97, with an MAE of 0.11 m (Table 8). Simulated current speeds between February 2022 to June 2022 also achieved a very high IOA score of 0.91 (Table 8) with a low MAE of 6 cm/s when compared to the measured data. Additionally, the linear regression of measured versus simulated current speeds indicates a reasonable correlation (r^2=0.76), a slope similar to the 1:1 line and a marginal offset of -4 cm/s in simulated currents compared to the measurements. This indicates currents are typically underestimated by a small degree (4 cm/s compared to a range of 60 cm/s)

Qualitative comparisons of the simulated and measured water level (Figure 20), current speed (Figure 21) and current direction (Figure 22) also indicate a high degree of model skill in replicating the measured data. A comparison over a shorter time period (February 2022) is presented in Figure 23 to highlight additional detail.

Based on the outcomes of the verification assessment, the model is deemed fit-for-purpose for simulating the mixing zone of the far-field discharge scenario.

Table 8 ***Index of agreement and mean absolute errors of simulated water level and depth averaged current speeds for 2022.***

Location	Parameter	Period	IOA	MAE
BOM Groote Eylandt Station	Water Level	January 2022 to December 2022	0.97	0.11 m
Depth Average (ADCP site)	Current speed	February 2022 to May 2022	0.91	0.06 m/s

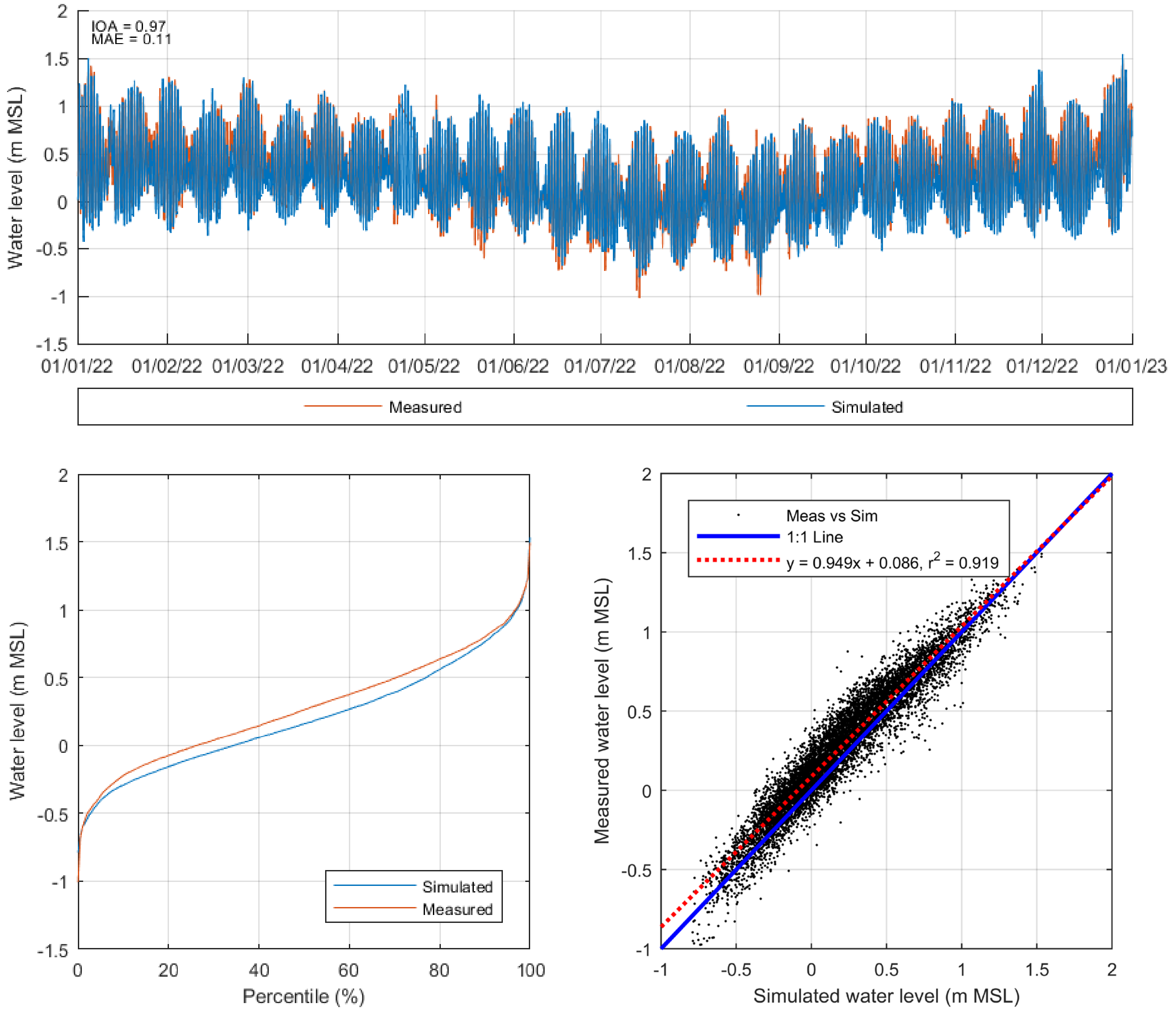


Figure 20 ***Comparison of simulated and measured water level during January 2022 and December 2022 (top panel: time series, bottom left panel: percentile distribution, bottom right panel: measured vs simulated water level with linear regression fit)***

