Mardie Project

Dredge Plume Modelling Report

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Mardie Project

Dredge Plume Modelling Report

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Executive Summary

The Mardie Project is a greenfields high-quality salt project proposed in the Pilbara region of Western Australia. Baird Australia Pty Limited (Baird) have been engaged by Mardie Minerals, a wholly owned subsidiary of BCI Minerals Limited (BCIM) to develop a hydrodynamic modelling program to support the environmental approvals process to assess:

- Modelling of dredge plumes to inform the preparation of a Dredging and Spoil Disposal Management Plan (DSDMP); and
- Modelling of mixing and dilution of bitterns discharge into the marine environment to inform the preparation of a Environmental Quality Plan (EQP).

The dredging requirements through project footprint will require approximately 800,000m^3 of sediment to be removed from the seabed for disposal onshore. The dredging approach and methodology was defined by BCIM for incorporation into the dredge plume modelling process based on a backhoe dredge operating from a barge with a hopper alongside. Dredge rates adopted in the modelling process are based on a target production rate of 2,000m^3 a day, with a sensitivity case examined based on an upper limit production rate of 2,500m^3 a day. Sediment plumes from dredging are generated in the model from two principal sources: mobilisation of fine sediments at the excavator bucket with each load and overflow water from the hopper barges.

An established Delft3D hydrodynamic model (Baird 2020) was used as a basis for the dredge plume modelling program. The Delft3D Online Sediment model (Online-MOR) has been activated in the model to investigate the transport of fine sediments released through the dredging program in four representative fractions – fine sand, silt, fine silt and clay. There is a detailed geotechnical investigation and sediment sampling program which has informed understanding of the composition of the seabed material which will be dredged. The dredge material is very high in fine sediments (clays, silts) representing as much as 75% of the material by volume in sections of the channel. The required volume of dredging material was calculated through the footprint based on high resolution multibeam survey and requirements to achieve the target design depth which is -3.9m LAT in the channel and -6.7mLAT in the berth pocket.

The modelling process simulates dredge plume generation from their source and examines the fate of fine sediments in suspension, as suspended sediment concentration (SSC) both spatially and vertically through the water column in 3D. Sediment plumes are driven in the model by the hydrodynamic forcing (water levels, winds, waves, currents) with erosion, resuspension and deposition of the dredge material permitted in the model based on bed shear stress.

The Environment Protection Authority spatially based zonation scheme to describe the predicted extent, severity and duration of impacts associated with dredging for the Mardie project have been determined through the processing and assessment of the dredge plume model results. The Zone of High Impact (ZoHI) and Zone of Moderate Impact (ZoMI) have been determined by analysing model results as running mean values of modelled SSC against possible and probable coral mortality thresholds applying the method presented in Fisher et al (2019, WAMSI dredging node). The ZOMI and ZOHI for the Mardie project are presented spatially in Section 5 for application in the DSDMP.

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1. Introduction

1.1 Background

Mardie Minerals Pty Ltd, a wholly owned subsidiary of BCI Minerals Limited (BCIM), seek to develop the Mardie Project (the proposal), a greenfields high-quality salt project in the Pilbara region of Western Australia. Baird Australia Pty Limited (Baird) have been engaged by BCIM to address two study scopes associated with the Definitive Feasibility Study (DFS) and environmental approvals for the Mardie Project. The two study scopes are:

- Modelling of dredge plumes to inform the preparation of a Dredging and Spoil Disposal Management Plan (DSDMP); and
- Modelling of mixing and dilution of bitterns discharge into the marine environment to inform the preparation of a Environmental Quality Plan (EQP).

The following report presents the dredge plume modelling. The dredge plume modelling program has been completed adopting the validated hydrodynamic model presented in Baird (2020).

Details on the Mardie Project and Baird's scope of engagement are presented in the following sections.

1.2 Project Overview

The proposal is a solar salt project that utilises seawater and evaporation to produce raw salts as a feedstock for dedicated processing facilities that will produce a high purity salt, industrial grade fertiliser products, and other commercial by-products. Production rates of 4.0 Million tonnes per annum (Mtpa) of salt (NaCl), 100 kilo tonnes per annum (ktpa) of Sulphate of Potash (SoP), and up to 300 ktpa of other salt products are being targeted, sourced from a 150 Gigalitre per annum (GLpa) seawater intake. To meet this production, the following infrastructure will be developed:

- Seawater intake, pump station and pipeline;
- Concentrator ponds;
- Drainage channels;
- Crystalliser ponds;
- Trestle jetty and transhipment berth/channel;
- Bitterns disposal pipeline and diffuser;
- Processing facilities and stockpiles;
- Administration buildings;
- Accommodation village,
- Access / haul roads;
- Desalination plant for freshwater production, with brine discharged to the evaporation ponds; and
- Associated infrastructure such as power supply, communications, workshop, laydown, landfill facility, sewage treatment plant, etc.

Seawater for the process will be pumped from a large tidal creek into the concentrator ponds. All pumps will be screened and operated accordingly to minimise entrapment of marine fauna and any reductions in water levels in the tidal creek.

Concentrator and crystalliser ponds will be developed behind low permeability walls engineered from local clays and soils and rock armoured to protect against erosion. The height of the walls varies across the project and is matched to the flood risk for the area.

Potable water will be required for the production plants and the village. The water supply will be sourced from a desalination plant which will provide the water required to support the Project. The high salinity output from the plant will be directed to a concentrator pond with the corresponding salinity.

A trestle jetty will be constructed to convey salt (NaCl) from the salt production stockpile to the transhipment berth pocket. The jetty will traverse the intertidal zone for approximately 3.6 km before extending into the ocean for a further 2.4 km. The jetty will not impede coastal water or sediment movement, thus ensuring coastal processes is minimal.

Dredging of approximately 800,000 m^3 will be required to ensure sufficient depth for the transhipper berth pocket at the end of the trestle jetty, as well as along a 4.5 km long channel out to deeper water. The dredge spoil is inert and will be transported to shore for use within the development.

The production process will produce a high-salinity bittern that, prior to its discharge through a diffuser at the far end of the trestle jetty, will be diluted with seawater to bring its salinity closer to that of the receiving environment.

The Project was referred to the Department of Water and Environmental Regulation – Environmental Protection Authority (DWER-EPA) Services and the Level of Assessment (LOA) was set at Public Environmental Review (PER). The EPA determined on 13 June 2018 that there were seven preliminary key environmental factors related to the Project, with Benthic Communities and Habitat (BCH) and Marine Environmental Quality (MEQ) being relevant to this Scope of Works (SOW). BCI are currently finalising the Environmental Scoping Document (ESD) with the DWER and Department of the Environment and Energy (DoTEE), with potential BCH and MEQ impacts and risks associated with the SOW being:

- 3.6GL/a of Bitterns disposal (salinity) at discharge location;
- Localised reduction in water quality around the bitterns outfall location;
- Direct disturbance / removal of benthic communities and habitat;
- Direct loss and degradation of marine fauna habitat;
- Marine fauna injury or fatality as a result of vessel strike or contact with dredge equipment;
- Changes to water quality due to intertidal dredging including:
    - Increased sedimentation resulting in settlement and smothering of habitat;

Baird Australia (Baird) have been engaged by BCIM to deliver a numerical modelling study which will provide the basis to support the environmental approvals for the Mardie project.

1.3 Dredge Plume Modelling Scope

This report provides a detailed summary of the inputs, assumptions and outputs from the dredge plume modelling scope. Baird were engaged by BCIM to assess the dredge plume impacts associated with the planned dredging program for the project. The established hydrodynamic model (Baird 2020) was used as a basis for the dredge plume modelling program. The tasks for the modelling as detailed in Baird's engaged scope for BCIM are as follows:

1. Attend an inception meeting and discussion with BCIM on their proposed dredging program and methodology for definition in the modelling scope.
2. Prepare a summary of the metocean, water quality, bathymetric data and dredging methodology to define the key inputs for the dredge plume modelling. The metocean summary has been drawn from the hydrodynamic modelling study (Baird, 2020)
3. The hydrodynamic model with wave effects (Baird, 2020) has been applied to model the generation, transport and fate of dredge plume(s) from the dredging activities. The hydrodynamic modelling completed by Baird includes:
    - Adopting the calibrated coupled 2D/3D model as specified in Baird (2020);
    - 2D and 3D modelling of the representative dry season (winter) period of the dredging campaign;

- Wave effects from offshore swell and local sea conditions included with coupling to the SWAN wave model as specified in Baird (2020).

4. Dredge Plume Modelling has been undertaken with the Delft3D Online Sediment model to include coupled wave and hydrodynamic forcing described above. The tasks undertaken for the dredge plume modelling include:
   - Classification of dredging plume composition and specification of modelled sediment fractions including physical parameters;
   - Schematisation of dredge plan and preparation of time series inputs for the Delft3D model; and
   - Time series modelling of the dredging programme.
5. Deliverables

   The results from the dredge plume modelling have been analysed and presented in the following outputs:
   - The location, extent and duration of a potential dredge plume extent over the course of the dredging programme;
   - Potential worst-case impact scenarios to guide appropriate management techniques in the DSDMP; and
   - Definition of the likely dredge plume impact areas based on threshold suspended sediment concentration (SSC) limits which may impact on light intensity for biota and BCH.

The model outputs have been adopted in the development of the DSDMP to determine environmental monitoring and management measures to be implemented during dredging activities to achieve defined Environmental Protection Objectives (EPOs). The DSDMP is being prepared by O2Marine.

2. Background Information

2.1 Key Reports

The background reports referenced in the development of the hydrodynamic model and application in the dredge plume modelling program are outlined in this section.

2.1.1 Site Specific Reports Prepared for the Mardie Project

- CMW (2019), Mardie Salt Project Jetty and Port Facilities – Factual Geotechnical Report, Mardie WA. Report prepared for Mardie Minerals, 30 October 2019.
- EGS Survey (2019), Mardie Salt Project Geophysical Survey - BCI Minerals SURVEY REPORT, EGS PROJECT REF: AU025918, Prepared for O2Marine 21 January 2019.
- O2Marine (2018), Mardie Project Progress Report #1 for Metocean Data Collection, REPORT No.: R1800106, ISSUE DATE: 22 Oct 2018.
- O2Marine (2019), Mardie Project Progress Report for Metocean Data Collection, R1800132 ISSUE DATE: 15th January 2019.
- RPS (2017), Mardie Salt Project, Preliminary Storm Surge Study, Prepared for BCI.
- Surrich and EGS (2019), Detailed Bathymetry data provided by the Mardie project , Surrich_EGS_Datasets_Merged_Mardie_Creek_MGAZ50_1m_Shoal_Final_GRIDDED_DepthPos_AHD.
- TAMS (2019), Dive Operations Field Report, Report prepared for BCI Minerals detailing Dive operations and Core Samples collected on site 15th July - 30th August 2019.

2.1.2 Western Australian Marine Science Institution (WAMSI) Dredging Node

- Fisher R, Jones R, Bessell-Browne P, (2019). Effects of dredging and dredging related activities on water quality: Impacts on coral mortality and threshold development Report of Theme 4 - Project 4.9, prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 94 pp.
- Kemps H and Masini R (2017) Estimating dredge source terms – a review of contemporary practice in the context of Environmental Impact Assessment in Western Australia. Report of Theme 2 – Project 2.2, prepared for the Dredging Science Node, Western Australian Marine Science Institution. Perth, Western Australia, 29pp.
- Mills D (2019) Predicting and measuring the characteristics of sediments generated by dredging. Synthesis Report of Theme 2 – prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 12 pp.
- Sun C, Shimizu K, Symonds G (2016) Numerical modelling of dredge plumes: a review. Report of Theme 3 - Project 3.1.3, prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia, 55 pp.
- Sun C, Lowe R, Fearns P, Ghisalberti M, Branson P (2019), WAMSI Dredging Science Node Theme 3 I Synthesis Report: Characterisation and prediction of dredge-generated sediment plume dynamics and fate, prepared for the Dredging Science Node, Western Australian Marine Science Institution, Perth, Western Australia.

2.1.3 Key EPA Documents

- EPA (2016a), Statement of Environmental Principles, Factors and Objectives, EPA, Western Australia.
- EPA (2016b), Environmental Impact Assessment (Part IV Divisions 1 and 2) Administrative Procedures 2016.
- EPA (2018a), Environmental Impact Assessment (Part IV Divisions 1 and 2) Procedures Manual, EPA, Western Australia.

- EPA (2016c), Environmental Factor Guideline – Marine Environmental Quality, EPA, Western Australia.
- EPA (2016d), Environmental Factor Guideline – Benthic Communities and habitat, EPA, Western Australia.
- EPA (2016e), Environmental Factor Guideline – Marine Fauna, EPA, Western Australia.
- EPA (2018b), Instructions on how to prepare Environmental Protection Act Part IV Environmental Management Plans.
- EPA (2016f), Technical Guidance – Protecting the Quality of Western Australia's Marine Environment, EPA, Western Australia.
- EPA (2016g), Technical Guidance - Environmental Impact Assessment of Marine Dredging Proposals, EPA, Western Australia.

2.1.4 Other Policy and Guidance

- DoE (2006), Pilbara Coastal Water Quality Consultation Outcomes – Environmental Values and Environmental Quality Objectives, Department of Environment (DoE), Government of Western Australia, Marine Series Report No. 1.
- MScience (2009). *Wheatstone LNG Development: Baseline Water Quality Assessment Report November 2009*. MSA134R3. Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project - Appendix Q7.
- ANZECC & ARMCANZ (2000), Australian and New Zealand Guidelines for Fresh and Marine Water Quality (Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ).

2.2 Measured Data Sources

The key measured data sources which have been applied in the Dredge Plume model program are summarised in Table 2.1.

Table 2.1: Data Summary – Key Datasets

Dataset	Description
Sediment Sampling	Detailed geotechnical core samples with sediment sampling from seabed areas adjacent the proposed dredging footprint were reported in CMW 2019. Sediment sampling results were collected at locations west of the proposed dredging footprint by O2 Marine reporting Particle Size Distribution (PSD) for the dredge material (O2 2018b,2019b).
Bathymetry Ordered Highest to lowest priority	In August 2019 a high-resolution bathymetric survey using a Multibeam Echosounder was completed to define the seabed level of the revised channel infill, transhipment route and proposed cyclone mooring site (Surrich and EGS 2019). In November 2018 a Class A survey was completed to define the seabed level for the proposed access channel route and berth pocket in high resolution. Bathymetry was provided in a Digital Elevation Model (DEM) as reported in EGS 2019. In September 2018 low resolution bathymetry survey was collected by O2Marine and provided as DEM covering the proposed dredge corridor and surrounds.

<table>
<tr><th>Dataset</th><th>Description</th></tr>
<tr><td></td><td>Hydrographic Charts (soundings and contours):
AUS742 - Australia - North West Coast - Western Australia - Rosemary Island to Barrow Island
AUS743 - Australia - North West Coast - Western Australia - Barrow Island to Onslow</td></tr>
<tr><td>Baseline Metocean Data</td><td>Offshore ADCP:
Approximately 16km offshore in 11.2m depth (MGA50 391,362 7,685,272)
8 Deployments covering the period 5 April 2018 – 9 July 2019
Wave height and direction, Current speed and direction, Water Level
Inshore Aquadopp:
Approximately 4km offshore in 5.9m depth (MGA50 388,514 7,673,522)
4 Deployments covering period 8 November 2018 – 8 July 2019 (deployment in 2018 dry season had instrument failure).
Current speed and direction, Water Level</td></tr>
<tr><td>Baseline Water Quality</td><td>Offshore (ADCP) Location:
Light, Temperature, turbidity (TDS)
Inshore (Aquadopp) Location:
Temperature, pH, salinity (EC), Dissolved oxygen (DO)</td></tr>
</table>

The location of the measured metocean data is shown in Figure 2.1.

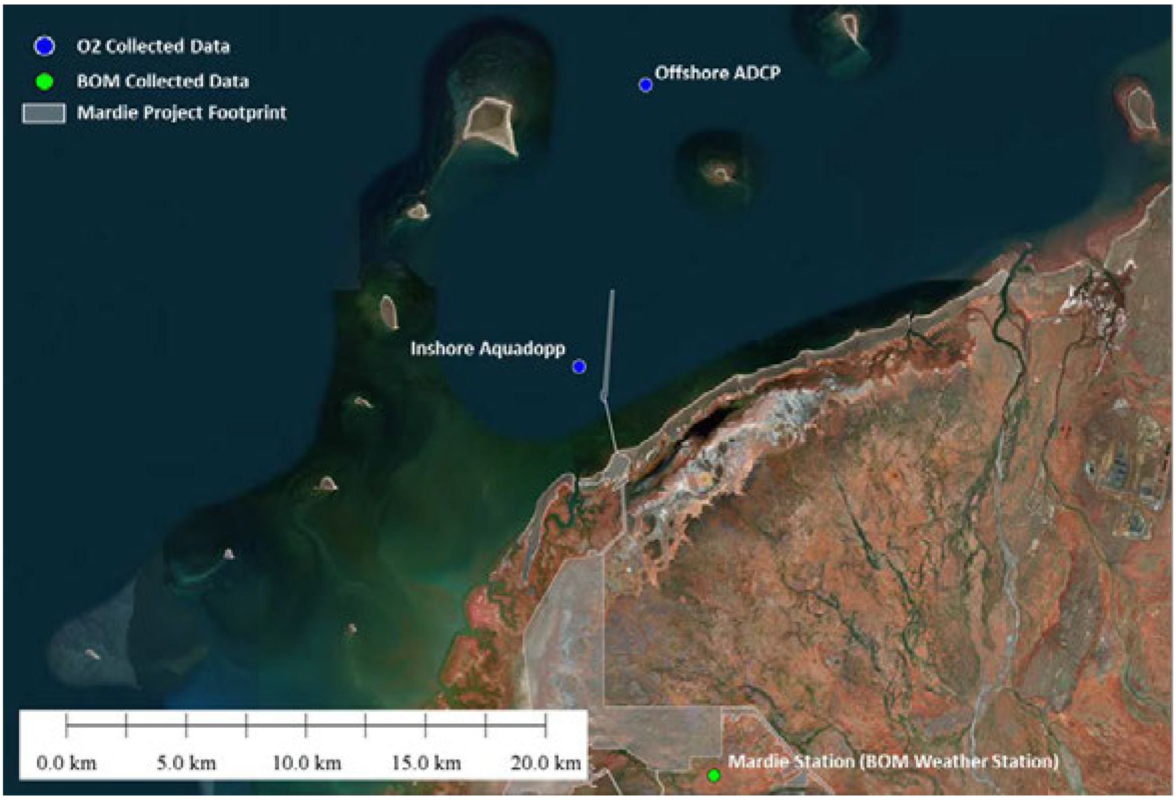

Figure 2.1: Measured Data Locations

3. Dredging Method

3.1 Project Location and Dredging Requirements

3.1.1 Project Location Summary

The local setting and metocean conditions for the Mardie project location are described in detail in Baird (2020). A brief summary follows.

The Mardie project location experiences a semi-diurnal tide (two highs and two lows a day) with a tidal range of 5.185 m (LAT to HAT) and mean sea level at 2.75m LAT. The mean tide range is 3.6m in springs and 1m in neaps.

The inner shelf region is very wide along the Mardie section of the coast, and consequently the near shore bathymetry is very shallow, with water depths of approximately 5m (below LAT) at a distance of 10km offshore. A series of offshore islands and reefs are located immediately offshore of the Mardie coast (Passage Islands). Due to the alignment of the island and reef features of the Passage Islands the majority of incoming tidal flow on the flood tide is directed through the opening between Scholl Island and Mardie Island to the north of the project site. At this offshore location, between the islands, the tidal flow is directed along a general north-south axis whilst closer inshore at the project marine facility location, the tidal flows align along a northeast-southwest axis in the ebb and flood tide.

The measured currents at the marine precinct area show:

- Depth averaged peak current speed of $0.3ms^{-1}$ - $0.5ms^{-1}$ in springs and $0.2ms^{-1}$ – $0.3ms^{-1}$ in neaps
- Current direction (direction to) consistent in Ebb 40˚ - 70˚ and Flood 220˚ - 250˚
- The flood speeds are generally stronger than the ebb current speed

In general, wave conditions are dominated by locally generated sea conditions within the range of 0.5m to 1m (significant wave height) at short wave periods (peak periods < 5 s).

3.1.2 Project Footprint and Dredging Requirements

The project footprint extends across the tidal flats at Mardie with the settling ponds approximately 5km inland and the port facility (berth pocket, loader, trestle jetty) located approximately 2.4km offshore as shown in Figure 3.1.

A trestle jetty, with a conveyer-based system to transport processed salt to the ship loader at the port over the intertidal areas, will be located on the eastern side of the berth pocket. The berth pocket has a maintained depth of -6.7m LAT, around which, there is a turning circle area and marine operations area dredged to a depth of -3.9m LAT. A navigation channel 100m wide will be dredged through the natural seabed north of the berth, over a distance of approximately 4.5km to a design depth of -3.9m LAT. The design of the navigation channel and berth pocket are shown in Figure 3.2 with the surrounding seabed bathymetry.

The design of the berth pocket, marine precinct and channel alignment has been optimised based on the dredging requirements, length of trestle jetty and design vessel requirements.

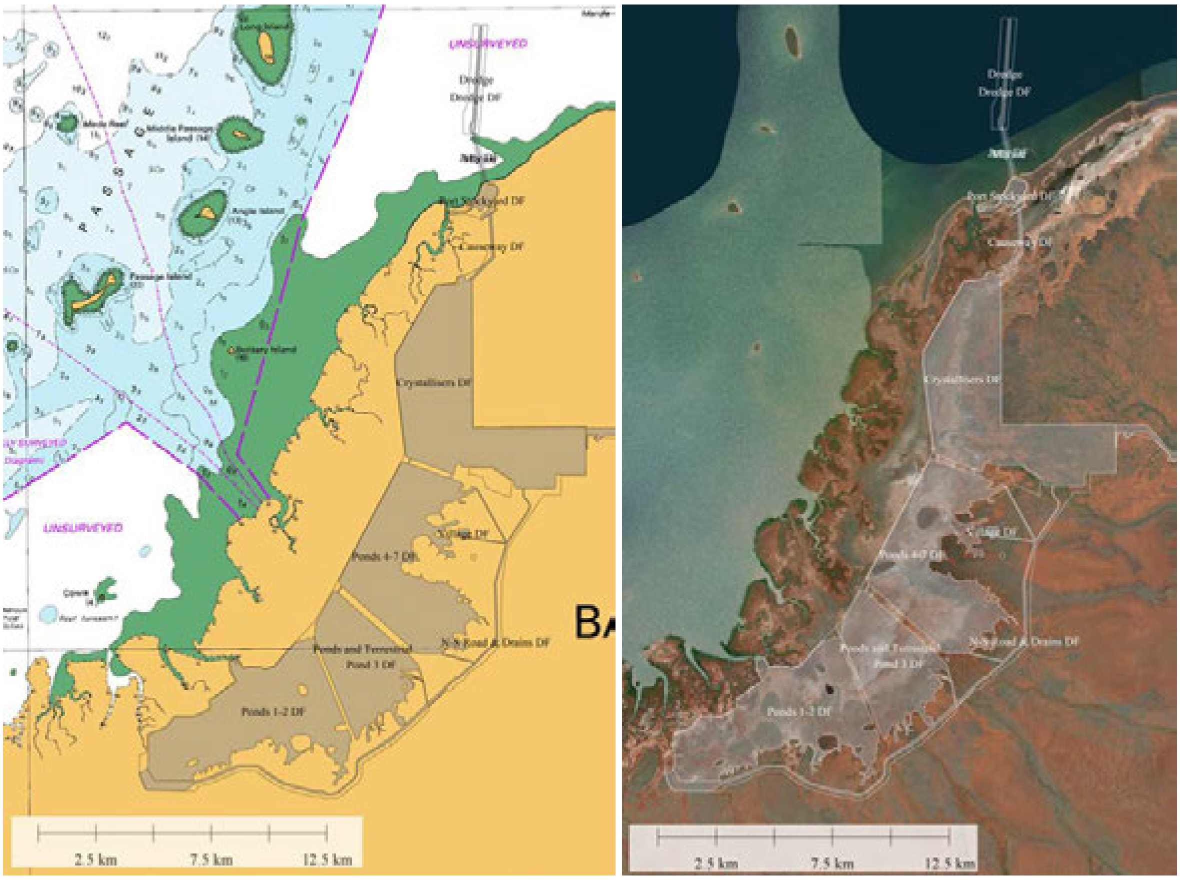

Figure 3.1: Mardie Project Footprint (underlain by Hydrographic Chart AUS743)

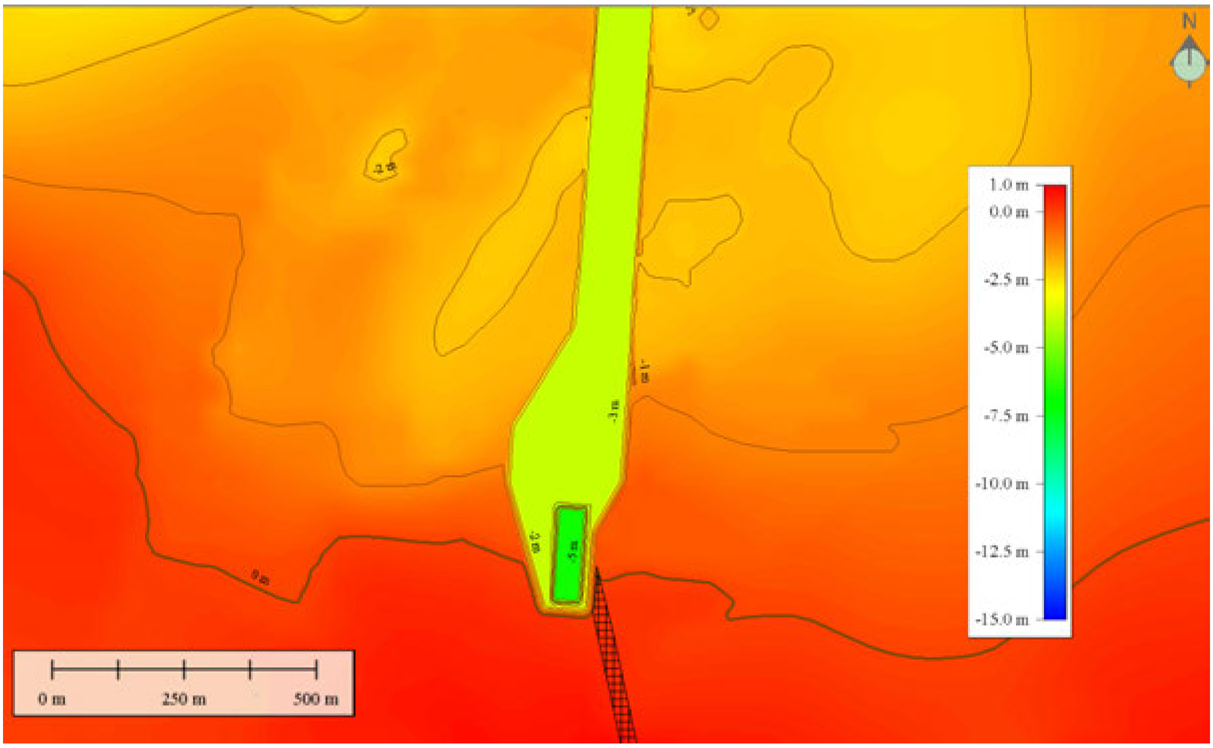

Figure 3.2: Configuration of Berth Pocket and Navigation Channel (Datum mLAT)

Around the berth pocket the natural seabed depth is shallow with water depths approaching 0m LAT. The dredging requirements and volumes are weighted to the nearshore section of the dredge footprint, with the berth pocket (-6.7m LAT) and marine precinct/ navigation channel (-3.9m LAT) requiring significant dredging of the natural seabed. Offshore, the dredging requirements to get to design depth through the channel areas require approximately 1m of dredging below the natural seabed. This is discussed further in Section 3.6.

The intended method for the dredge program is for a backhoe dredger on a barge to operate through the dry season months, extracting sediment from the seabed and depositing it into hoppers alongside (Figure 3.3). The hoppers are to transfer the dredged material to the onshore area for re-use on site. The program will commence from inshore and complete the berth pocket and marine precinct and then proceed with dredging requirements offshore progressing along the offshore channel footprint.

An over dredge allowance of 0.5m is included in the dredge program and incorporated into the modelled volumes. For areas where the natural seabed is already at the design depth along the channel (-3.9m LAT) no over dredge is undertaken.

Figure 3.3: Example of Backhoe Dredge (TAMS, 2020)

3.2 Dredging Approach and Methodology

The dredging methodology was defined by BCIM for incorporation into the dredge plume modelling process as summarised in Table 3.1.

Table 3.1: Dredging Method - Summary Statement

Dredge Design	Channel	Berth Pocket
Total Length	4,500m	210m x 40m
Design Depth	-6.65m AHD (-3.9m LAT)	-9.45m AHD (-6.7m LAT)
Design Width	90m at Floor	40m at Floor
Batters	1V:5H	1V:5H
Over Dredge Allowance	Allowance of 0.5m over dredge in all areas being dredged (ie not where natural seabed level is already at design depth).	
Dredge Volume	735,000m^3	75,000m^3
Dredge Volume Total	Approximately 810,000m^3 (including over dredge)	
Dredge Method		
Dredge Plant	Long reach excavator / Backhoe on Barge	
Production Rates – Basis	Based on Contractor Submissions (Advice L Huck BCIM) Dredging to be completed in Dry Season Months (April to October)	
Excavation Rate	Target Rate = 100m^3/hr, Maximum Rate = 125m^3/hr Target Rate = 2,000m^3/day, Maximum Rate = 2,500m^3/day	
Operational Constraints	Excavator Reach is not Constrained by Tide Level and no downtime is assumed in the model for environmental issues.	
Operating Hours	20hr non-stop dredging (2x 10 hr shifts). 4hr stopped (0400-0800)	
Dredge spoil disposal method	Spoil placed in hopper barge and disposed onshore Hoppers will be overfilled and there will be overflow of fines in suspension from the hopper into the water column	

Sediment plumes will be generated during the channel dredging at different scales. The sediment plume generation sources are summarised in Table 3.2 for the dredging activities with relevant assumptions adopted in the modelling based on literature and studies as referenced.

Table 3.2: Model Assumptions – Plume Generation Sources from Dredging Activities

Plume Source	Approach to define plume generation in model
Sediment Plume Sources	Sediment plumes from dredging will be generated from 2 principal sources: 1. Mobilisation of fine sediments at the excavator bucket with each load: and 2. Overflow water from the hopper barges
Material Loss from Bucket	4% by mass of total fine sediments (fine sand, clay and silt fractions) lost as the bucket comes up through the water column from the seabed to the Hopper barge on surface. Of the load input into the model, 40% is input at the seabed, 30% mid depth and 30% at the surface
Material Loss from Hopper Overflow	An assumption that 10% by mass of fines (< 62um) in suspension is discharging from overflow at top of water column (conservative assumption i.e. worst case). Input to model from the top of the water column.

3.3 Construction Schedule

A construction schedule has been developed based on target production rates of 2,000m^3 a day. The schedule aims to complete the requirements of the project over dry season months in 2 successive years and incorporates a range of assumptions for the plant and equipment (eg production rates, working hours) as shown in Table 3.3. The proposed schedule has been implemented in model simulations developed from a range of local information including survey data and geotechnical information.

The dredging requirements are considered in 7 individual sections along the dredge footprint (dredge sequences shown in Figure 3.4). Within each dredge sequence, the sediment composition of dredge spoil is determined from available geotechnical information (CMW 2019) closest to each respective section. The dredge volume in each section is then calculated in terms of sand, silt and clay components and assigned to plume sources in the numerical model based on the assumed dredging method of long reach excavator and hopper discussed in the sections to follow.

Table 3.3: Proposed Dredging Schedule Adopted in Model Program

Activity	Dredge Assumption	Time - Target Production
Sequence 1 – Berth Pocket	2,000m^3 /day x 58 days 116,000m^3 Total	Month 1 - Month 2, Year 1
Sequence 2 and 3 – Marine Precinct	2,000m^3 /day x116 days 232,000m^3 Total	Month 3 - Month 6, Year 1
Sequence 4 and 5 – Channel Section North	2,000m^3 /day x114 days 228,000m^3 Total	Month 1 - Month 4, Year 2
Sequence 6 and 7 – Offshore Channel Section	2,000m^3 /day x109 days 218,000m^3 Total	Month 5 - Month 8, Year 2

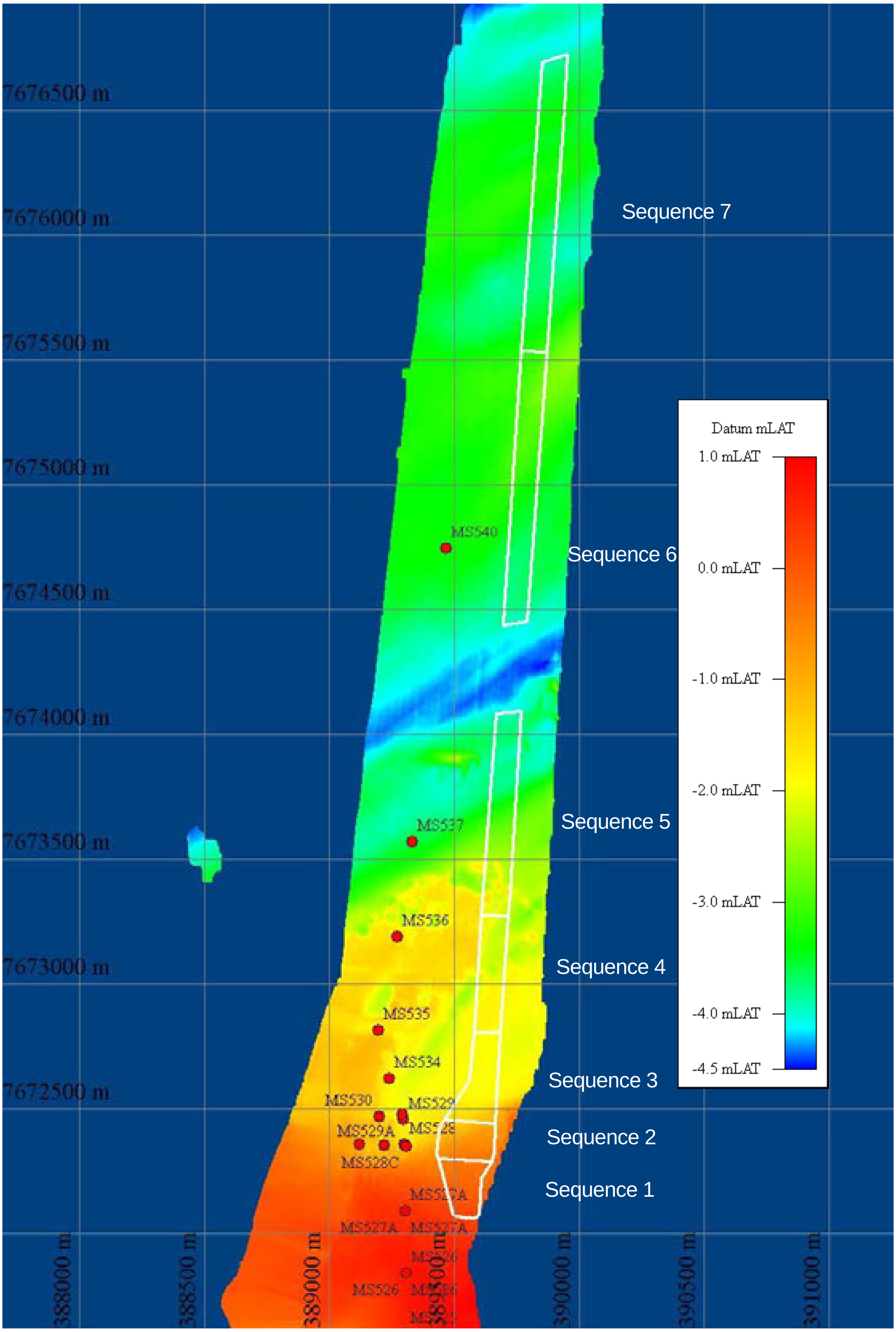

Figure 3.4: Sediment sampling locations (CMW, 2019) and Dredge Alignment. The design depth of the channel is -3.9mLAT and the berth pocket design depth is -6.7mLAT.