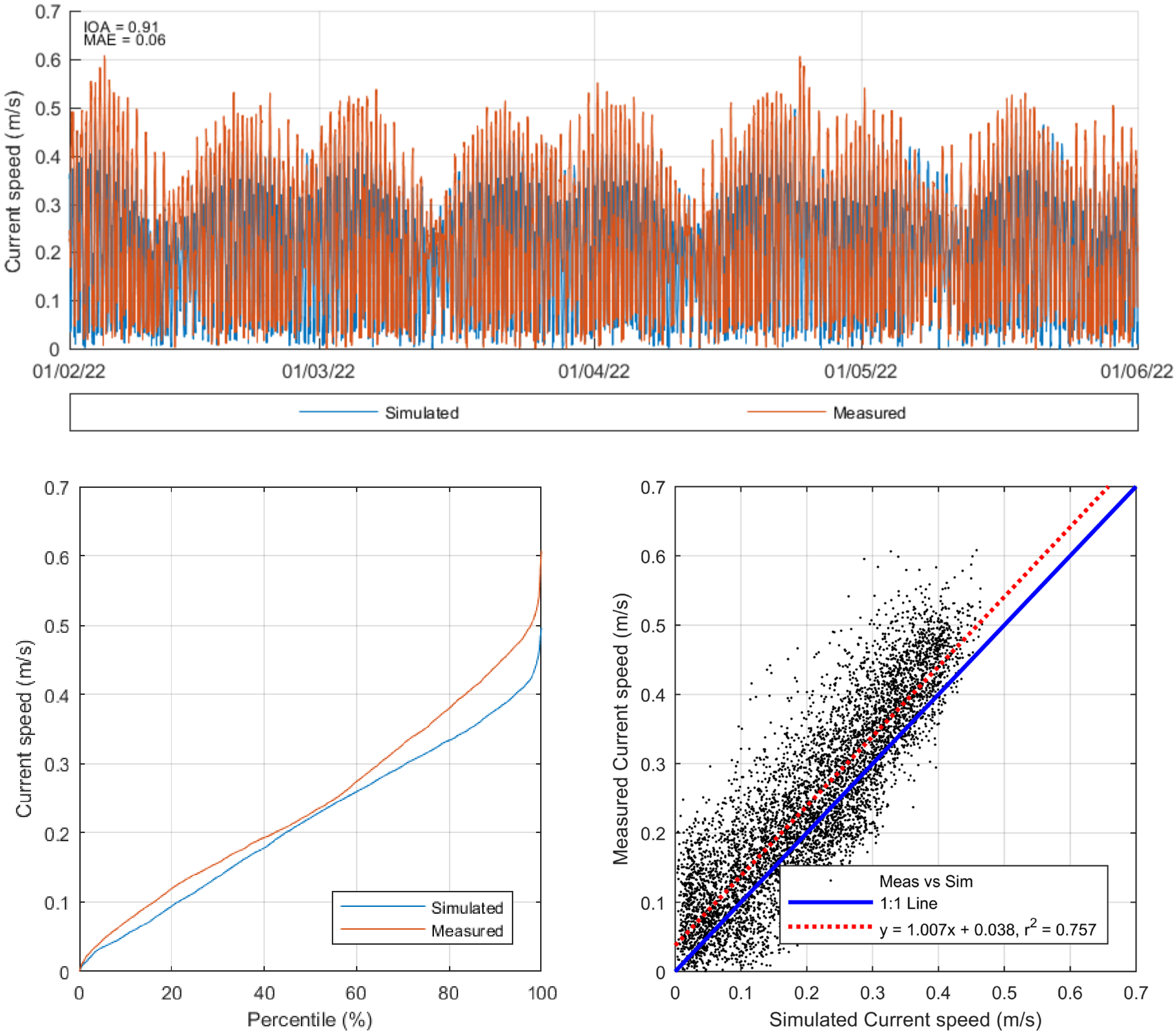


Figure 21 ***Comparison of simulated and measured current speed during February 2022 and May 2022 (top panel: time series, bottom left panel: percentile distribution, bottom right panel: measured vs simulated water level with linear regression fit)***

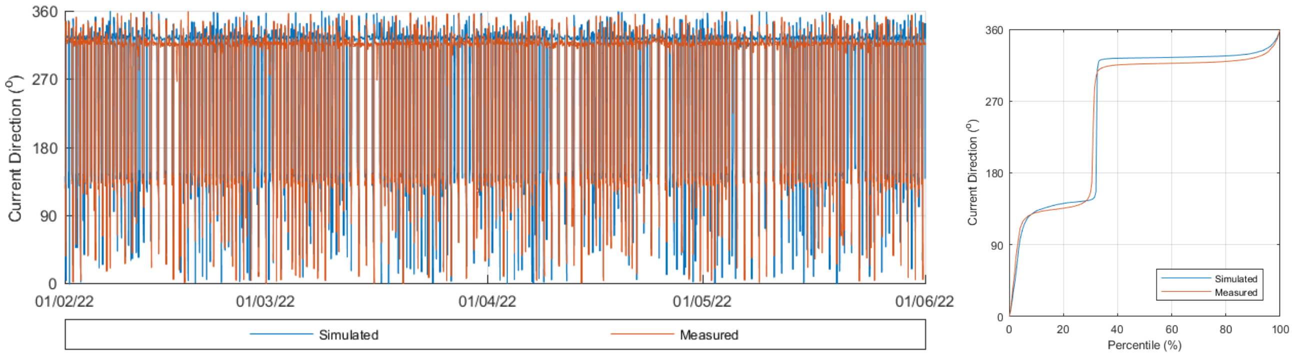


Figure 22 ***Comparison of simulated and measured current direction during February 2022 and May 2022 (left panel: time series, right panel: percentile distribution)***