3.4 Sediment Classifications in Model

There is a detailed geotechnical investigation and sediment sampling program which has informed understanding of the composition of the seabed material which will be dredged (CMW2019).

The sediment classifications considered in the modelling are based on the range of sizes described in Table 3.4. The dredge plume modelling examines fine cohesive sediments (clays, silts) and also considers non-cohesive fine sand. The sediment classifications larger than fine sand are not included in the sediment plume modelling. It is assumed that these will fall out of suspension and be deposited at the seabed rapidly a short distance from their source.

Table 3.4: Summary of Sediment Classes in Model (from Wentworth Scale)

Sediment Class	Size Range (µm)	Model Assumptions
Gravel, Cobbles	>2mm	Not considered in the model. Assumed that these larger sediments will fall to the seabed locally from the source location.
Medium to Coarse Sand	0.25mm – 2mm	
Fine sand	62µm – 0.25mm	Modelled as non-cohesive sediment with Median Sediment D_{50} = 125µm
Coarse Silt	16µm to 62µm	Modelled as cohesive sediment, Settling Velocity 1.7mm/s
Fine Silt	2µm to 16µm	Modelled as cohesive sediment, Settling Velocity 0.06 mm/s
Clay	< 2µm	Modelled as cohesive sediment, Settling Velocity 0.004 mm/s

A key determinant of the dredge plume dispersion and settlement in the model is the settlement rate parameter for the fine fractions. According to Stoke's Law, the settling rate of particles is affected by the gravitational force exerted on the particle, the density of the particle relative to the density of the medium, and the viscosity (resistance to flow-settling) of the medium.

For the modelled fine fractions, the following settlement rate has been adopted:

- Coarse Silt = 1.7 mm/s
- Fine Silt = 0.06 mm/s
- Clay = 0.004 mm/s

These values fall within the ranges of settling velocity adopted in similar modelling studies as noted in Sun et. al., 2016.

3.5 Dredge Material - Sediment Sampling and Analysis

The sediment sample locations collected through the alignment of the transhipment channel are shown in Figure 3.4 based on locations reported in CMW (2019). The sediment samples are taken from various depths under the seabed from boreholes extracted from locations approximately 250m west of the channel alignment. The boreholes are considered to represent the sediment conditions of the dredged material in the channel.

There are seven dredge sequences shown as white polygon areas in Figure 3.4. The sequences are distinct areas considered along the dredging footprint in which the sediment composition and volume has been assessed and input into the model to determine the dredge plume impacts. Within each of the areas the volume of sediment removed varies between 112,000m^3 and 116,000m^3.

The dredge sequences commence at the most inshore location and progress offshore. Sequence 1 (SEQ1) is the first section that is dredged in the model simulations and the region covers the berth pocket area. The SEQ1 section is completed in the model (approximately 8 weeks of dredging) and the next section of the channel in SEQ2 commences. At the start of SEQ2, the bathymetry is updated in the model to represent the completed SEQ1 section and hydrodynamics in the model run are based on interaction with the partially completed dredged channel and footprint in SEQ1.

Within each of the dredge sequences SEQ1 through to SEQ7 offshore, the particle size distribution of the dredged material for application in the model has been calculated based on the measured geotechnical data. This process is summarised in Table 3.5 and Figure 3.4 outlining the samples that have been considered for each of the sections and the calculation of the respective sediment fractions (clay, silt, sand). It is noted that for the sand fraction, only fine sands (62µm – 0.25mm) are included in the dredge plume modelling. It is assumed that medium and coarse sand particles (0.25mm – 2mm) will fall to the seabed close to the source. The PSD have been examined in each sample to define the representative proportion of fine sand to include in the model, which is generally about one third of the total sand.

Table 3.5: Sediment Composition of dredged material by Zone – based on CMW 2019

			Sediment Composition			
Dredge Zone	**Ref. Sample**	**Depth of Sample Below Seabed**	**Clay %**	**Silt %**	**Sand %**	**Gravel %**
SEQ1	MS527A	2.4m to 2.5m	18	24	11	47
	MS527A	4.0m to 4.2m	18	16	53	13
	Average	Applied in Model	**18**	**20**	**32**	-
SEQ2	MS528	1.2m to 1.5m	36	37	17	10
	MS529	1.0m to 1.5m	34	34	26	6
	MS529A	1.2m to 1.35m	46	36	14	4
	MS531	2.7m to 3.0m	17	33	25	25
	Average	Applied in Model	**33**	**35**	**21**	-
SEQ3	MS534	0.4m to 0.7m	40	26	30	4
	MS529	1.0m to 1.5m	34	34	26	6
	MS529A	1.2m to 1.35m	46	36	14	4
	MS535	1.5m to 1.8m	48	31	18	3
	Average	Applied in Model	**42**	**32**	**22**	-
SEQ4	MS534	0.4m to 0.7m	40	26	30	4
	MS535	1.5m to 1.8m	48	31	18	3
	MS536	1.6m to 2.0m	34	44	19	3
	Average	Applied in Model	**41**	**34**	**22**	-
SEQ5	MS536	1.6m to 2.0m	34	44	19	3
	MS537	0.0m to 0.5m	31	39	26	4
	Average	Applied in Model	**33**	**42**	**23**	-
SEQ6 and SEQ7	MS537	0.0m to 0.5m	31	39	26	4
	MS540	0.0m to 0.3m	4	4	62	31
	Average	Applied in Model	**17**	**21**	**44**	-

An overview of the incorporation of the CMW 2019 sediment sampling results into the model is provided as follows:

- The boreholes are considered to represent the sediment conditions of the dredged material in the dredge areas. Boreholes closest the dredge sections (SEQ1 to SEQ7) at depths consistent with the planned dredge program were used as the basis for calculations with the average calculated for each representative section in the model as shown in Table 3.5
- The sediment samples show that the fines content is very high through the dredge footprint. The fines (clay + silt) material represents 38% of dredged material in SEQ1 at the berth pocket area and the fines content increases to between 68% to 75% of the dredged material in SEQ2, SEQ3, SEQ4 and SEQ5. In the most offshore dredge areas, the sediments in SEQ6 and SEQ7 are similar to the SEQ1 section with a fines content of 38%.

To illustrate the application of the geotechnical information, the core sample from borehole 529A used to define the sediment composition in SEQ2 and SEQ3 is shown in Figure 3.5. The upper layers in the core are very high in clay and silt, to a depth of approximately 2.5m below the seabed. The sediment sample reported from 1.2m to 1.35m in the core showed there was 46% clay and 36% silt. It is noted that the lower section of the core sample in Figure 3.5, shows a distinct change in the sediment composition to gravel. For the dredging along the SEQ2 and SEQ3 sections the required depth of dredging below the seabed is within 2.5m of the surface and the dredged material in the model assumes a high fines content (ie gravel is not encountered).

Figure 3.5: Core Sample for site MS529-A (TAMS, 2019). Cores at 1m length are shown as recovered from the seabed. Sediment sampling from the core was extracted from 1.2m – 1.35m below the surface and showed very high fines content of 82% (CMW, 2019).

3.6 Calculation of Dredging Volumes

The analysis of the required volume of dredging was calculated through the transhipment channel and berth pocket dredge footprint based on the target design depth (Table 3.1) and the natural seabed levels with an allowance for over dredging of 0.5m. The calculation was completed through a GIS based analysis utilising the high resolution multibeam bathymetry dataset collected through the transhipment corridor in 2019 (Surrich and EGS, 2019).

The natural seabed level is shown in Figure 3.4 based on multibeam bathymetry data collected in 2019.

A transect along the channel centreline through the offshore Sequence 6 and Sequence 7 areas is shown in Figure 3.6. The natural seabed level along the transect varies between -3.9m LAT and -2.9m LAT. Along this offshore section the target depth of the navigation channel is 1m or less below the natural seabed.

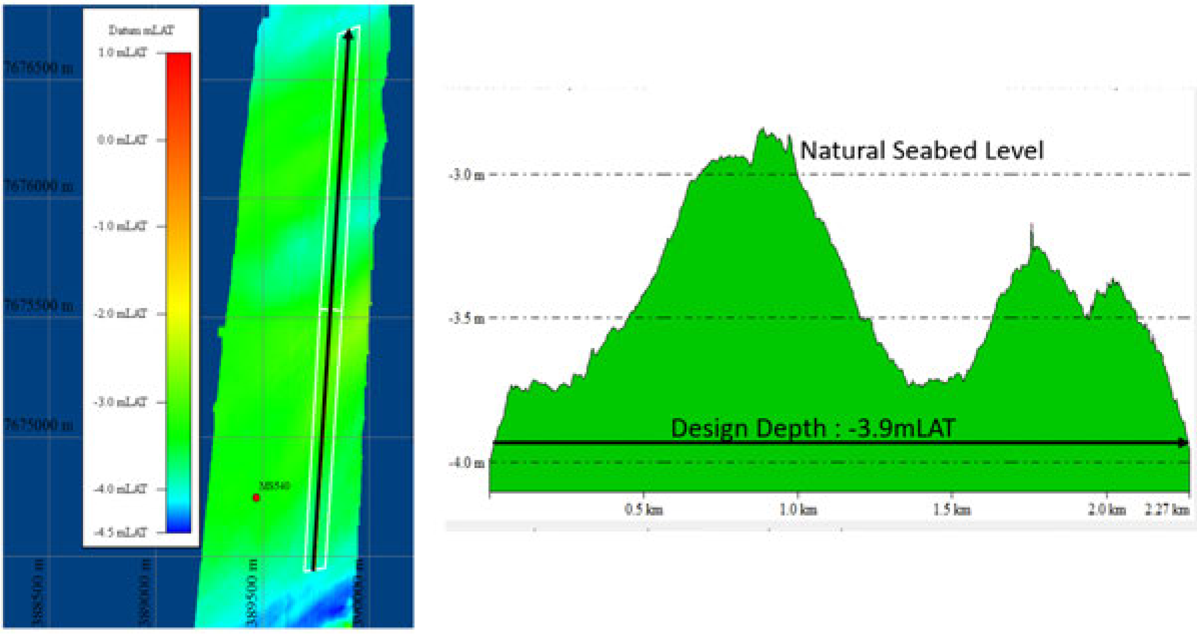

Figure 3.6: Natural Seabed Level through offshore dredged channel alignment (SEQ6 to SEQ7). The natural seabed is generally within 1m of the design channel depth of -3.9mLAT.

A transect along the channel centreline through the inshore Sequence 1 to Sequence 5 areas is shown in Figure 3.6. The transect shows that the natural seabed level in Sequence 1 is 0m LAT to -0.5mLAT. In this section the design depth of the channel (-3.9mLAT) as well as the berth pocket (-6.7mLAT) will require significant dredging. In Sequence 2 the natural level of the seabed falls to -1mLAT, which will still require dredging to go 3m below the natural seabed to reach design depth. In Sequence 3 and Sequence 4, the natural seabed is at approximately -2m LAT. The design depth of the channel will be around 2m below this natural seabed. For the Sequence 5 section the natural seabed deepens to design depth over a distance of approximately 800m.

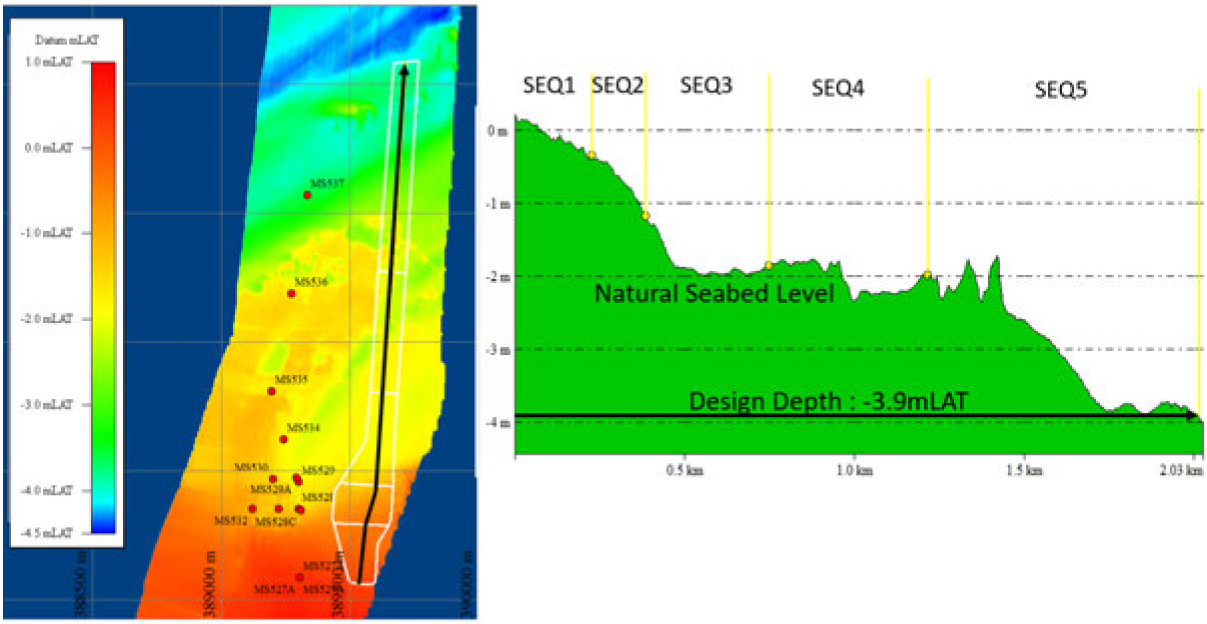

Figure 3.7: Natural Seabed Level through inshore dredged channel alignment (SEQ1 to SEQ5). The natural seabed through the sections is shown against the design channel depth of -3.9mLAT.

4. Dredge Plume Model Setup

4.1 Model System

Hydrodynamic, wave and sediment transport models have been developed for the Mardie project to model dredge plume development and dispersal. The model system is used for predicting the likely extent, severity, and persistence of environmental impacts by the proposed dredging activity. For this project the Delft3D modelling system (Deltares, 2020) has been adopted. Delft3D is an industry leading integrated modelling suite, which simulates two-dimensional (in either the horizontal or a vertical plane) and three-dimensional flow, sediment transport and morphology, waves, water quality, and ecology and can handle the interactions between these processes. The model has been applied in many similar studies of dredging impacts at sites around Australia with modules for investigation of far-field water quality, mid-field water quality, ecological modelling, and cohesive and non-cohesive sediment transport (Sun et al 2016).

4.1.1 Hydrodynamic Model (Delft3D FLOW-WAVE-FLOW)

The hydrodynamic and wave models established for the Mardie project are detailed in Baird (2020) with components summarised in brief as follows:

1. A regional scale hydrodynamic model extending across the northwest of Australia using Delft-Flow Flexible Mesh (D-Flow FM) model. The model is driven by tidal constituents along its open boundaries with bathymetry defined from hydrographic chart data and local scale bathymetry sources where available. For this project, winds and atmospheric pressure have been sourced from the NCEP Climate Forecast System (CFSR). The climatic conditions were then applied spatially in D-Flow FM and updated hourly across the regional model in conjunction with the tides, so their influence was captured in the determination of hydrodynamic forces acting in the domain.
2. A local scale Delft3D hydrodynamic model is established over the Mardie area with boundary conditions defined by the Regional model (Figure 4.1).
3. The local model is setup in a domain decomposition grid arrangement to optimise the efficiency of the model performance. The outer grid extends along the shoreline approximately 70km with a cross shore extent of approximately 45km. The outer grid is setup on a 200m grid size. For the dredge plume analysis, a smaller domain sized at 40m resolution describes the dredge footprint including the channel and marine precinct of the port. Inshore dredge sequences SEQ1 through SEQ5 are assessed on one 40m grid and the offshore dredge sequences SEQ6 and SEQ7 use a separate 40m domain centred over the offshore channel extent (Figure 4.2).
4. A SWAN wave model was developed to cover the local scale domain with the following attributes:
    - The model is setup with an outer grid domain extending across the hydrodynamic grid, with a grid size of 400m. A nested grid of 40m grid size over the transhipment channel and port facility area is nested within.
    - The wave conditions inside the SWAN model develop under the local wind forcing applied in the model. Swell conditions are applied at the boundary based on the measured data from the offshore ADCP.
    - Wave conditions are updated in the local hydrodynamic model every 2 hours using Delft3D coupled FLOW-WAVE-FLOW module.