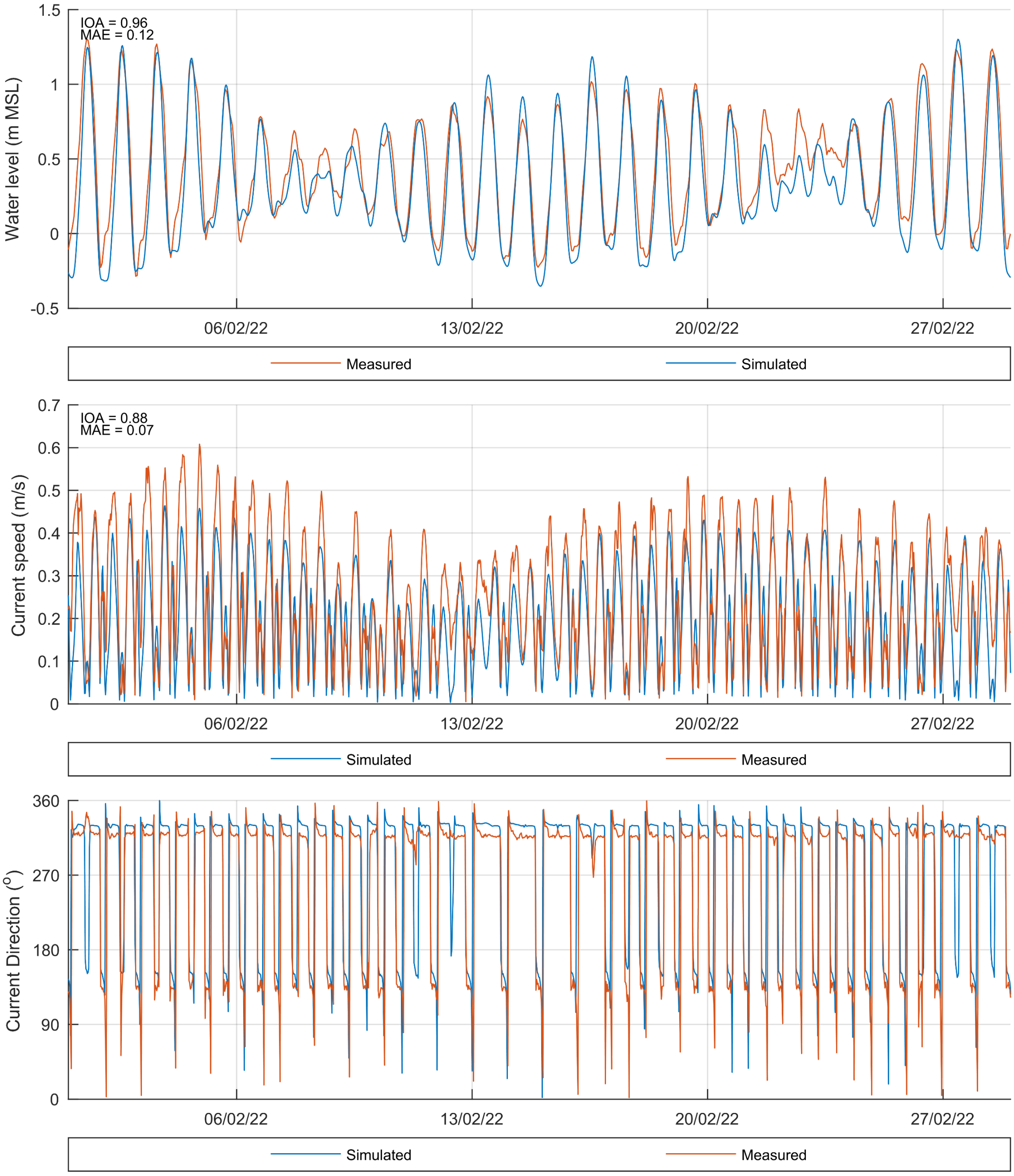


Figure 23 ***Comparison of simulated and measured water levels (top), current speed (middle) and current direction (bottom) for February 2022***

4.3 Hydrodynamic results

Spatial contours of current speed statistics are presented in Figure 26 for the 5th percentile, median (50th percentile) and 95th percentile of depth-averaged currents. At the diffuser location, 5th percentile, median and 95th percentile current speeds are approximately 0.02 m/s, 0.3 m/s and 0.4 m/s, respectively. Low current speeds likely occur primarily during flood tides, whereby the project site is largely sheltered from the jet of southward currents that form through the span between Connexion Island and Groote Eylandt (Figure 24). In contrast, northward currents that primarily occur during ebb tides sweep past the Project site before becoming constricted in the span between the islands (Figure 25). Given the large estimated discharge rate of mine water (80 GL/a), plume dilution rates will largely be driven by the flushing rate of the near-shore waters, which is elevated during periods of northward currents compared to southward currents.

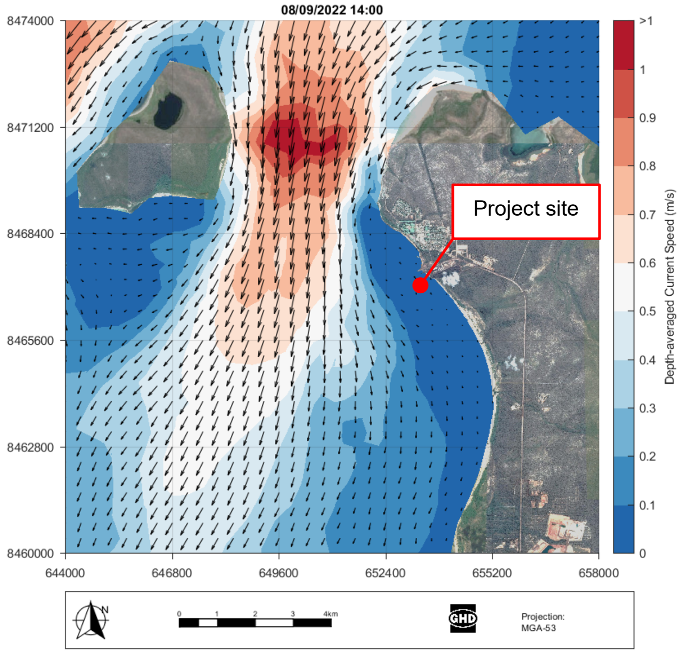


Figure 24 Example snapshot of southward currents during flood tide

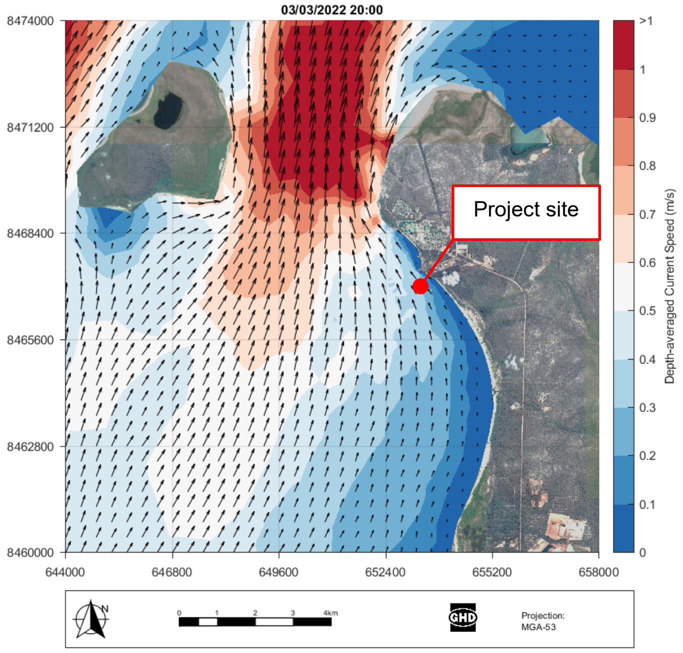


Figure 25 Example snapshot of northward currents during ebbing tide

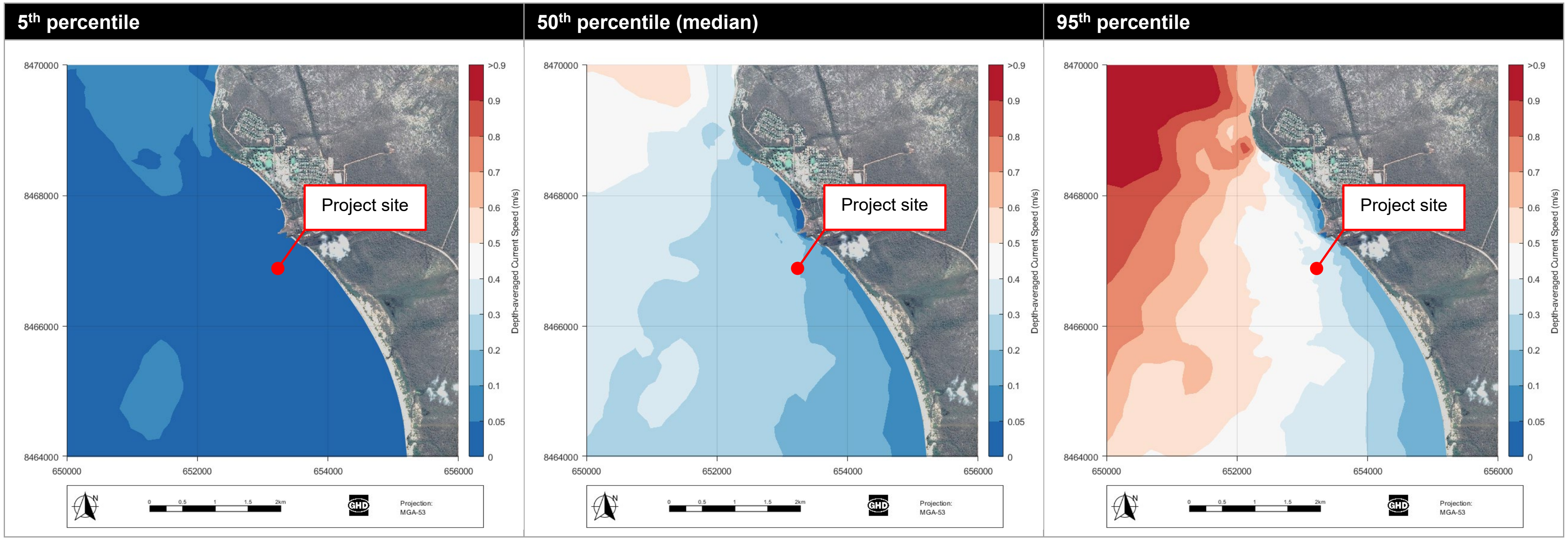


Figure 26 *5th percentile (left), median (middle) and 95th percentile (right) of depth-averaged current speeds at the Project site.*

4.4 Mixing zone predictions

The extent of the mixing zone for the operational discharge scenario has been defined as the 1st percentile of dilution. Due to a range of compounding conservative assumptions adopted in this study (flow rates and discharge concentrations both highly conservative), presenting the minimum dilution is anticipated to significantly overestimate the spatial scale of the mixing zone as compared to the more probable discharge conditions. Adopting the 1st percentile dilution is a means of reducing this over-estimate while still remaining conservative.

The mixing zone prediction (for surface waters) is presented in Figure 27. The following summarised outcomes are predicted:

– Plume trajectories are generally predicted to be northwest and southeast, aligned with the coastline and the predominant directions of the tidal currents.

– Due to the buoyant nature of the discharge, the plume is primarily constrained to the surface waters and did not result in dilution rates below the adopted dilution targets at the seabed.

– The outer extent of the surface mixing zone for **potential indirect effects** (42-fold dilution target related to nitrate enrichment) is predicted to extend ~650 m north and ~550 m southeast from the diffuser.

– The outer extent of the surface mixing zone for **potential direct effects** (35-fold dilution target related to salinity reduction) is predicted to extend ~400 m north-northwest and ~350 m southeast from the diffuser.

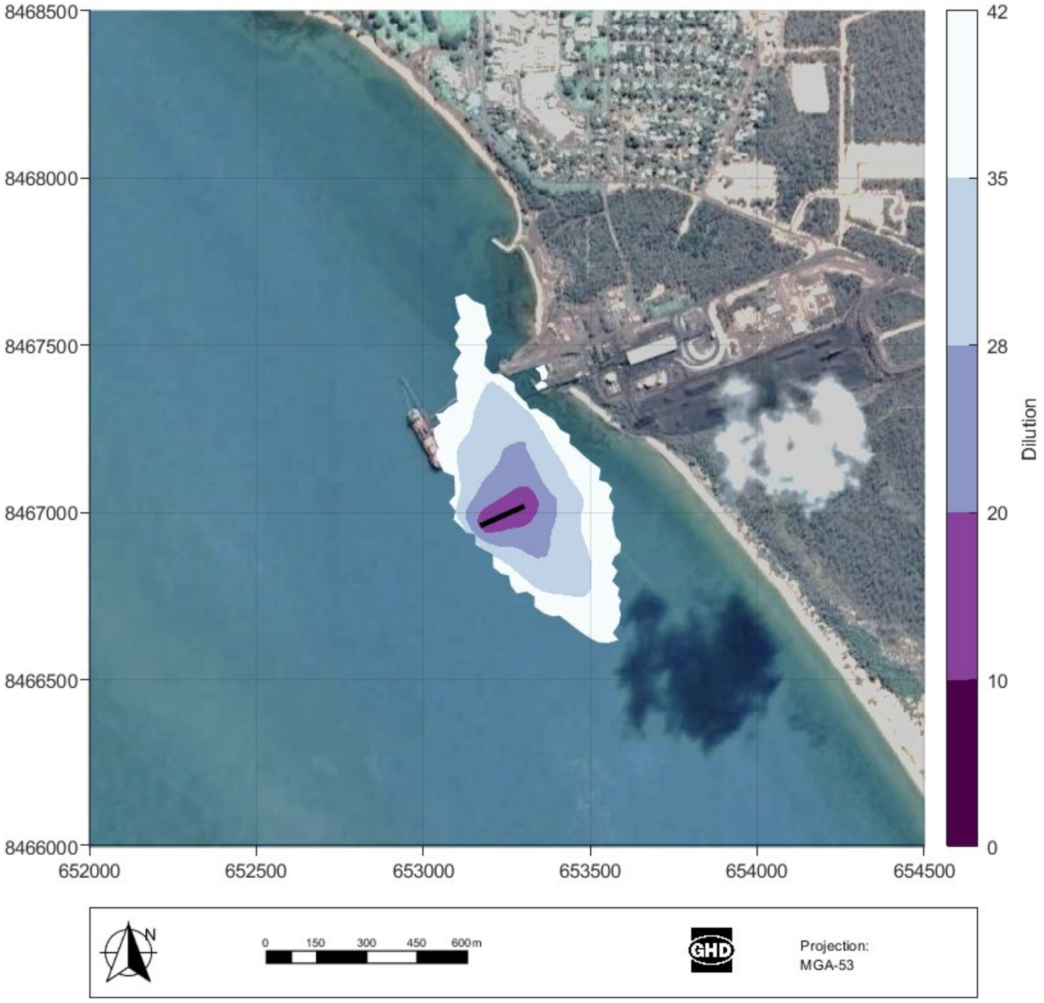


Figure 27 ***Predicted surface mixing zone for various dilution targets for far-field Scenario 1 (80 GL/a), with the zone of potential indirect effects represented by the 42-fold dilution contour and the zone of potential direct effects represented by the 35-fold dilution contour.***

4.5 Flushing

Flushing was assessed for ten scenarios as described in Section 3.6.9.2.

4.5.1 Spatial e-folding flushing rates

Contour plots of spatially varying flushing rates within the nearshore control volume are presented in Figure 28-Figure 29. The northern portion of the control volume that extends into the span between Connexion Island and Groote Eylandt is rapidly flushed in all cases, whereas for some of the scenarios the location-specific flushing rate of the project site is longer (up to ~3 days in the worst-case scenario of 6 Feb 2022). Spatially varying flushing rates however were faster than the PIANC (2008) limit for “good” flushing of four days, indicating flushing rates are adequate to avoid potential issues related to stagnation (e.g. eutrophication related to long-duration exposure to elevated nutrients).