The validation of the hydrodynamic model against available measured data is presented in Baird (2020) for neap and spring tide periods through the wet season and dry season period. The validation shows good validation metrics calculated for water level, depth averaged current velocity and direction at both the inshore and offshore measurement sites for Mardie. The SWAN wave model has been validated against the measured data from the offshore measurement location showing good agreement to wave height, direction and period.

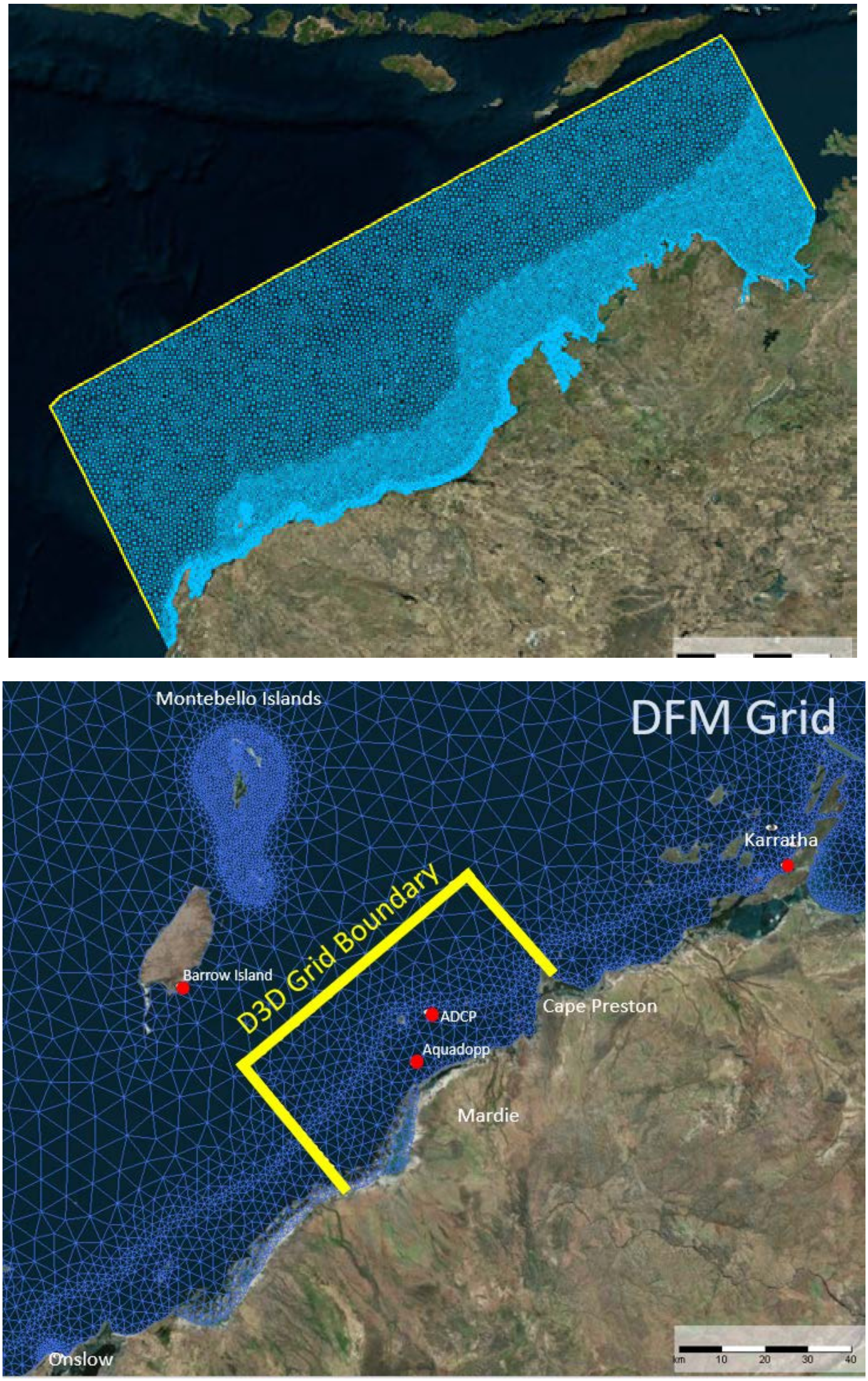

Figure 4.1: Upper plot – Regional Hydrodynamic Model Domain (DFM). Lower plot – Local scale Delft3D model developed for Mardie Project with boundary conditions defined from the Regional model. Measured data was available for model validation from the ADCP and Aquadopp Locations.

Figure 4.2: Local Delft3D Hydrodynamic Model grid setup applied for dredge plume modelling. Domain Decomposition Grids - Outer grid (yellow, grid resolution 200m x 200m) and Inner grids (green, grid resolution 40m x 40m).

4.1.2 Sediment Transport Model - Delft3D Morphology Module (Online-MOR)

The Delft3D Online Sediment model (Online-MOR) is used to investigate the transport and fate of sediments released into the water column through the dredging program. The sediment transport module is part of the Delft3D suite developed by Deltares in the Netherlands and designed to simulate sediment transport of non-cohesive (sandy) or cohesive (silt) sediments under combined processes of wave propagation, currents and morphological developments in coastal, river and estuarine areas (Deltares 2020).

The Delft3D model system is one of the passive plume models reviewed in Sun et al 2016 and the model has been applied in similar dredging studies completed in Western Australia and many locations globally. The passive plume dispersal is managed through three separate model components, namely a hydrodynamic model, a sediment transport model and surface wave model. The validated Delft3D hydrodynamic and wave model system outlined in Section 4.1.1 has been adopted as the platform for hydrodynamics and waves, with the sediment transport module (Online-MOR) activated to investigate the release of sediments from dredge plume sources (backhoe operation and hopper overflow) and examine the diffusion, dispersion and resuspension processes of the plume.

The sediments released through the dredging program are assessed in the model in four sediment fractions – fine sand, coarse silt, fine silt and clay. The following ranges are used:

1. Fine Sand represents sediment sizes in the range 0.062 mm to 0.25 mm (62 µm-250 µm) with a median value of 0.125 mm adopted in the model
2. Coarse Silt represents sediment sizes in the range 0.016 mm to 0.062 mm (16-62 µm)
3. Fine Silt represents sediment sizes in the range 0.002 mm to 0.016 mm (2-16 µm)
4. Clay represents sediment sizes in the range <0.002mm (<2 µm)

Sediment size larger than 0.25mm is not included in the model. Any gravel, medium or coarse sand that is lost from the backhoe bucket or hopper barge is assumed to settle immediately to the seabed within the immediate vicinity of the dredging area.

4.2 Representative Seasonal Scenarios Modelled

The modelling program for the Dredge Plume Modelling phase is based on scenario modelling. The scenario modelling approach has been adopted to optimise the model run times, as continuous modelling of environmental conditions through the full duration of the dredging campaign would be impractical due to the long run times of the model system (Baird, 2020).

The dredging is planned to be completed over the dry season months (i.e. outside of cyclone season) over successive years. In developing the scenario approach, modelling cases of four weeks duration have been selected that are representative of the dry season at Mardie:

- The period selected as representative of the dry season period was 4 July – 1 August 2018.

The modelling applies the representative dry season period to examine the influence of the metocean conditions (winds and waves climate) on the dredge plumes generated. It is noted that the dry season period selected exhibit the general characteristics of winds and waves from the long-term records available at the location (Baird, 2020).

The model is forced by hydrodynamic conditions for the representative dry season period (Baird 2020). through each of the seven dredge sequences. The time taken to dredge each of the sequences is approximately 2-months in the model. The dredge plumes are represented as modelled SSC of the respective sediment fractions (fine sand, silt, fine silt, clay).

The dredge plumes are driven in the model by the hydrodynamic forcing (water levels, winds, waves, currents) with erosion, resuspension and deposition of the dredge material permitted in the model based on bed shear stress. It is noted that the layer of sediment at the existing seabed is not erodible in the model.

4.3 Model Setup

4.3.1 Schematisation of dredge method

It is intended the dredging program will achieve a target production rate of 2,000m^3 a day over a 20-hour shift period (20-hours dredging, 4-hours stopped).

The preparation of the time series inputs to the model were developed based on the dredging volume requirements along the sections of the transhipment channel under the assumption that 2,000 m^3 a day was dredged every day, during 2 x 10-hour shifts. This resulted in the total volume of 810,000m^3 distributed across seven dredge sequences summarised in Figure 3.4. The modelled point of discharge moves through the transhipment footprint area based on the dredging requirements (volumes of dredge material / rate of production) for each of the seven respective dredging sequences to simulate the dredging process.

The model outcomes were used to assess dredge plume impacts associated with the target production rate of 2,000m^3 a day and an upper limit production rate of 2,500m^3 a day in the analysis presented in Section 5.

4.3.2 Summary of Model Parameters

An overview of the key model settings and characteristics is provided in Table 4.1.

Table 4.1: Delft3D Dredge Plume Model Settings

Feature	Description
Grid size / type	Domain Decomposition (DD) - Regular Grids at 200m and
Grid Extent	Outer Grid: 45km x 70km
3D sigma layer model	5-vertical sigma layers with layer thicknesses of 20% all the way through the water column.
Vertical Datum	Mean Sea Level (m MSL) which is approximately Australian Height Datum (AHD)
Horizontal eddy diffusivity coefficient	Across the DD Grids 200m / 40m: 25 / 5 m^2/s
Horizontal eddy viscosity coefficient	Across the DD Grids 200m / 40m: 25 / 5 m^2/s
Vertical eddy viscosity / diffusivity	k-ε turbulence closure model
Time step (2D model)	0.25 mins (15 secs)
Time step (3D sigma-layer)	0.1 mins (6 secs)
Bed friction	Chezy $55m^{1/2}/s$
Sediments Specific Density	2650 kg/m^3
Fine Sand	D50 = 0.125mm, Dry Bed Density 1600kg/m^3
Silt	Settling Velocity 1.7mm/s, Dry Bed Density 500kg/m^3
Fine Silt	Settling Velocity 0.06mm/s, Dry Bed Density 500kg/m^3
Clay	Settling Velocity 0.004mm/s, Dry Bed Density 500kg/m^3
Van Rijn's reference height factor	1
Threshold sediment thickness	0.005 m
Critical Bed Shear Stress for Sedimentation	0.1 N/m^2
Critical Bed Shear Stress for Erosion	0.5 N/m^2
Background Suspended Sediment	Modelled as zero. Background SSC is added into model results in post processing (refer Section 5)
Mapping Output	60-minute output for every point on the DD grids through the full duration of model. 5 vertical layers of water column

4.3.3 Sediment Discharge Volumes

The sediment sampling results were analysed in detail to determine the time series sediment discharge in the model by relative sediment fraction. The release by sediment fraction is summarised Table 4.2 to Table 4.7 for dredge Sequence 1 to Sequence 7 respectively.

From the table summaries, the dredge plume source rates are highest in SEQ2, SEQ3, SEQ4 and SEQ5 in the range of 9.9m^3/hr to 10.8m^3/hr of fines released into the water column whilst the dredger is in operation 20hrs per day. The fines content reduces in the offshore sections SEQ6 and SEQ7 and around the berth pocket in SEQ1 with only about 6m^3/hr of fine sediments released into the water column whilst dredging.

Table 4.2: Sediment Discharge Rates by Fraction for Sequence 1

	Fine Sand (m^3/hr)	Silt (m^3/hr)	Clay (m^3/hr)	Total (m^3/hr)
Assumed PSD	11%	20%	18%	-
Dredge Rate (m^3/hr)	11	20	18	49 (out of 100 Total Production Rate)
Bucket Loss @ 4% (m^3/hr)	0.5	0.8	0.7	2.0
Overflow Loss @ 10% of Total (m^3/hr)	NA	2.0	1.8	3.8
Total (m^3/hr)	**0.5**	**2.8**	**2.5**	**5.8**

Table 4.3: Sediment Discharge Rates by Fraction for Sequence 2

	Fine Sand (m^3/hr)	Silt (m^3/hr)	Clay (m^3/hr)	Total (m^3/hr)
Assumed PSD	7%	35%	33%	-
Dredge Rate (m^3/hr)	7.0	35	33	75 (out of 100 Total Production Rate)
Bucket Loss @ 4% (m^3/hr)	0.3	1.4	1.3	3.0
Overflow Loss @ 10% of Total (m^3/hr)	NA	3.5	3.4	6.9
Total (m^3/hr)	**0.3**	**4.9**	**4.7**	**9.9**

Table 4.4: Sediment Discharge Rates by Fraction for Sequence 3

	Fine Sand (m^3/hr)	Silt (m^3/hr)	Clay (m^3/hr)	Total (m^3/hr)
Assumed PSD	7%	32%	42%	-
Dredge Rate (m^3/hr)	7	32	42	81 (out of 100 Total Production Rate)
Bucket Loss @ 4% (m^3/hr)	0.3	1.3	1.7	3.3
Overflow Loss @ 10% of Total (m^3/hr)	NA	3.2	4.2	7.4
Total (m^3/hr)	**0.3**	**4.5**	**5.9**	**10.7**

Table 4.5: Sediment Discharge Rates by Fraction for Sequence 4

	Fine Sand (m^3/hr)	Silt (m^3/hr)	Clay (m^3/hr)	Total (m^3/hr)
Assumed PSD	7%	34%	41%	-
Dredge Rate (m^3/hr)	7.4	33.7	40.7	81 (out of 100 Total Production Rate)
Bucket Loss @ 4% (m^3/hr)	0.3	1.4	1.7	3.4
Overflow Loss @ 10% of Total (m^3/hr)	NA	3.4	4.0	7.4
Total (m^3/hr)	**0.3**	**4.8**	**5.7**	**10.8**

Table 4.6: Sediment Discharge Rates by Fraction for Sequence 5

	Fine Sand (m^3/hr)	Silt (m^3/hr)	Clay (m^3/hr)	Total (m^3/hr)
Assumed PSD	7%	42%	33%	-
Dredge Rate (m^3/hr)	7.4	42	33	82 (out of 100 Total Production Rate)
Bucket Loss @ 4% (m^3/hr)	0.3	1.7	1.3	3.3
Overflow Loss @ 10% of Total (m^3/hr)	NA	4.2	3.3	7.5
Total (m^3/hr)	**0.3**	**5.9**	**4.6**	**10.8**

Table 4.7: Sediment Discharge Rates by Fraction for Sequence 6 and 7

	Fine Sand (m^3/hr)	Silt (m^3/hr)	Clay (m^3/hr)	Total (m^3/hr)
Assumed PSD	15%	21%	17%	-
Dredge Rate (m^3/hr)	14.5	21.1	17.2	53 (out of 100 Total Production Rate)
Bucket Loss @ 4% (m^3/hr)	0.6	0.9	0.7	2.2
Overflow Loss @ 10% of Total (m^3/hr)	NA	2.1	1.7	3.8
Total (m^3/hr)	**0.6**	**3.0**	**2.4**	**6.0**

5. Modelling Outcomes

5.1 General Plume Behaviour

For the nearshore region of the dredging footprint (marine precinct, berth pocket), the general tidal currents are aligned along a north-east to south-west axis for the ebb and flood tides (Section 3.1.1). As a result, the dredge plumes are directed along this axis, with dredge plume impacts elongated to the southwest driven by the stronger flood tides in comparison to ebb tide.

The dredge plume impacts are most pronounced inshore from dredging of the sections SEQ1 to SEQ5 (Figure 3.4). This is due to the large volume of material being dredged at the seabed over a comparatively small spatial area. For the offshore sections of the channel (SEQ6 and SEQ7) the dredging requirements are spread out over a much larger area and the dredge plumes impact are significantly less. Additionally, the fines content is much higher inshore than offshore (up to 75% inshore compared with 38% through the offshore sections of the channel). Finally, the offshore current direction is more aligned with the general channel alignment and as a result the plume is often directed along the dredge footprint reducing impacts to regions outside of the main channel.

5.1.1 Spatial Extents of Modelled Dredge Plumes

5.1.1.1 Modelled Dredge Plume – Nearshore Section

Time series spatial mapping of the modelled plume for the inshore dredging at SEQ2 is shown in Figure 5.1 for the upper surface layer and Figure 5.2 for the seabed layer. The modelled dredge plume is shown at 2-hour intervals and a comparison of the surface and seabed layers from the model shows the surface layer experiences comparatively higher SSC within the immediate dredge channel footprint due to the influence of the overflow of fines from the hopper. At approximately 500m distance from the channel outlines the SSC from the surface layer and bed layer are consistent in Figure 5.1 and Figure 5.2. The depth averaged current velocity is shown in the spatial plots with the dredge plume entrained into the current. The current direction is shown to be changing through the spatial mapping plots, initially directed offshore (ebb tide) and then moving onshore (flood tide). The very high region of modelled SSC (>50mg/L) is seen from the dredging source within the confines of the channel, extending beyond the channel extents and decreasing at a distance from the channel as the plume disperses (Figure 5.1). The dredge plume area of influence extends a considerable distance to the southwest outside of the channel footprint on the flood tide.

5.1.1.2 Modelled Dredge Plume – Offshore Section

Time series spatial mapping of the modelled plume for offshore section SEQ6 is shown in Figure 5.3. The modelled dredge plume is shown at 2-hour intervals for the upper layer of the water column which experiences the highest SSC as a result of overflow from the hopper of fines. The plume is directed by the current velocity shown in Figure 5.3 based on depth averaged current direction. The current direction is shown to be changing through the spatial mapping plots, initially directed offshore (ebb tide) and then moving onshore (flood tide). The very high region of modelled SSC (>50mg/L) is generally contained within the confines of the channel with a rapid decrease in SSC level modelled outside of the channel. It is clear the plume impacts (SSC) outside of the channel at any time during the dredging is directly related to the direction of the tidal current. When dredging, modelled SSC is high at the location of the dredge and hopper in the model at up to 100mg/L. This high level of SSC is shown within the confines of the channel in Figure 5.3. Moving from the source and along the axis of the current direction, the modelled SSC in the plume reduces quickly. Generally, within 100m of the channel bounds the SSC reduces to 20mg/L or lower. Away from the main current direction on the lee side of the dredge plume the modelled SSC is almost at background.

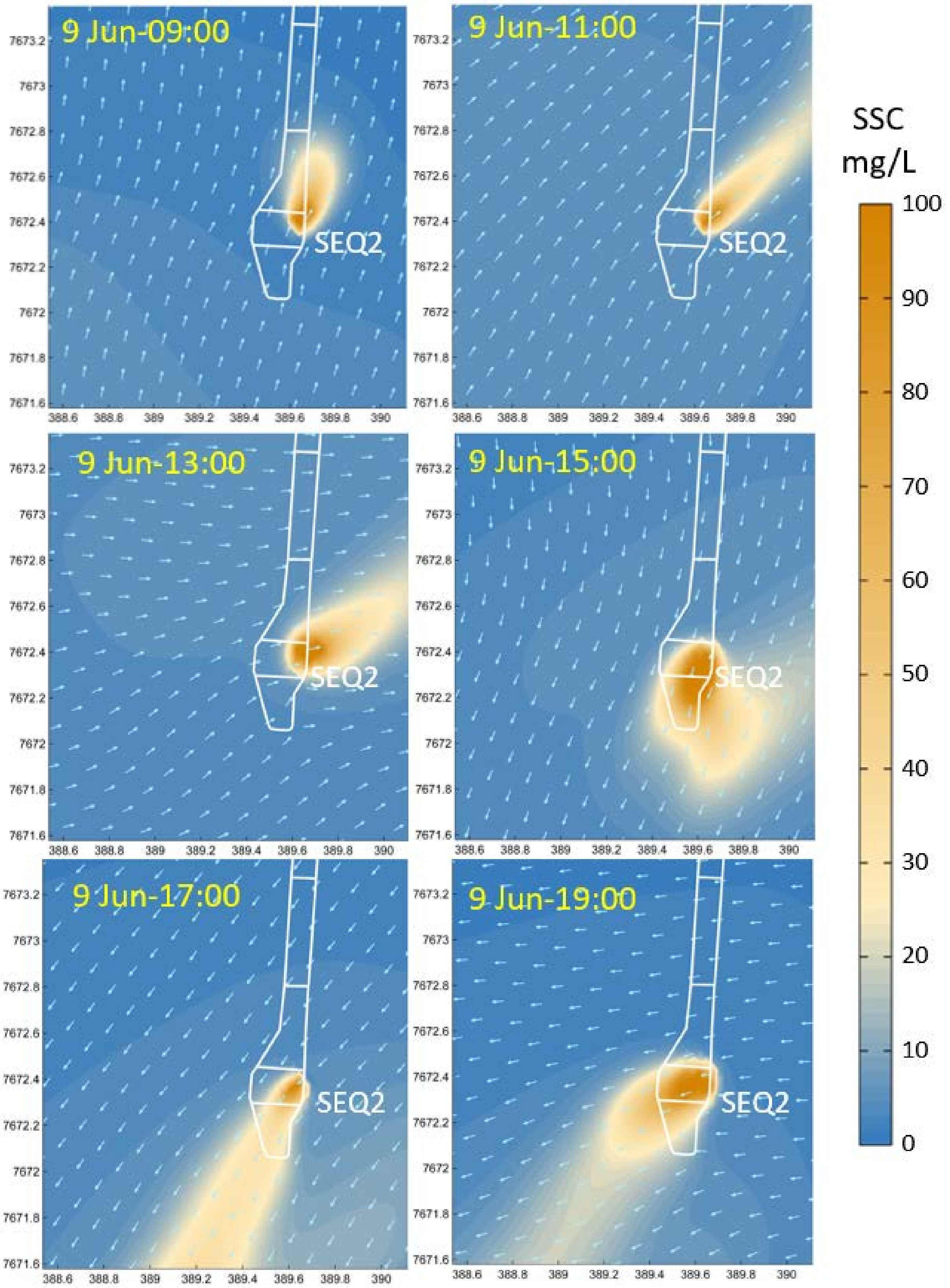

Figure 5.1: Modelled dredge plume results for SEQ2 showing modelled SSC in the upper water column (surface) at 2-hour intervals.

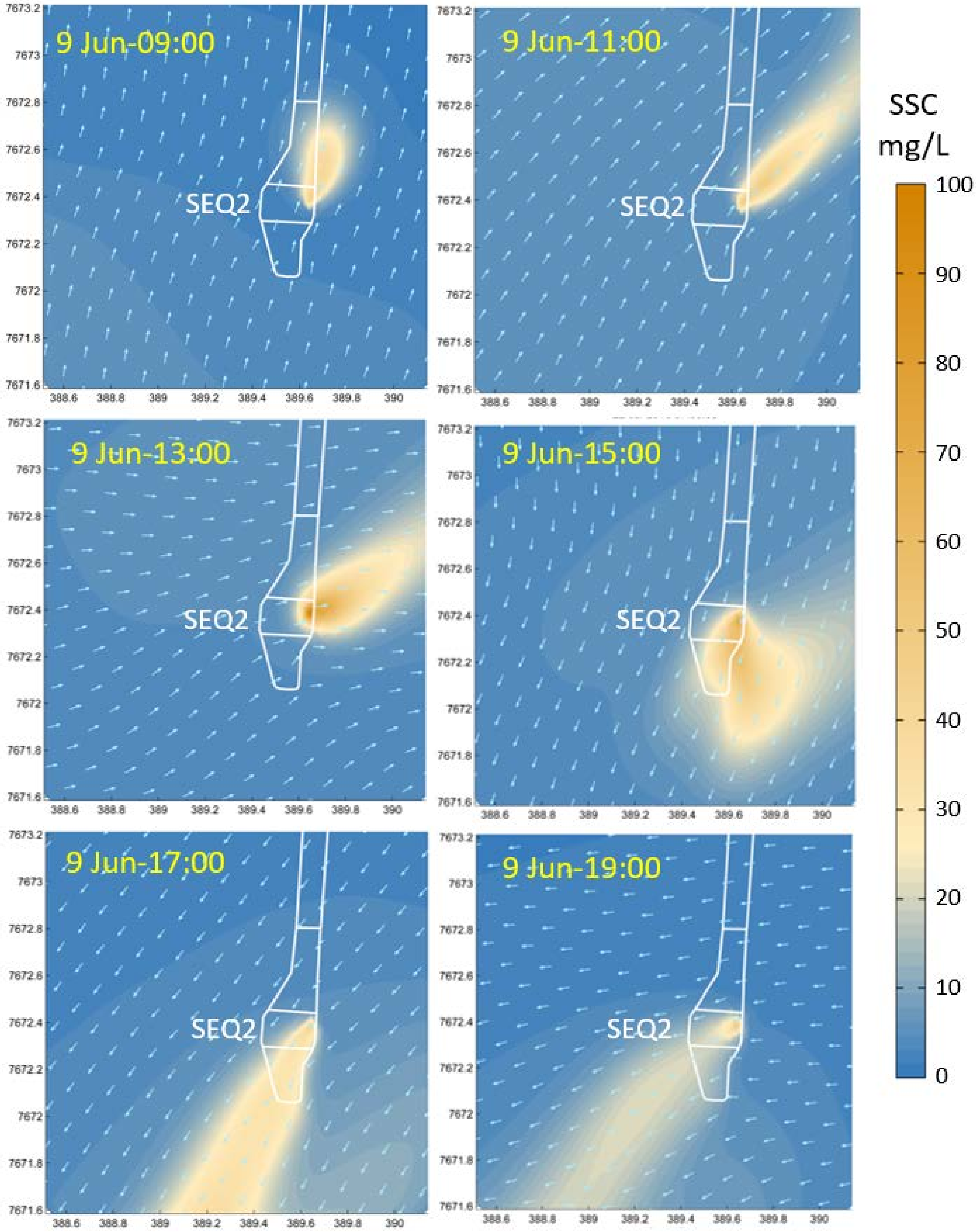

Figure 5.2: Modelled dredge plume results for SEQ2 showing modelled SSC in the lower water column (above seabed) at 2-hour intervals.

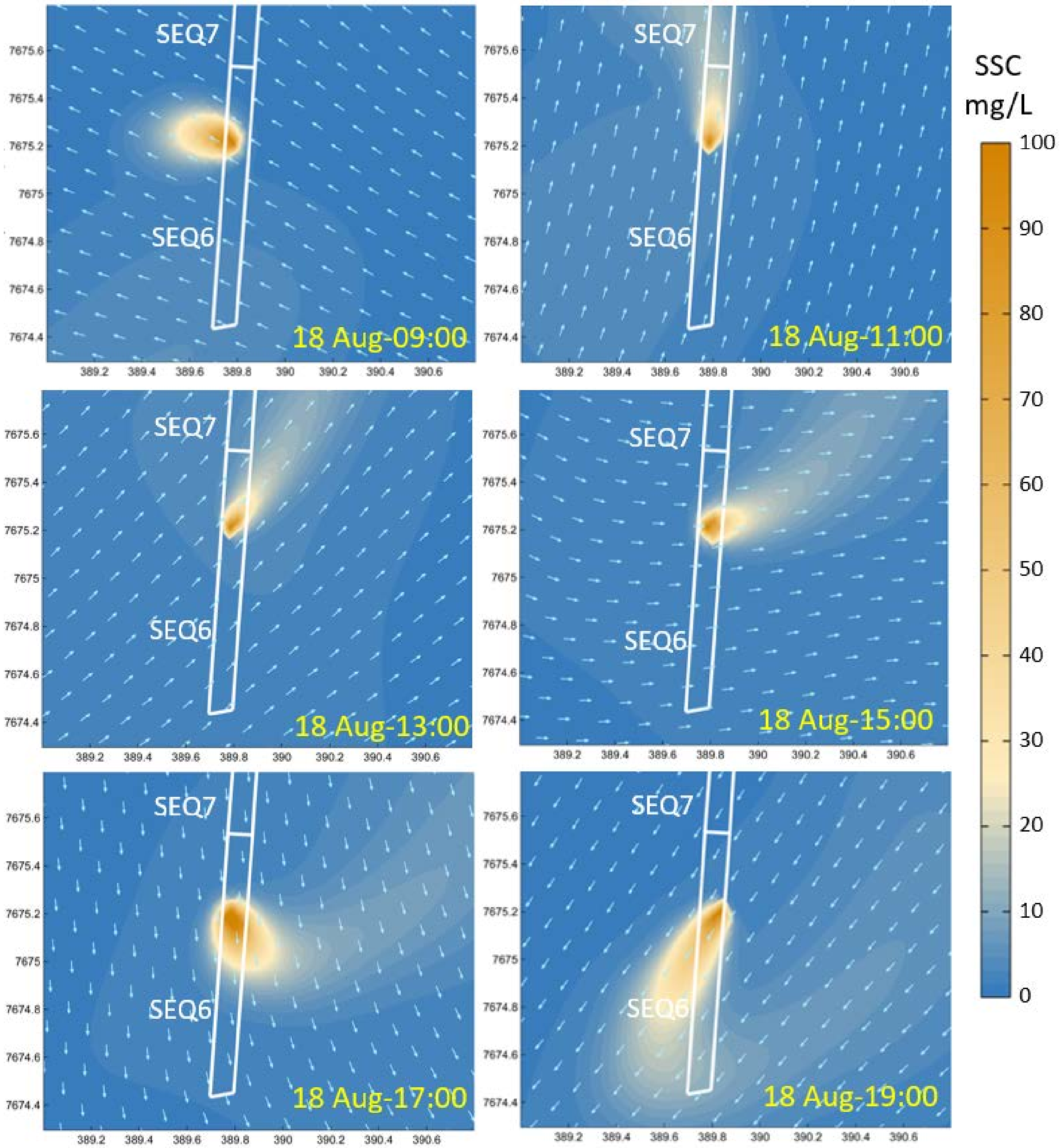

Figure 5.3: Modelled dredge plume spatial results for dredging in SEQ6 showing modelled SSC (mg/L) at 2-hour intervals with the dredge operating. Dredge plumes are shown for the upper water column where SSC is at its highest concentration.

5.2 Modelled Time Series Data through the Dredge Program

The modelled dredge sequences were compiled to provide a continuous time series of the dredging program for detailed analysis.

5.2.1 Modelled Time Series Year 1 – Inshore Areas

An example of the time series data from the dredge plume model in year one of the dredge program at inshore locations is shown in Figure 5.4. The modelled SSC from the sediment fractions (fine sand, silts, clays) are combined at each timestep in each respective vertical layer of the water column (5-layer 3D model). The modelled SSC is excess above background (mg/L) and the highest SSC through the water column at each location at each timestep is adopted in the time series plots in Figure 5.4.

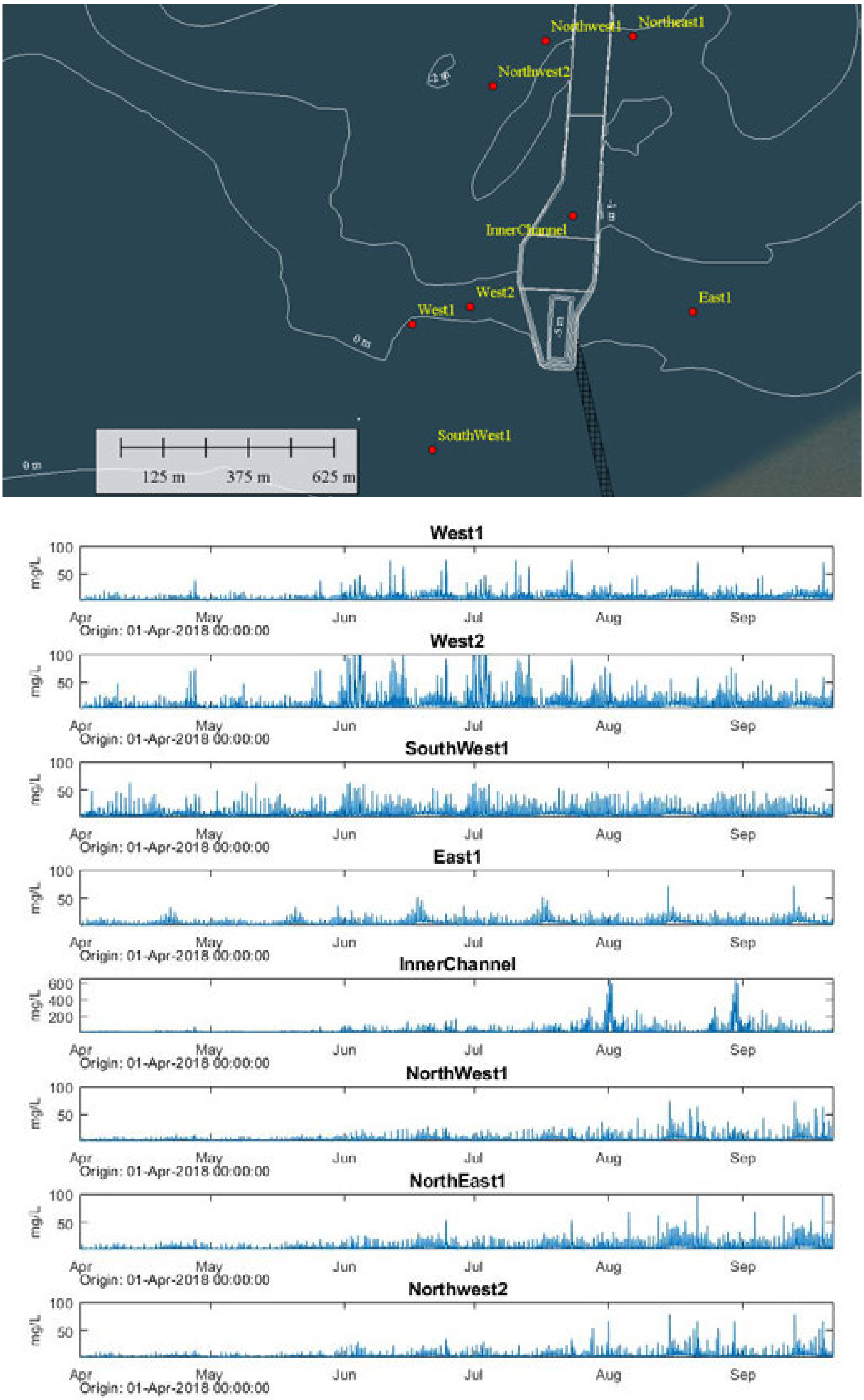

Figure 5.4: Modelled Suspended Sediment Concentration (mg/L) above background for locations around the Marine Precinct in Year One of dredging program (target dredging rate 2000m^3/day).