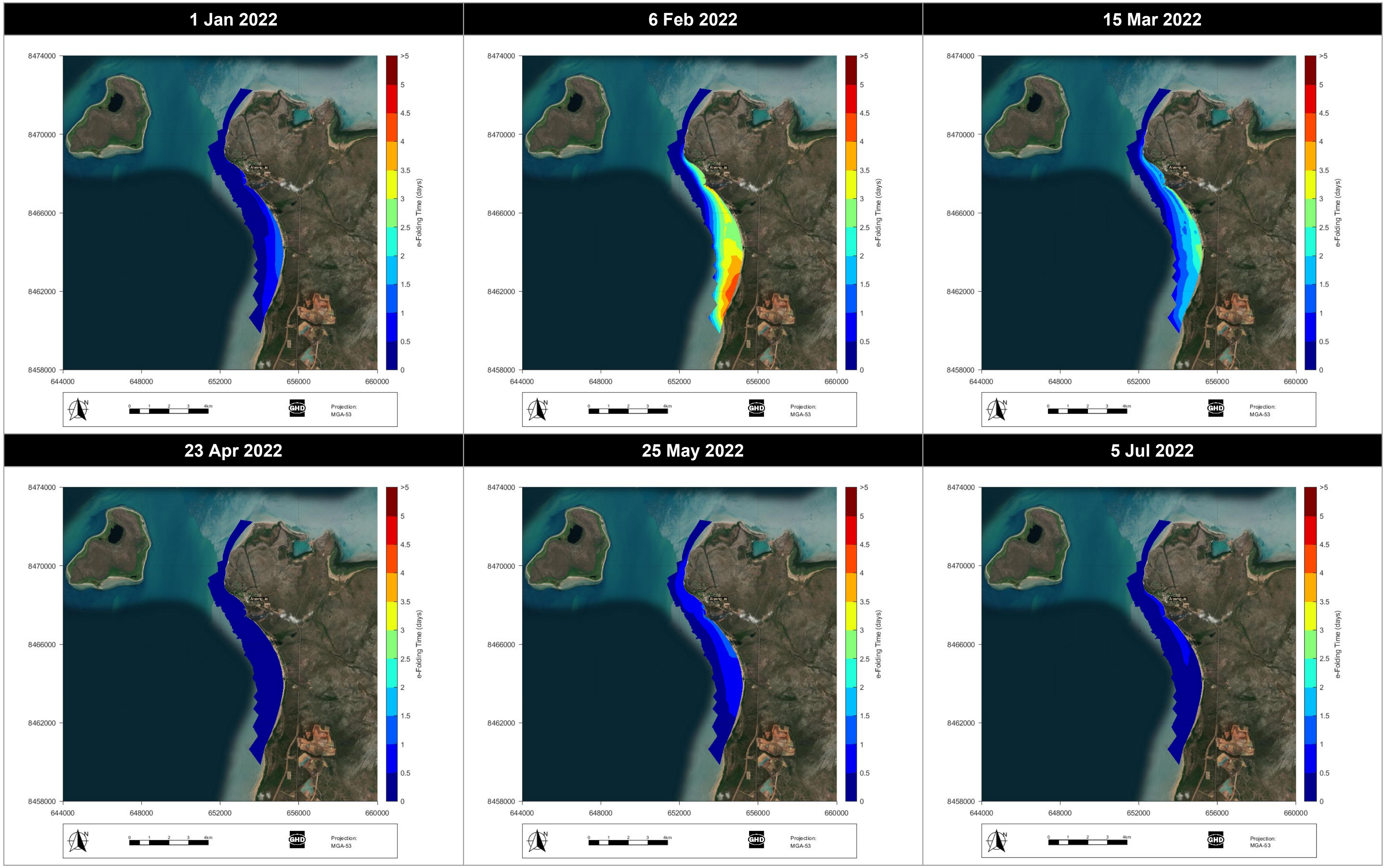


Figure 28 *Spatial e-folding flushing times for simulations beginning 1 Jan 2022 (top-left), 6 Feb 2022 (top-middle), 15 Mar 2022 (top-right), 23 Apr 2022 (bottom-left), 25 May 2022 (bottom-middle) and 5 Jul 2022 (bottom-right).*