Analysis of the time series data from the first year of modelled dredge program indicates:

- The dredging is completed in the SEQ1 area over the April to May period, with modelled SSC in these months highest in West 1, West 2 and Southwest1 locations. The SSC reduces markedly between the West2 and West1 locations showing the dispersion of the SSC at a distance from the dredge plume source. At the same three locations the SSC increases in the June to September period as the SEQ2 and SEQ3 regions are dredged in the model which contain a higher fines content vs SEQ1.
- For the East1 location the SSC level is generally consistent through the dredging campaign and lower than SSC on the west side of the channel. This is likely due to the alignment of the plume and concentration along the NE-SW axis of the general current direction.
- The Inner Channel location SSC is far higher magnitude compared to locations outside the channel due to the proximity to the dredge operations. The SSC values peak when the SEQ3 is dredged in August and September adjacent the reporting location.
- Locations Northwest1, Northwest 2 and Northeast 1 show consistent SSC outcomes which peak in the August and September months as SEQ3 is dredged in close proximity.

For year one of the dredge program, the 99th percentile SSC values were calculated and are shown in Figure 5.5 as excess above background. The spatial plot does not represent a single moment in time, rather it shows the 99th percentile value in each grid cell over the approximate 6-month model period. The 99th percentile SSC values are very high in the dredged footprint (100mg/L to 300mg/L) and reduce away from the dredged channel to a value of 50mg/L or less within 500m. Within 1km of the dredged footprint the 99th percentile SSC has generally reduced below 20mg/L. The concentrated plume area in Figure 5.5 shows elongation to the southwest of the 50mg/L concentration (green) due to the tidal current axis and stronger flood tides noted previously in Section 3.1.1.

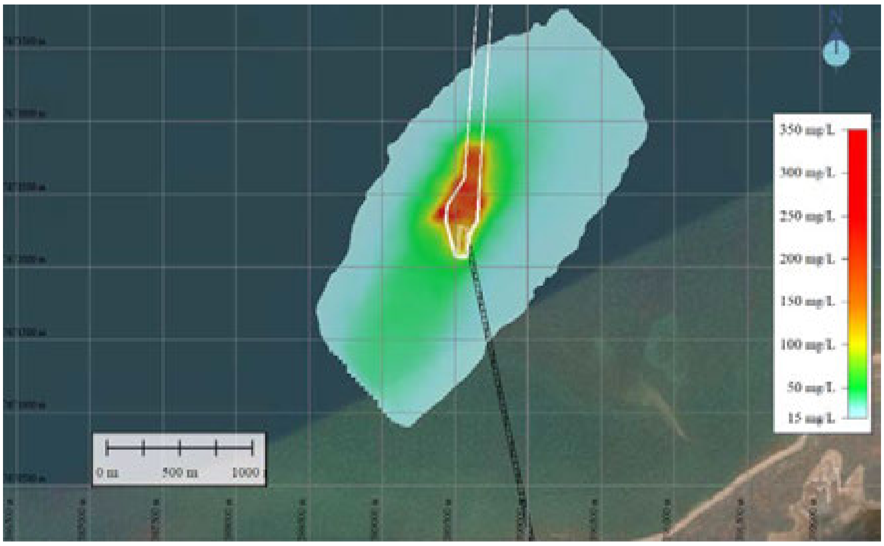

Figure 5.5: Modelled value of 99th percentile SSC through the first year dredging period. Values represent excess above background SSC (15mg/L to 350mg/L)

5.2.2 Modelled Time Series Year 2 – Offshore Areas

An example of the time series data from the dredge plume model in year two during dredging of the offshore areas of the channel is shown in Figure 5.6. Analysis of the time series data shows that the magnitude of the SSC offshore is lower than that modelled for the inshore locations (Figure 5.4). As the dredging is completed moving north over the scheduled dredging program, the peak SSC occurs through the offshore reporting locations when the dredger is in close proximity, however outside of these times the SSC is generally low.

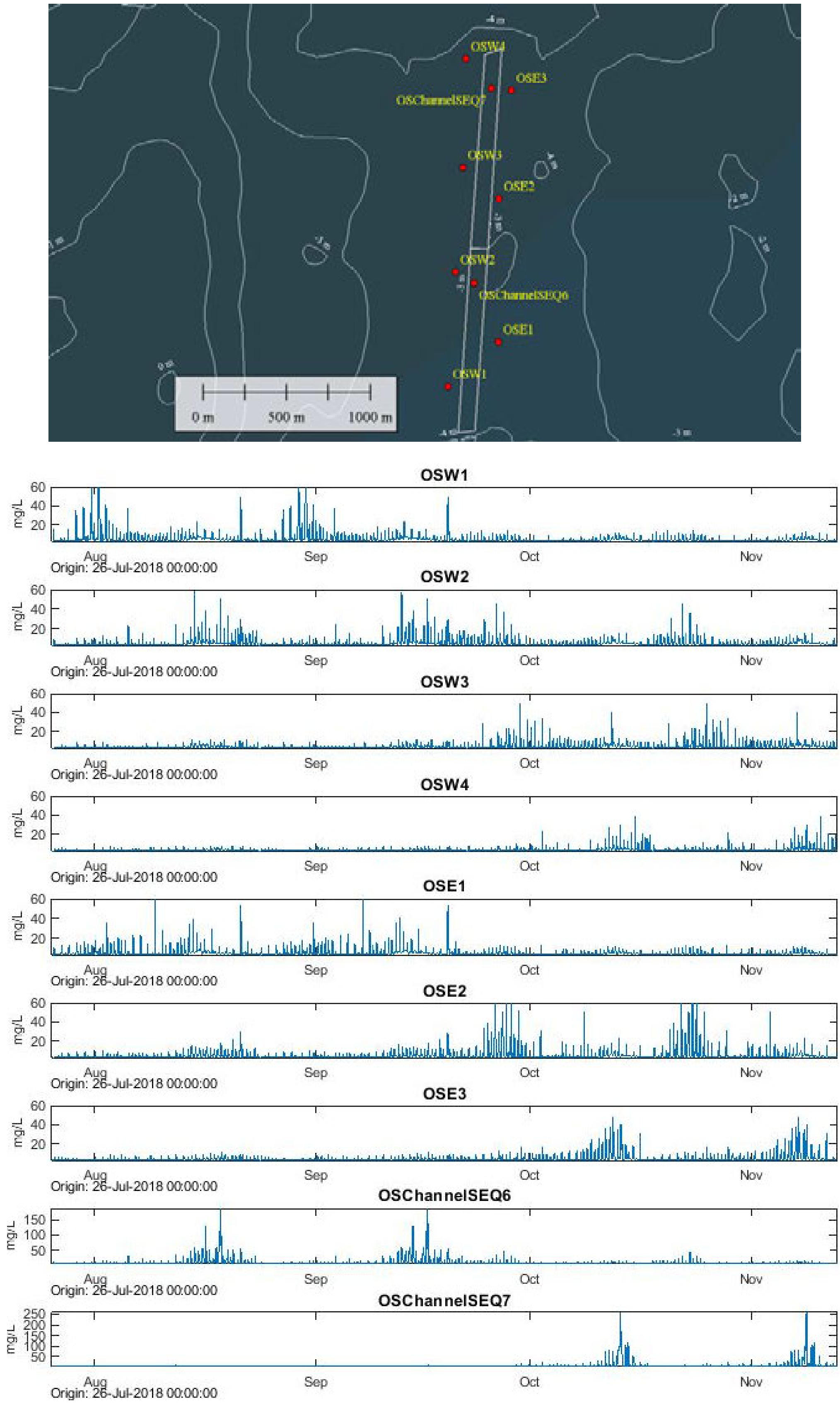

Figure 5.6: Modelled Suspended Sediment Concentration (mg/L) above background for locations in the offshore section of the dredged channel (based on target dredging rate 2000m^3/day).

5.3 Background Suspended Sediment Concentration

The Dredge Plume model simulations were executed with no background suspended sediment concentration (SSC). The model results represent excess above the background SSC.

Natural background SSC at Mardie will vary due to a range of factors. For the analysis of the model results and predicted extent, severity and duration of dredging impacts a background SSC was applied in the post processing of results based on analysis of historic MODIS imagery (MODIS, 2020) for the nearshore coastal waters around Onslow (MS Science, 2009). The analysis of the modelled data has been undertaken adopting a median background (50th percentile, P50) SSC value of 3.2mg/L.

5.4 Zones of Impact Calculation

The EPA has developed a spatially based zonation scheme for proponents to use as a common basis to describe the predicted extent, severity and duration of impacts associated with their dredging proposals (EPA, 2016g). The scheme consists of three zones that represent different levels of impact:

1. Zone of High Impact (ZoHI) is the area where impacts on benthic communities or habitats are predicted to be irreversible. The term irreversible means 'lacking a capacity to return or recover to a state resembling that prior to being impacted within a timeframe of five years or less'. Areas within and immediately adjacent to proposed dredge and disposal sites are typically within zones of high impact.
2. Zone of Moderate Impact (ZoMI) is the area within which predicted impacts on benthic organisms are recoverable within a period of five years following completion of the dredging activities. This zone abuts, and lies immediately outside of, the zone of high impact. The outer boundary of this zone is coincident with the inner boundary of the next zone, the Zone of Influence.
3. Zone of Influence (ZoI) is the area within which changes in environmental quality associated with dredge plumes are predicted and anticipated during the dredging operations, but where these changes would not result in a detectible impact on benthic biota. These areas can be large, but at any point in time the dredge plumes are likely to be restricted to a relatively small portion of the Zone of Influence.

5.4.1 Calculation Method for Zones of Impact

The calculation of the ZoMI and ZoHI areas from the dredge plume modelling has been completed based on analysis of the running mean of modelled SSC against possible and probable coral mortality thresholds, from the method presented in the recent work by Fisher et. al. (2019) and Jones et. al. (2019) from the Dredging Science Node of the WAMSI.

The time series dredge plume mapping output of suspended sediment is analysed spatially to calculate the running mean of SSC at 7-day, 14-day and 28-day periods across the grid over the dredge program. At each model grid point location, the modelled SSC value is defined at one-hour timestep through the dredging program. At each time step the SSC is calculated based on the combined total of all sediment fractions (clay, silt, sand). The results from the model are in 5 vertical layers through the water column and the level in the water column where the highest SSC occurs is adopted. The stratification of the plume is most pronounced adjacent the generation source with the SSC approaching uniform distribution through the water column at a distance away in the model.

The calculated running means were assessed against 7-day, 14-day and 28-day threshold limits for corals based on advice from O2Marine and work presented in Fisher et. al. (2019) as shown in Table 5.1. The ZoHI and ZoMI regions were categorised as those locations where the modelled running mean crossed the respective 7-day, 14-day or 28-day threshold at any point in the dredging program.

Table 5.1: Threshold Limits for Modelled Suspended Sediment Concentration used to define ZoMI and ZoHI regions through the dredge program (from Fisher et. al., 2019)

Threshold Type	Running Mean Period	ZoMI Threshold (>SSC)	ZoHI Threshold (>SSC)
Running Mean (SSC)	7 day	14.7 mg/L	24.5 mg/L
	14 day	11.7 mg/L	18.0 mg/L
	28 day	9.3 mg/L	13.2 mg/L

5.4.2 Best Case and Worst-Case Scenarios

The following conditions were analysed from the model results to determine ZoHI and ZoMI:

- The 'best case' scenario for dredge plume impacts is defined as the case where expected dredge production rate is achieved throughout the duration of the dredge program. The assumption is based on 2 x 10hr shifts per 24-hour period where 2,000m^3 / day is dredged. The dredge operates 7 days a week);
- The 'worst-case' scenario for dredge plume impacts is defined as the case where an upper limit dredge production rate is achieved throughout the duration of the dredge program. The assumption is based on 2 x 10hr shifts per 24-hour period where 2,500m^3 / day is dredged. The dredge operates 7 days a week);

The mapping output from the model was made available on a 60-minute time interval from 5 vertical layers. The SSC was analysed in all five model layers and the highest SSC through the water column at each location on the model output grid was adopted in the analysis at each timestep. As discussed in Section 5.1.1.1 the SSC is notably higher in the upper water column around the hopper overflow, when compared to the seabed, becoming more uniform at a distance away from the dredge footprint.

Running mean values of modelled SSC were calculated (7-day, 14-day and 28-day) and analysed against possible and probable coral mortality thresholds applying the method presented in Fisher et. al. (2019). This analysis has determined the zones of impact that will be used in the environmental monitoring and management program.

5.4.3 Analysis Steps

The process for calculating the ZoMI and ZoHI regions has utilised a custom Matlab algorithm which applies the following steps:

1. The dredge model output is a spatial grid on a 60-minute timestep. The grid points store the SSC value through the water column based on the combined sediment fractions from dredge plumes (total SSC from fine sand, silt, fine silt and clay).
2. The model is in 3D with the mapping at 5 vertical layers from the surface to seabed (units mg/L). The highest modelled SSC through the 5 layers of the water column in the model is adopted at each timestep in the analysis;
3. Modelled outcomes represent excess above background. Background SSC is added to the dredge plume model results adopting a P50 value of 3.2mg/L.
4. The algorithm calculates the SSC running mean over a 7-day, 14-day and 28-day period at every individual model grid location from the modelled time series data. This is done for year one and year two of the dredge program separately
5. Analysis of the calculated running mean against the 7-day, 14-day and 28-day thresholds (Table 5.1) is used to define the spatial extent of the ZoMI and ZoHI areas (based on Fisher et. al., 2019). The calculated ZoMI and ZoHI region is defined as a polygon area bounding the point where any of the 7-day, 14-day or 28-day running mean thresholds is exceeded during the dredge program;

6. The ‘Best Case’ ZoMI and ZoHI is assessed for model results developed for the expected dredging production rate of 2,000m^3/day. The ‘Worst Case’ is based on an upper limit production rate of 2,500m^3/day.
7. For the ZoHI, the spatial extent adopts a minimum distance from the dredged channel of 25m. For the ZoMI a minimum distance from the dredged channel of 150m is applied. These distances have been set as a conservative basis for including consideration of the coarse sand fractions assumed to fall out of suspension close to the source of dredging.

An example of the analysis of running mean SSC against the 7-day, 14-day and 28-day thresholds is presented in Figure 5.7 based on the target production rate of 2,000m^3 a day. The locations analysed are the points shown in Figure 5.4 as ‘West1’, ‘Inner Channel1’ and ‘East1’. From the analysis of Figure 5.7:

- West1 location is categorised as ZoMI as the 14-day and 28-day moving average cross the possible coral mortality threshold but stay just below the probable threshold in all categories;
- InnerChannel location is categorised as ZoHI as the 7-day,14-day and 28-day moving average cross the probable coral mortality threshold for all categories. The very high SSC spikes in August and September are associated with the close proximity of the dredging to the reporting location during completion of SEQ3; and
- At the East1 location, the calculated 7-day and 14-day running mean does not reach the respective coral mortality threshold. However, the 28-day running mean just reaches the 28-day threshold value and as a result this location is within the ZoMI.

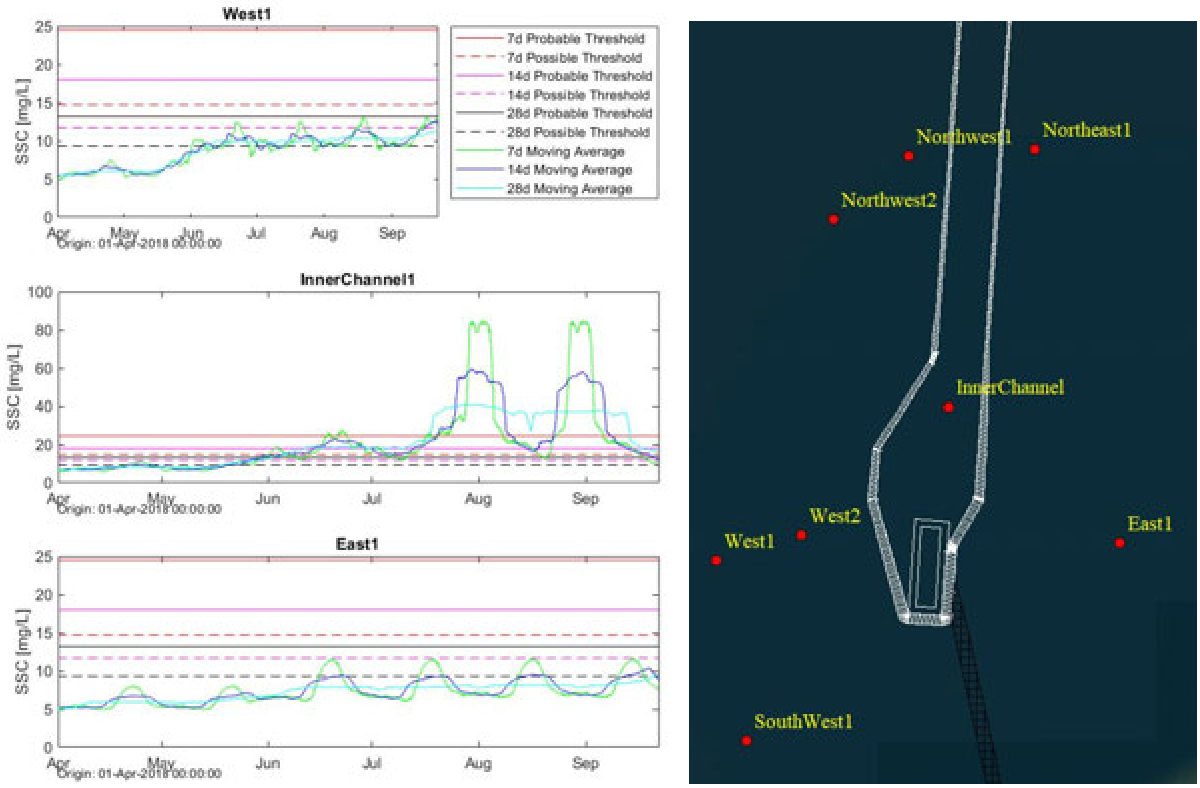

Figure 5.7: Calculation of Running mean values of modelled SSC analysed against possible and probable coral mortality thresholds (based on Fisher et. al., 2019). Analysis shown for the target dredge rate of 2000m^3 a day.