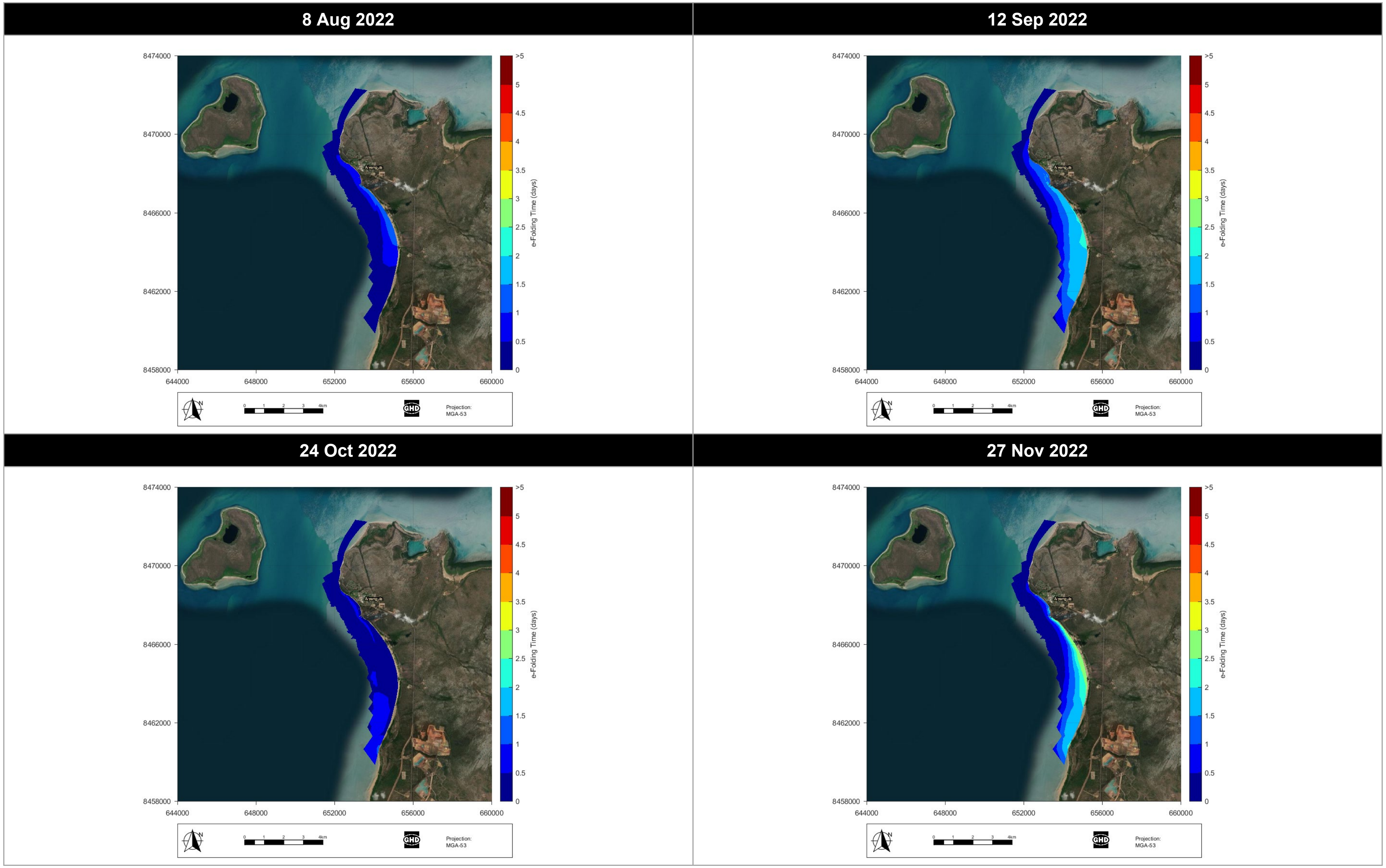


Figure 29 ***Spatial e-folding flushing times for simulations beginning 8 Aug 2022 (top-left), 12 Sep 2022 (top-right), 24 Oct 2022 (bottom-left) and 27 Nov 2022 (bottom-right).***

4.5.2 Volumetric e-folding flushing

The volumetric flushing rates for the whole control volume are summarised for each scenario in Table 9 and Figure 30, with time-series of tracer exchange rates further for each scenario further presented in Figure 31-Figure 33.

The control volume is generally very rapidly flushed, with e-folding timescales averaging ~16 hours, and ranging from 6 hours at a minimum to ~35 hours maximum. Again, the flushing rate of the nearshore waters in all cases was faster than the PIANC (2008) limit for "good" flushing of four days. The high degree of flushing is therefore expected to mitigate any potential water quality issues related to stagnation such as eutrophication, even in the event of increased nutrient concentrations from the discharge.

Table 9 ***Simulated flushing times for the ten (10) simulations.***

Simulation Number	Start Date/time	e-folding time (days)	e-folding time (hours)
1	01/01/2022 06:00	0.42	10.1
2	06/02/2022 02:00	1.44	34.6
3	15/03/2022 21:00	1.06	25.4
4	23/04/2022 00:00	0.28	6.7
5	25/05/2022 07:30	0.68	16.3
6	05/07/2022 07:30	0.25	6.0
7	08/08/2022 16:00	0.44	10.6
8	12/09/2022 00:00	0.94	22.6
9	24/10/2022 09:00	0.49	11.8
10	27/11/2022 03:30	0.62	14.9
Average		**0.66**	**15.9**

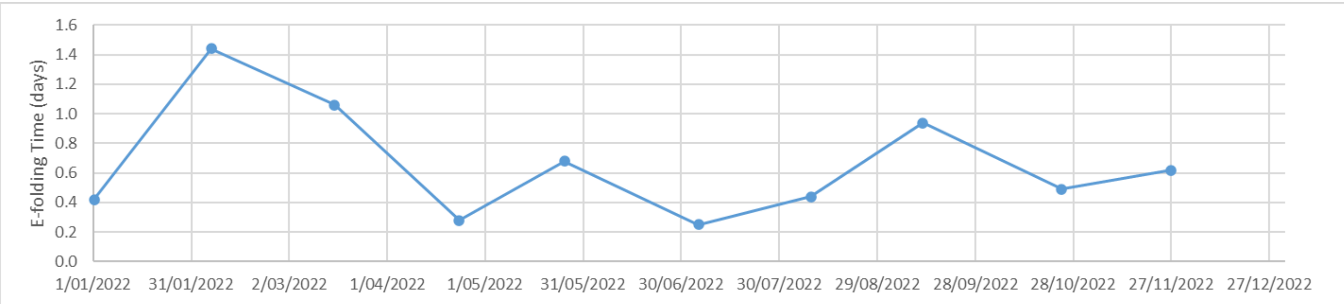


Figure 30 ***Time series of simulated flushing times of the ten (10) simulations***

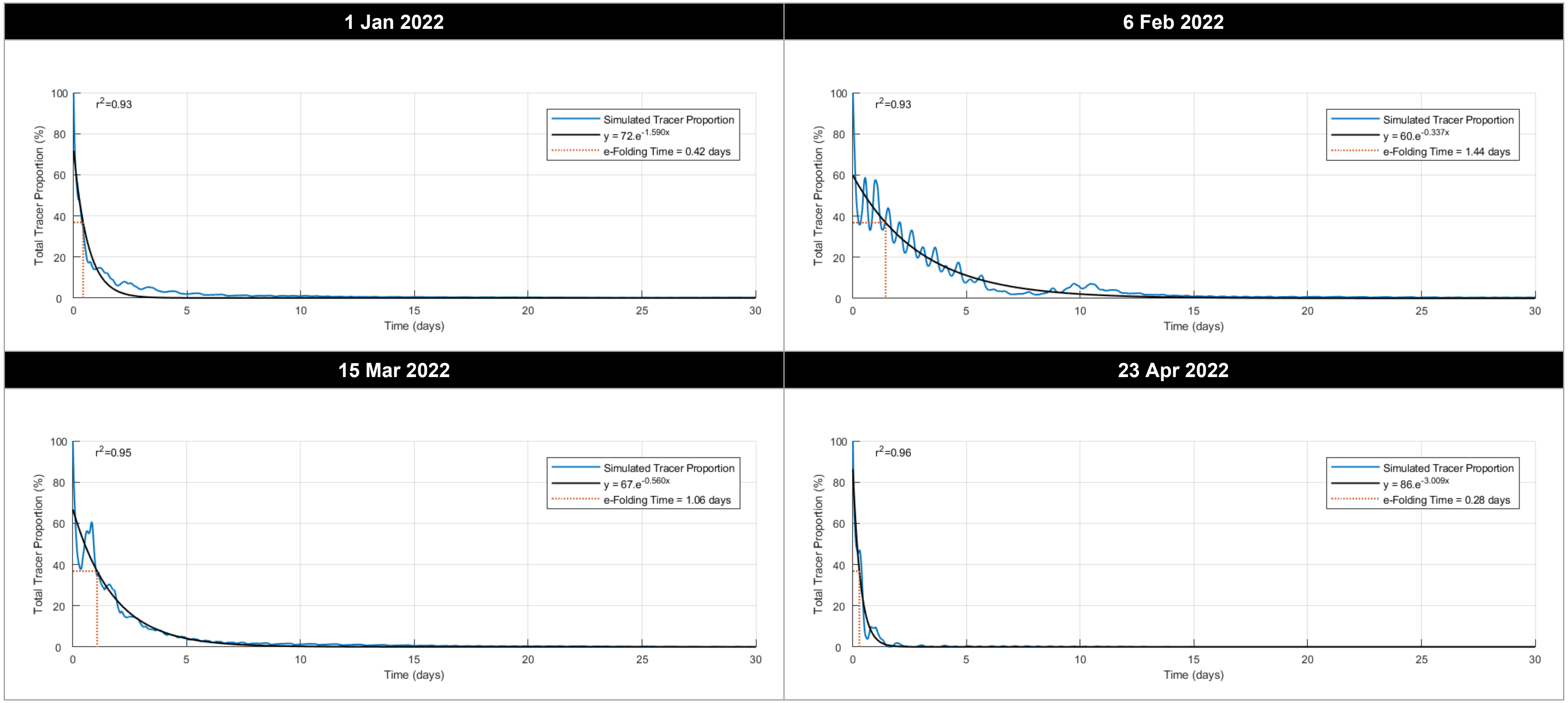


Figure 31 ***Volumetric e-folding flushing times for simulations beginning 1 Jan 2022 (top-left), 6 Feb 2022 (top-right), 15 Mar 2022 (bottom-left) and 23 Apr 2022 (bottom-right).***