5.5 Final Calculated Zones of Impact

5.5.1 Inshore Dredging – Sequence 1 to Sequence 3

The modelled dredge plume impact regions are shown in Figure 5.8 for the inshore dredge sequence SEQ1, SEQ2 and SEQ3 covered in the first dry season period. This represents the analysis of 6 continuous months of dredging. The spatial extent of the zones of impact are shown for the target production rate of 2,000m^3/day ('best case') and upper limit 2,500m^3/day production rate (ie 'worst case').

- For the ZoHI the modelled impact region under the 2,000m^3/day target production case extends over a spatial area of 0.5km^2 and is a minimum 60m to maximum 180m from the edge of the dredged channel. Under the modelled 2,500m^3/day upper limit production case the ZoHI extends over a spatial area of 0.8km^2 and is a minimum 100m to maximum 390m from the edge of the channel
- For the ZoMI the modelled impact region under the 2,000m^3/day target production case extends over a spatial area of 2.5km^2 with a minimum 330m to maximum 1.4km distance as measured from the edge of the dredged channel. Under the modelled 2,500m^3/day upper limit production case the ZoMI region is 6.2km^2 with a minimum 460m to maximum 2.7km distance measured from the edge of the dredging. The plume extent is elongated along the southwest axis.

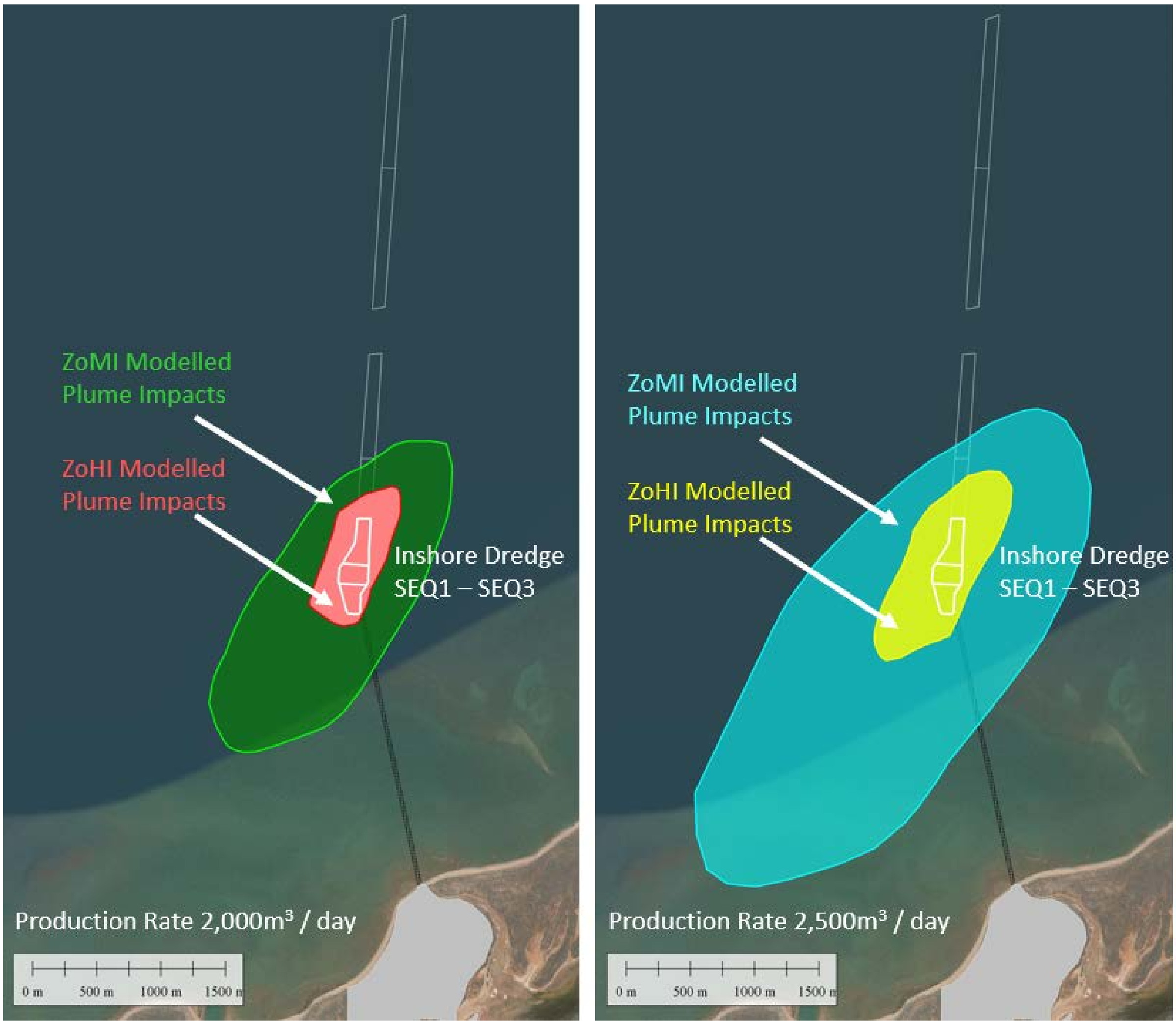

Figure 5.8: Calculated dredge plume impact areas for inshore Section SEQ1 to SEQ3. Left Image: Modelled dredge plume impact ZoMI and ZoHI based on target production rate 2,000m^3/day ('Best Case'). Right Image: Modelled dredge plume impact areas ZoMI and ZoHI based on upper limit production rate of 2,500m^3/day ('Worst Case').

5.5.2 Inshore Dredging – Sequence 4 to Sequence 5

The modelled dredge plume impact regions are shown in Figure 5.8 for the inshore dredge sequence SEQ5 and SEQ6. This represents the analysis of 4 continuous months of dredging. The modelled spatial extent of the zones of impact are shown for the target production rate of 2,000m^3/day ('best case') and the upper limit 2,500m^3/day production rate (ie 'worst case').

- For the ZoHI the modelled impact region under the 2,000m^3/day target production case extends over a spatial area of 0.5km^2 and is a minimum 60m to maximum 180m from the edge of the channel. Under the modelled 2,500m^3/day upper limit production case the ZoHI extends over a spatial area of 0.8km^2 and is a minimum 100m to maximum 390m from the edge of the dredged channel
- For the ZoMI the modelled impact region under the 2,000m^3/day target production case extends over a spatial area of 2.8km^2 and is a minimum 30m to maximum 1.9km from the edge of the channel. Under the modelled 2,500m^3/day upper limit production case the ZoMI extends over a spatial area of 6.5km^2 and is a minimum 180m to maximum 3.1km from the edge of the channel. The plume extent is elongated along the southwest axis.

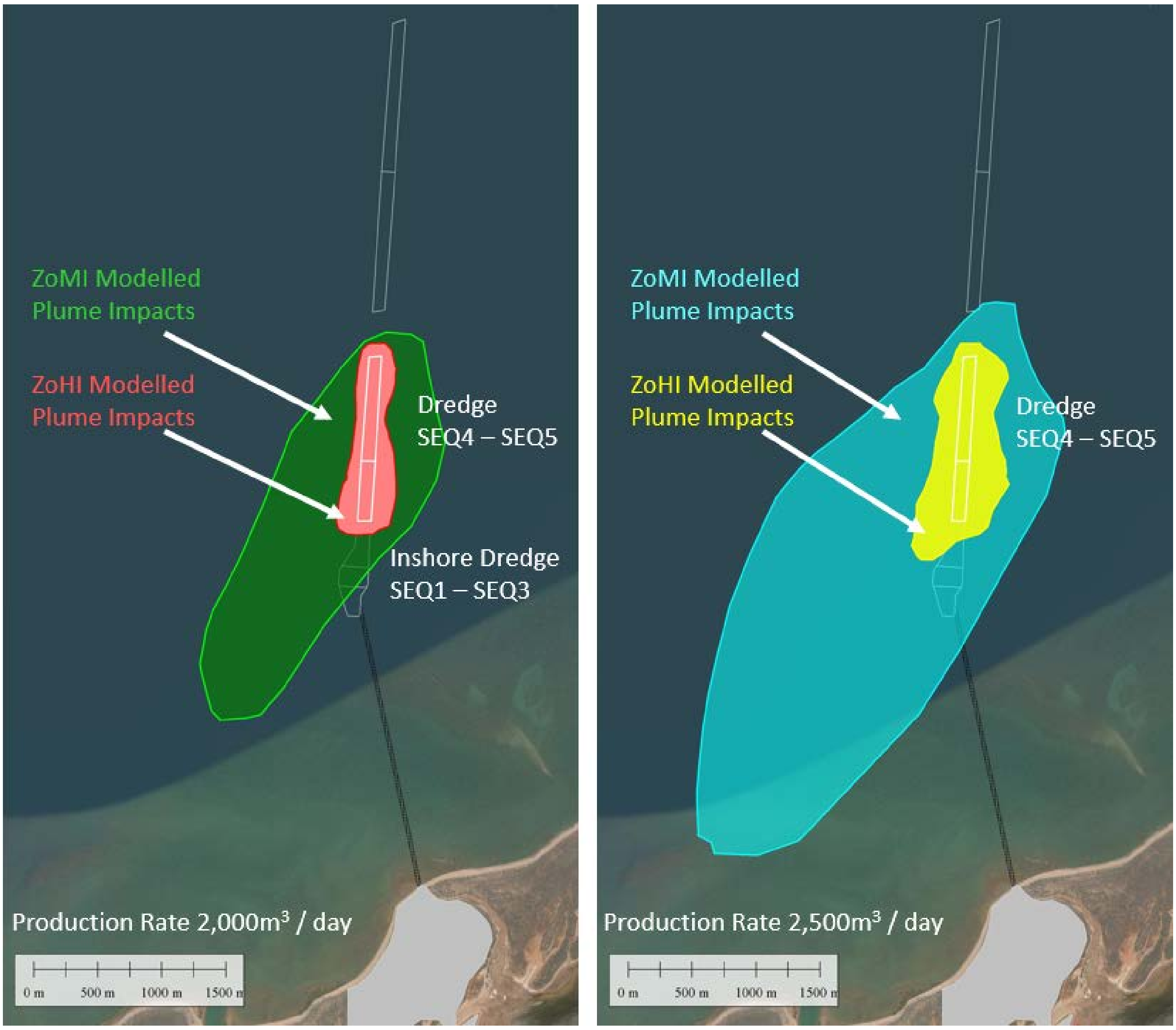

Figure 5.9: Calculated dredge plume impact areas for inshore Section SEQ5 to SEQ6. Left Image: Modelled dredge plume impact ZoMI and ZoHI based on target production rate 2,000m^3/day (best case). Right Image: Modelled dredge plume impact areas ZoMI and ZoHI based on upper limit production rate of 2,500m^3/day (worst case).

5.5.3 Offshore Dredging – Sequence 6 to Sequence 7

For the offshore dredge sections Sequence 6 and Sequence 7 the calculation method for the zones of impact is presented in Figure 5.10. The modelled dredge plume impact regions are much reduced compared to the inshore dredge region as previously discussed in Section 5.1. The modelled spatial extent of the zones of impact is shown for the 2,500m^3/day production rate (ie 'worst case') in Figure 5.10

- For the ZoHI the plume impacts are generally within 20m of the edge of the channel. The adopted ZoHI region is conservatively defined based on a 25m distance from the edge of the channel and shown as the yellow polygon.
- The ZoMI modelled dredge plume impact is shown in Figure 5.10 as a spatially varying region along the channel sections of SEQ6 and SEQ7. Conservatively the ZoMI extent adopted is defined by a blue polygon area 150m from the edge of the channel.

The modelled outcomes for the ZoMI and ZoHI under target production rate of 2,000m^3/day 'best case' are smaller than the regions shown in Figure 5.10. Applying the conservative approach outlined above, the adopted extents of the ZoMI are defined at 150m from the edge of the channel and the ZoHI at 25m from the edge of channel.

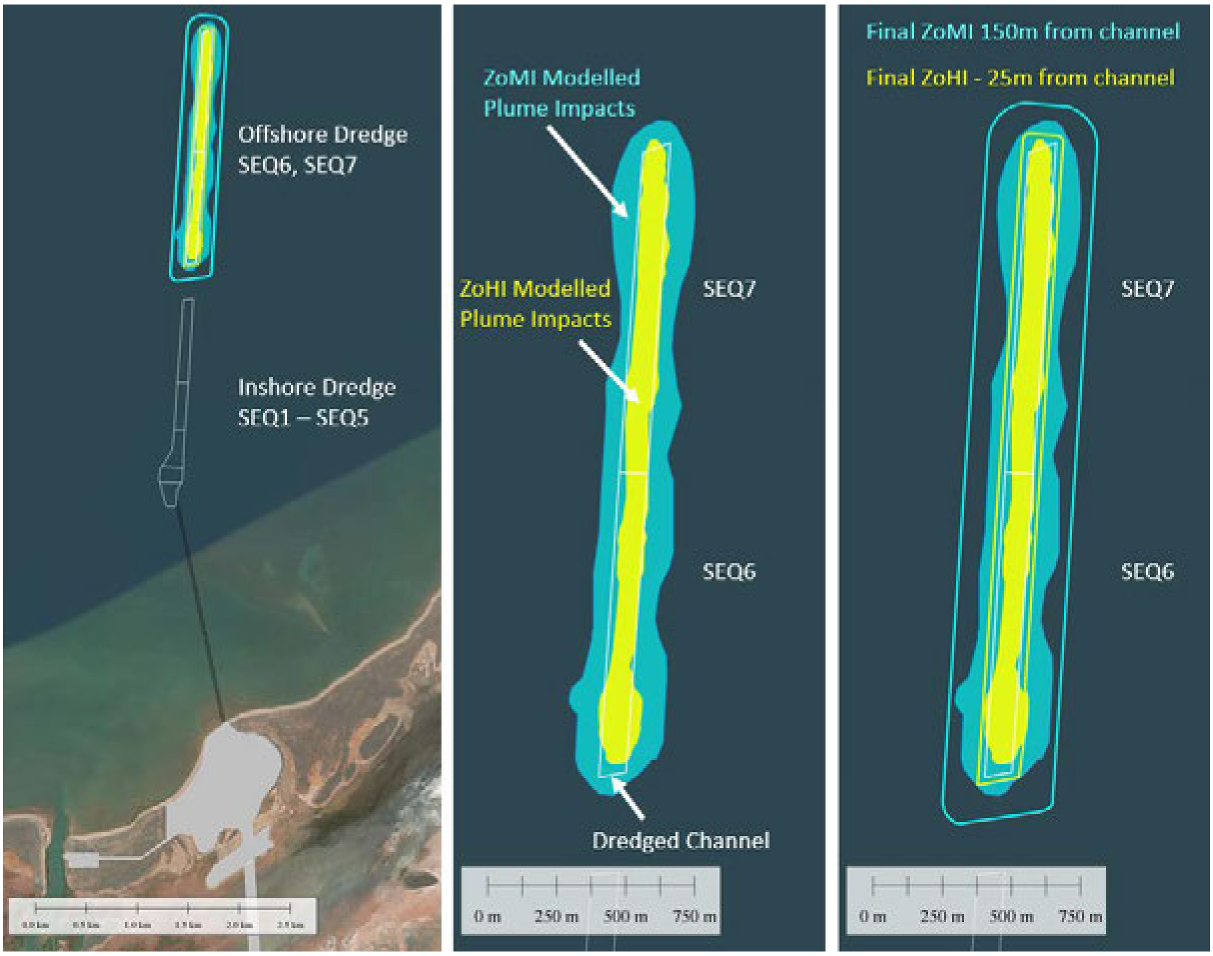

Figure 5.10: Analysis of Zones of Impact for offshore dredging in Sequence 6 and Sequence 7. Left image: Offshore dredging location. Middle Image: Modelled dredge plume impact ZoMI and ZoHI for offshore sections based on upper limit production rate (2,500m^3/day). Right image: Adopted ZoMI and ZoHI extents are shown as polygons based on adopting a minimum distance from edge of channel. ZoHI is 25m from channel, ZoMI is 150m from channel. Actual modelled results are shown spatially contained within the respective bounds.

5.5.4 Calculated Zones of Impact over Entire Dredge Campaign

The calculated zones of impact (ZoMI and ZoHI) have been compiled based on the complete dredging program. The spatial areas have been defined based on a polygon drawn around the extents defined in the presentations in Figure 5.8, Figure 5.9 and Figure 5.10. The zones of impact are presented in Figure 5.11 for the 'best case' (target 2,000m^3/day production) and Figure 5.12 for the 'worst case' (upper limit 2,500m^3/day production). A relative comparison of the spatial areas can be seen on the combined map in Figure 5.13:

- For the ZoMI the modelled impact region extends over a spatial area of 5.3km^2 for the best case to 9.7km^2 for the worst case; and
- For the ZoHI the modelled impact region extends over a spatial area of 1.2km^2 for the best case to 1.8km^2 for the worst case.