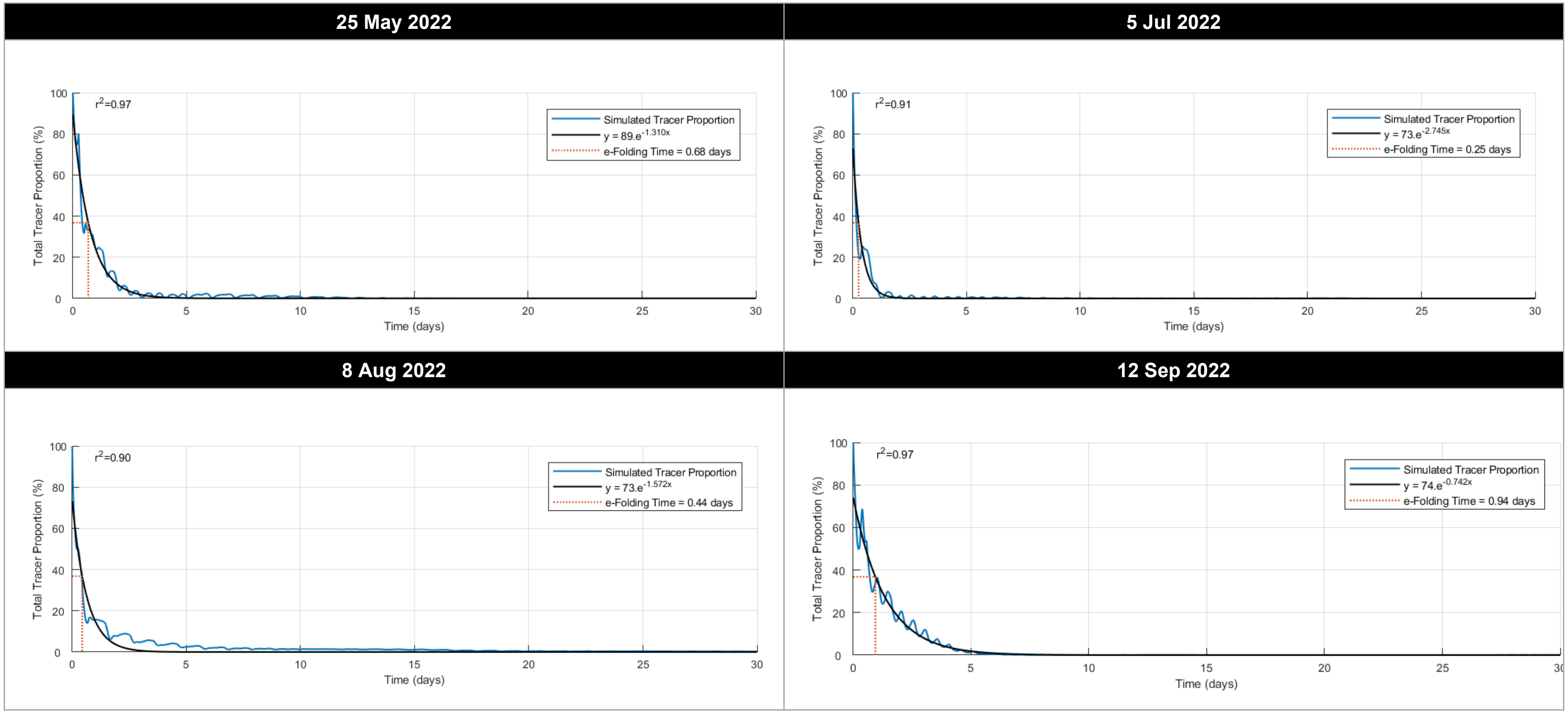


Figure 32 Volumetric e-folding flushing times for simulations beginning 25 May 2022 (top-left), 5 Jul 2022 (top-right), 8 Aug 2022 (bottom-left) and 12 Sep 2022 (bottom-right).

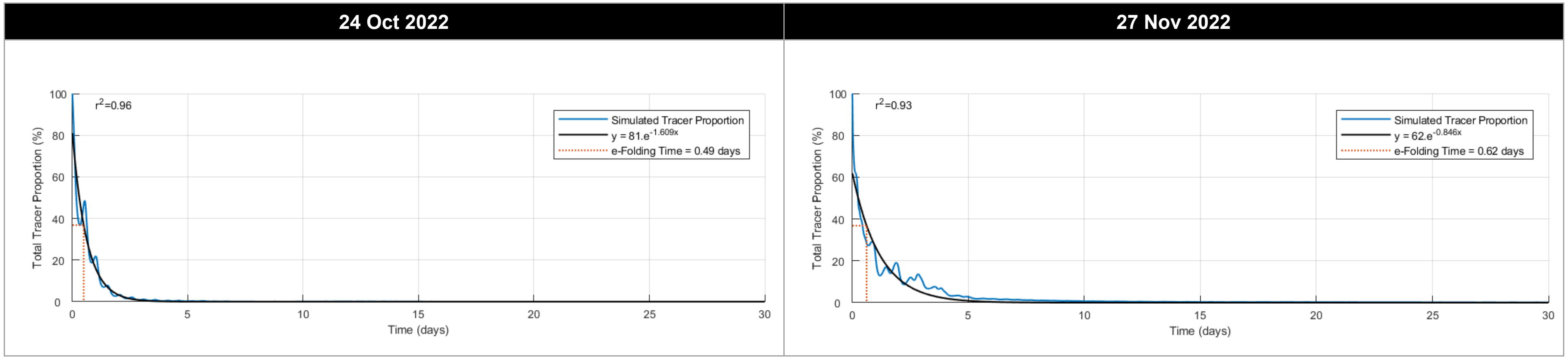


Figure 33 ***Volumetric e-folding flushing times for simulations beginning 24 Oct 2022 (left) and 27 Nov 2022 (right).***

5. Conclusions

This study has covered the following scope:

- Preliminary design of a marine multi-port diffuser that achieves elevated rates of near-field dilution for the range of discharge scenarios assessed.
- Definition of WQOs and associated dilution targets.
- Far-field mixing zone modelling for a discharge scenario of 80 GL/a.
- Flushing modelling of the near-shore coastal waters encompassing the mixing zone.