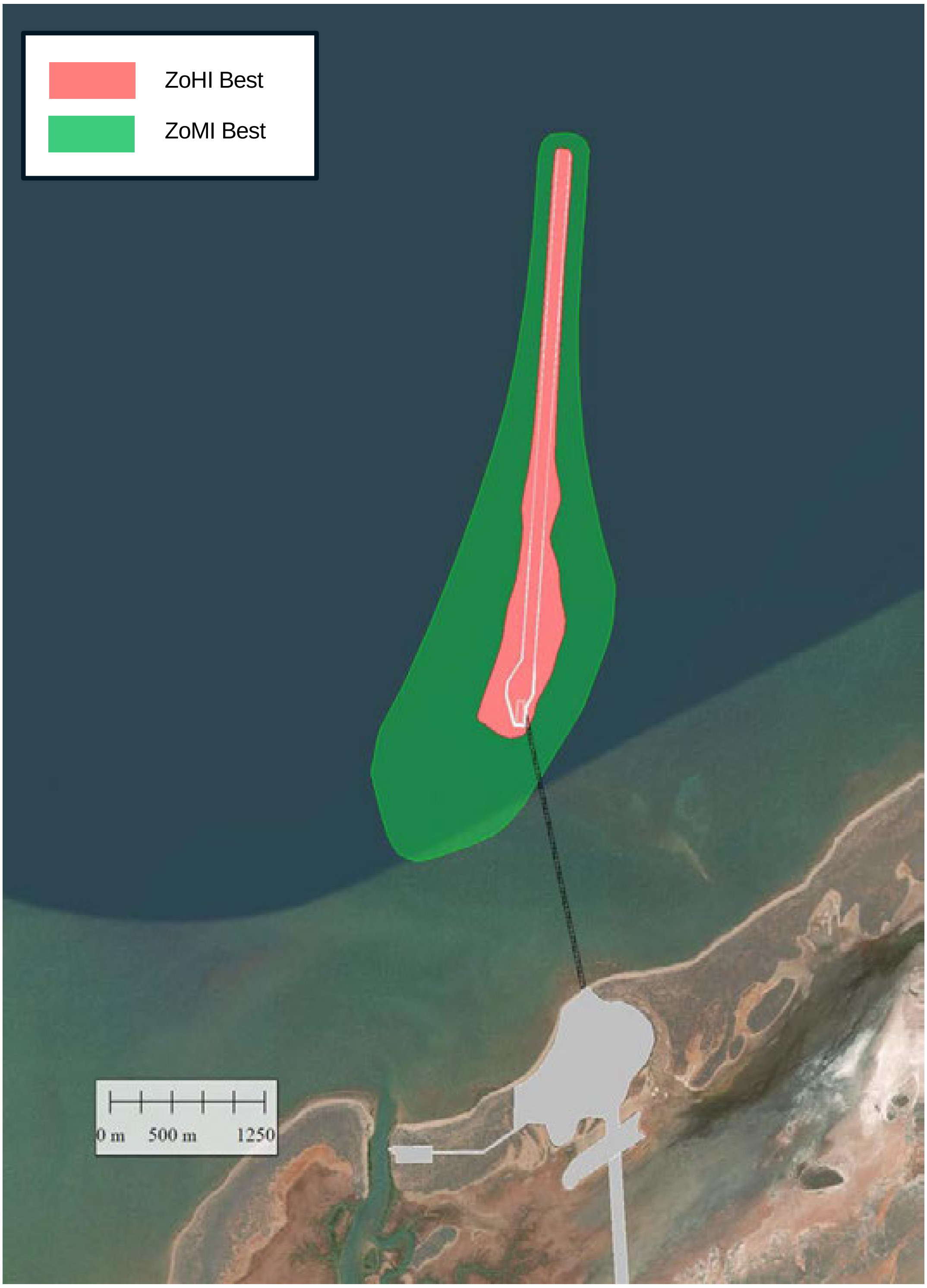

Figure 5.11: Calculated Zones of Impact for expected production rate scenario with a dredging rate of 2,000m^3/day ('Best Case'). Full dredge program.

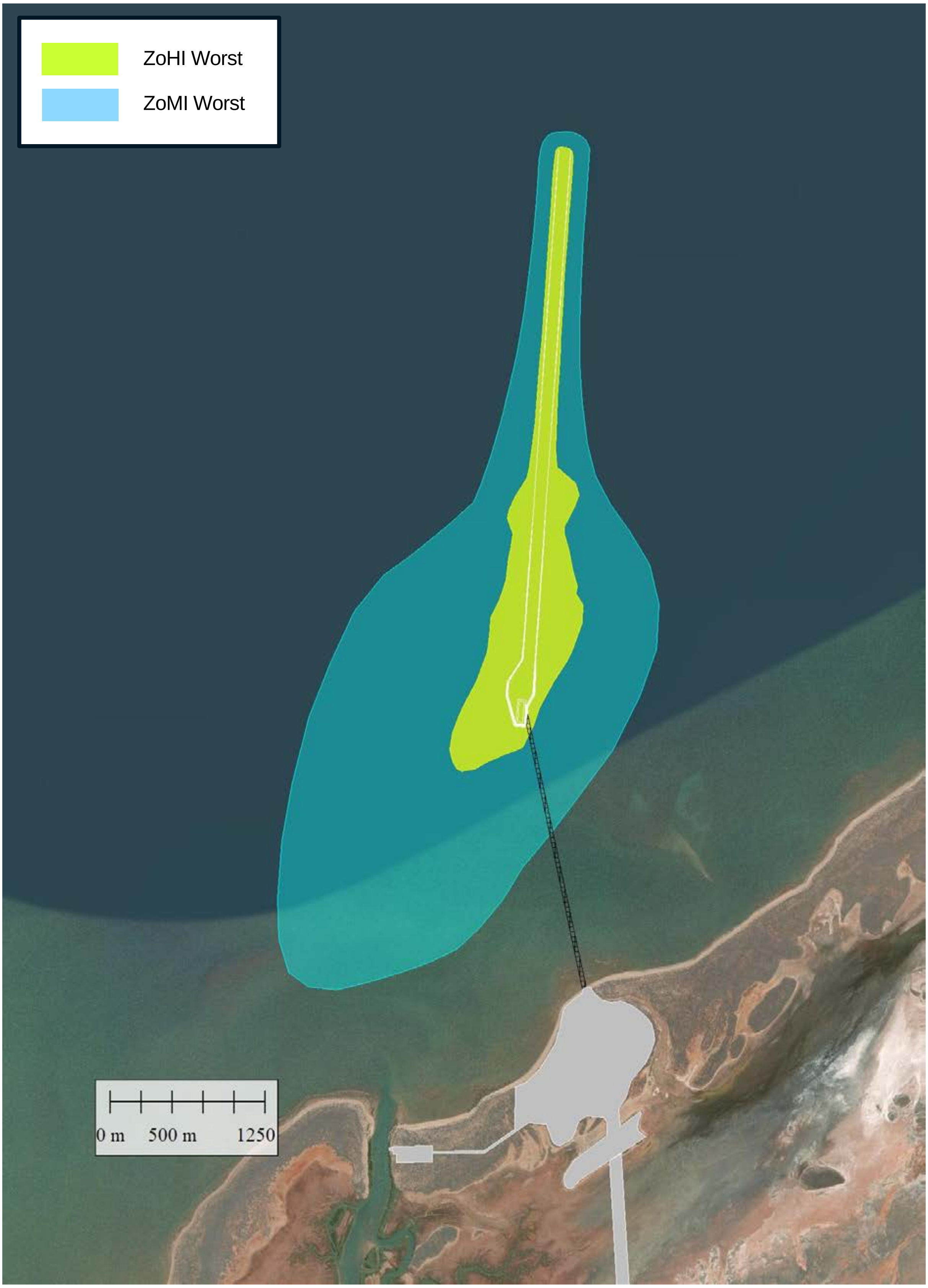

Figure 5.12: Calculated Zones of Impact for maximum production rate scenario with a dredging rate of 2,500m^3/day ('Worst Case'). Full dredge program.

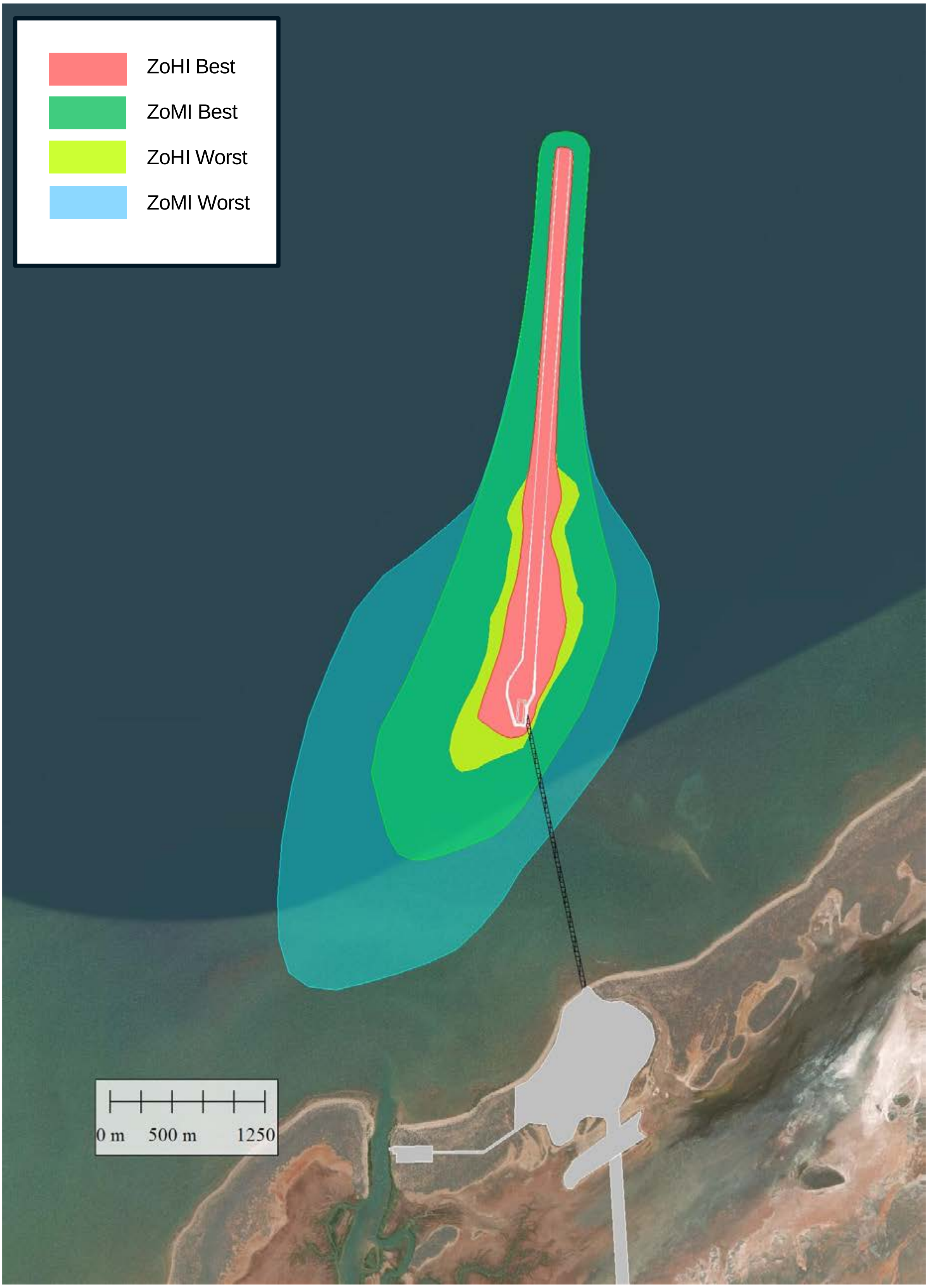

Figure 5.13: Calculated Zones of Impact (ZoMI and ZoHI) for 'Best Case' and 'Worst Case' Scenarios. Full dredge program.

6. Conclusions

The Mardie Project is a greenfields high-quality salt project proposed in the Pilbara region of Western Australia. Baird Australia Pty Limited (Baird) have been engaged by Mardie Minerals, a wholly owned subsidiary of BCI Minerals Limited (BCIM) to develop a hydrodynamic modelling program to support the environmental approvals process to assess:

- Modelling of dredge plumes to inform the preparation of a Dredging and Spoil Disposal Management Plan (DSDMP); and
- Modelling of mixing and dilution of bitterns discharge into the marine environment to inform the preparation of a Environmental Quality Plan (EQP).

The dredging requirements through the project footprint will require approximately 800,000m^3 of sediment to be removed from the seabed for disposal onshore. The dredging approach and methodology was defined by BCIM for incorporation into the dredge plume modelling process based on a backhoe dredge operating from a barge with a hopper alongside. Dredge rates adopted in the modelling process are based on a target production rate of 2,000m^3 a day, with a sensitivity case examined based on an upper limit production rate of 2,500m^3 a day.

An established Delft3D hydrodynamic model (Baird, 2020) was used as a basis for the dredge plume modelling program. The Delft3D Online Sediment model has been activated in the model to investigate the transport of fine sediments released through the dredging program in four representative fractions – fine sand, silt, fine silt and clay. There is a detailed geotechnical investigation and sediment sampling program which has informed understanding of the composition of the seabed material which will be dredged (CMW,2019). The dredge material is very high in fine sediments (clays, silts) representing between 38% and 75% of the material by volume in sections of the channel. The required volume of dredging material was calculated through the footprint based on high resolution multibeam survey (Surrich and EGS, 2019)) and requirements to achieve the target design depth which is -3.9m LAT in the channel and -6.7mLAT in the berth pocket.

Sediment plumes from dredging will be generated from 2 principal sources: mobilisation of fine sediments from the dredger bucket with each load and overflow water from the hopper barges. These have been input to the model as:

- 4% by mass of total fine sediments (fine sand, clay and silt fractions) lost as the bucket comes up through the water column from the seabed.
- 10% by mass of fines (< 62um) in suspension in the hopper discharging into the upper water column (conservative assumption).

The preparation of the time series inputs to the model cases were developed based on the dredging volume requirements and giving consideration to the geotechnical investigations and sediment sampling analysis of the seabed composition. Dredge sequences were established in the model to simulate the dredge program over two consecutive years of dry season conditions.

The modelling was completed without background concentration of SSC in the water column. For the analysis of the model results and predicted extent, severity and duration of dredging impacts a background SSC of 3.2mg/L was applied in the post processing of results based on P50 value of SSC analysed from historic MODIS imagery for the nearshore coastal waters around Onslow (MS Science, 2009).

For the nearshore region of the dredging footprint (marine precinct, berth pocket), the general tidal currents are aligned along a north-east to south-west axis for the ebb and flood tides (Baird, 2020). The dredge plumes are directed along this axis, with dredge plume impacts elongated to the southwest driven by the stronger flood tides in comparison to ebb tide. The dredge plume impacts are most pronounced inshore associated with dredging of large volumes of material over a comparatively small spatial area. For the offshore sections of the channel the dredging requirements are spread out over a much larger area and the dredge plumes impacts significantly less. Additionally, the fines content is much higher inshore than offshore (up to 75% inshore compared with 38% through the offshore sections of the channel).

The dredge plume model outcomes are examined as time series of SSC in Section 5. Analysis of the first year of the dredge program examining the 99th percentile SSC values shows these are very high in the dredged footprint (100mg/L to 300mg/L) and reduce away from the dredged channel to a value of 50mg/L or less within 500m. Within 1km of the dredged footprint the 99th percentile SSC has reduced below 20mg/L.

The Environment Protection Authority spatially based zonation scheme to describe the predicted extent, severity and duration of impacts associated with the Mardie project dredging have been determined through the processing and assessment of the dredge plume model results. The Zone of High Impact (ZoHI) and Zone of Moderate Impact (ZoMI) have been determined by analysing model results as running mean values of modelled SSC against possible and probable coral mortality thresholds applying the method presented in Fisher et. al. (2019).

The mapping output from the model was made available on a 60-minute time interval from 5 vertical layers through the water column. To analyse the modelled dredge plume impacts the SSC was combined from the 4 respective sediment fractions (fine sand, coarse silt, fine silt, clay) within each respective vertical layer. The highest SSC through the water column at each location on the model output grid was adopted at each timestep in the analysis. The ‘best case’ scenario for dredge plume impacts is defined as the case where expected dredge production rate of 2,000m^3/day is achieved throughout the duration of the dredge program. The ‘worst-case’ scenario for dredge plume impacts is defined as the case where an upper limit dredge production rate of 2,500m^3/day is achieved throughout the duration of the dredge program.

The final ZOMI and ZOHI for the Mardie project are presented spatially in Section 5 for application in the DSDMP.

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TAMS (2020), FT3 Backhoe Dredge Vessel Specification Sheet.

Appendix A

Summary of Final Mapping Datasets

Supplied Datasets

File	Filename
ZoMI Worst	MardieDredge2020_ZOMI_WorstCase_BgSSC_3.2mgL_2500m3dayProduction
ZoMI Best	MardieDredge2020_ZOMI_BestCase_BgSSC_3.2mgL_2000m3dayProduction
ZoHI Worst	MardieDredge2020_ZOHI_WorstCase_BgSSC_3.2mgL_2500m3dayProduction
ZoHI Best	MardieDredge2020_ZOHI_BestCase_BgSSC_3.2mgL_2000m3dayProduction