Based on conservative assumptions of discharge quality, the two analytes requiring the highest level of dilution were nitrate and salinity. Dilution targets of 42-fold for the mixing zone of **potential indirect effects** related to nitrate stimulation, and 35-fold for the mixing zone for **potential direct effects** related to salinity reduction have been defined for this study. The indirect effects are only likely to represent a risk if the receiving marine environment is not flushed rapidly enough, resulting in prolonged exposure to elevated nitrate concentrations for algae that drift through the mixing zone that may potentially stimulate algal growth and lead to algal blooms. Further, potential direct effects related to salinity reduction are only expected to yield ecological impacts when occurring at the seabed in the presence of benthic primary producers (seagrass or corals) that are unable to escape the plume.

Simulation of an operational discharge of 80 GL/a in the far-field model with the adopted 145 m long diffuser design yielded the following outcomes:

- The outer extent of the surface mixing zone for **potential indirect effects** (42-fold dilution target related to nitrate enrichment) is predicted to extend ~650 m north and ~550 m southeast from the diffuser.
- The outer extent of the surface mixing zone for **potential direct effects** (35-fold dilution target related to salinity reduction) is predicted to extend ~400 m north-northwest and ~350 m southeast from the diffuser.
- There was no predicted mixing zone at the seabed due to the buoyant nature of the plume.

Additionally, the flushing assessments predicted that the near-shore receiving waters encompassing the mixing zone are rapidly flushed, with e-folding timescales averaging 16 hours, and ranging from 6 hours at a minimum to 35 hours maximum. The PIANC (2008) standard for marinas states e-folding times of less than four days represent good flushing.

The modelling outcomes indicate that negative ecological effects to the receiving marine environment are unlikely for the assessed scenario due to the following reasons:

- Potential indirect effects due to nitrate stimulation causing algal blooms are unlikely to occur within an environment that flushes so rapidly (typically on the order of hours). The residence time of algal colonies drifting through the mixing zone is generally not long enough for algal stimulation to result in the formation of algal blooms.
- Potential direct effects due to salinity reductions are of primary concern for benthic primary producers (e.g. seagrasses) at the seabed that cannot escape the plume. The mixing zone for potential direct effects does not impinge on the seabed.

The predictions presented in this study are considered conservative for the following reasons:

- The discharge of 80 GL/a defined by GEMCO represents the assumed peak flow. The discharge rate in the model was held constant over a one-year duration simulation and therefore overestimates the likely discharge volumes on an annual timescale, which during operations are expected to average 60 GL/a.
- Concentrations of analytes within the discharge were generally defined as the 95th percentile of historical measurements from the site and therefore are over-estimates of loads for the majority of the time.
- Though the hydrodynamic model was verified with measured currents that were well reproduced, current speeds are marginally under-estimated. This resultant reduction in the simulated flushing of the nearshore environment relative to actual conditions therefore likely represents an over-prediction of the mixing zone spatial extent in general due to less volumetric dilution.

– All water quality analytes assessed (with the exception of pH) were treated as numerically conservative tracers, neglecting transformative processes (degradation, decay, biological uptake) that may otherwise occur for some analytes and will lead to lower concentrations during operations than those simulated here. In general, this assumption will over-estimate the spatial extent of the mixing zone.

On the basis of these outcomes, the discharge scenario assessed in this study is considered to pose a suitably low level of environmental risk.

6. References

ANZECC & ARMCANZ 2000, Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

ANZG (2018). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia. Available at **www.waterquality.gov.au/anz-guidelines**

Australian Government Department of Defence (2017). *Australian National Tides Tables 2018.* Australian Hydrographic Office, Wollongong, NSW.

CARS (2009). CSIRO Atlas of Regional Seas, CSIRO, Canberra. Available at **http://www.marine.csiro.au/~dunn/cars2009/**

Chassignet EP, Hurlburt HE, Smedstad OM, Halliwell GR, Hogan PJ, Wallcraft AJ, Baraille R & Bleck R (2007). The HYCOM (Hybrid Coordinate Ocean Model) data assimilative system. Journal of Marine Systems, Vol 65, Iss 1-4, pp 60-83.

Durrant, T., Hemer, M., Smith, G., Trenham, C., & Greenslade, D. (2019). CAWCR Wave Hindcast - Aggregated Collection. v5. CSIRO. Service Collection. Retrieved from **http://hdl.handle.net/102.100.100/137152?index=1**

Egbert, GD and Erofreeva SY (2002) Efficient Inverse Modelling of Barotropic Ocean Tides. Journal of Atmospheric and Oceanic Technology, Vol 19(2), pp 183-204.

Frick WE, Roberts PJW, Davis LR, Keyes J, Baumgartner DJ, George KP (2003). Dilution Models for Effluent Discharges 4^{th} Edition (Visual Plumes). Ecosystems Research Division, National Exposure Research Laboratory, US EPA.

IPE (2023a). Development of Water Quality Trigger Values for Discharge to Marine Environment. Prepared by Indo-Pacific Environmental for GEMCO, DRAFT revision B, July 2023.

IPE (2023b). Memorandum - Volume weighted assessment of dewatering discharge analyte concentrations. Prepared by Indo-Pacific Environmental for GEMCO, August 2023.

IPE (2023c). Volume weighted assessment of dewatering discharge pH. Draft memorandum produced by IPE for GEMCO, 21 November 2023.

Kalnay EM, Kanamitsu R, Kistler W, Collins D, Deaven L, Gandin M, Iredell S, Saha G, White J, Woollen Y, Zhu A, Leetmaa & Reynolds R. (1996). The NCEP/NCAR 40-Year Reanalysis Project: Bulletin of the American. Meteorological Society, Vol 77, pp 437–441.

Kistler R, Kalnay E, Collins W, Saha S, White G, Wollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, van den Dol H, Jenne R & Fioriono M. (2001). The NCEP/NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. Bulletin of the American. Meteorological Society, Vol 82, pp 247-267

Parkhurst DL, Appelo CAJ (2013). Description of input and examples for PHREEQC version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Techniques and Methods, book 6, ch. A43, 497 p., available at **http://pubs.usgs.gov/tm/06/a43/**.

PIANC (2008). Protecting Water Quality in Marinas. Report No. 98 – 2008. Recreational Navigation Commission.

Willmott, C. J. (1982). Some Comments on the Evaluation of Model Performance. *Bulletin American Meteorological Society, Vol 63, No. 11*, 1309-1313.

Willmott, C. J., Ackleson, S. G., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., Rowe, C. M. (1985). Statistics for the Evaluation and Comparison of Models. *Journal of Geophysical Research, Vol 90, No. C5*, 8995-9005.

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