

SPECIALIST STUDIES – SECTION C

C2.2 The utility of hydrodynamic and biogeochemical numerical modelling to better inform the assessment of potential water column and benthic impacts of proposed dredging of marine phosphates in Mining Licence Area ML 170, Namibia

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C2.2 The Utility of Hydrodynamic and Biogeochemical Numerical Modelling of Dredge Plumes

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SUMMARY

Background

The Mining Licence Area (ML 170) proposed to be mined by Namibian Marine Phosphate (Pty) Ltd is located on the Namibian continental shelf approximately 60 km off the coast of Conception Bay. The area of the mining lease area covers 2 233 km² within which there are three areas identified for exploitation: Sandpiper-1 (SP-1), Sandpiper-2 (SP-2) and Sandpiper-3 (SP-3). It is proposed to exploit each area systematically over time starting in SP-1. The mining licence would be granted for 20 years and the company proposes to mine an area of approximately 3 km² annually, i.e. an area of 60 km² over the period licenced.

The Ministry of Fisheries and Marine Resources in its evaluation of the specialist assessment of possible negative impacts in the water column and sediments, determined that that plume modelling should be undertaken. The purpose of this modelling would be to provide a more robust assessment of the nature and scale of potential impacts. This request was further emphasised during a peer review exercise by Dr M. O'Toole, who recommended that a preliminary numerical model be assembled using the data gathered by the project to date (the 90 day instrument mooring deployment). However it is considered by Dr Robin Carter that the value of the insights gained from interpretation of prior assessments, along with a robust understanding of plume dynamics, will far out-weigh the value provided by any newly commissioned modelling study.

Purpose of the Review

The purpose of this review is to provide an opinion on:

- the utility of a plume modelling study in reducing any existing residual uncertainties in the specialist assessments of potential water column and benthic impacts associated with the proposed NMP Sandpiper dredging project to the extent that the reviewing authorities confidently would be able to make the relevant environmental decisions around the proposed project, and
- provide a recommendation on the best approach going forward.

The initial impact assessment (Lwandle in 2012 EIA) and subsequent verification study (Lwandle, 2014) suggest that the majority of the impacts associated with the project are expected to be physical (e.g. water column turbidity and possibly smothering of benthos¹) rather than biogeochemical. This was confirmed by subsequent reviews of these studies, suggesting that the only residual uncertainty remaining being the behaviour, extent and duration of the sediment discharge charge plumes. This is the focus of this review.

This review indicates that it is *possible (but not certain) that the actual plume dimensions may exceed the dimensions assumed in the Lwandle (2012 EIA) assessment* (i.e. plume dimensions may be up to 2 to 5 times larger than indicated). However, the implication of these potentially increased plume dimensions for the overall impact assessment and subsequent environmental decision-making is limited. Should the plume dimensions exceed those originally estimated in the Lwandle (2012 EIA) study, the extent of the plume reported in the impact assessment tables of that study may increase from being limited to the

¹ Smothering implies a sediment deposition rate exceeding a level beyond which benthic organisms would be unable to process through normal bioturbation activities.

“Immediate Dredge Area” (per vessel cycle) to affecting possibly the “Annual Mining Area (3 km²)”. It is not anticipated that this change in the extent of the impact would be such that it affected the “Specific Mining Site” (SP-1). Therefore it is not expected that these possible, but modest, changes in the impacted area will materially affect the environmental decision-making for this project.

Two possible modelling approaches have been assessed in terms of providing greater certainty on the behaviour, extent and duration of the sediment discharge plumes. The first approach, comprising large-scale modelling with a nested high resolution modelling domain, is not considered viable due to the time that will be required to undertake such a modelling study, the likely high costs of such an exercise and the very real risk that such an approach may not manage to further constrain any of the key uncertainties in the existing environmental impact assessment specialist studies.

An alternate approach comprising high resolution modelling of a limited area with the open boundary conditions being provided by existing measurements (i.e. the 90 days of existing current and water quality data), is considered viable in terms of cost, duration of the study and likely outcomes. Such modelling indeed will help to constrain some of the residual uncertainties in the assessments around plume extent and duration, e.g. associated with uncertainties in sediment loads, sediment characteristics, settling rates, etc. It will also better characterise the sensitivity of the impact assessments to possible changes in the rates of dredging and nature of material being dredged. However, as indicated above, any changes in the estimated extent of the impacted area indicated by such modelling are expected to be modest and unlikely to affect substantially the environmental decision-making surrounding this project. This modelling will provide a more explicit means (than the existing assessments) of constraining the uncertainties (listed above) and providing greater confidence in the assessed impacts based on the plume behaviour extents and duration. Should this be a priority, such a limited area, high resolution modelling study should be undertaken, despite the fact that the outcomes of such modelling are unlikely to change the significance of assessed impacts materially.

The measurements required to support the above modelling studies are similar to those required to assess plume dynamics and resultant impacts should it be chosen to make these assessments based on measurements alone. Specific requirements for the modelling study will include:

- Initial sediment concentrations and discharge parameters such as discharge volumes, flow rates, grain size distributions
- Initial concentrations of biogeochemical parameters of concern;
- Current meter measurements for the proposed simulation periods.
- Wind and atmospheric flux data (which can be obtained from global data sets such as National Centre for Environmental Protection (NCEP) data should it not be able to measure these using an offshore weather station);
- Water column structure measurements and water quality data: however should such data not be available, seasonal profiles based on historical data will need to be used.

Finally, should such modelling not be undertaken prior to the commencement of dredging operations, it is recommended that modelling form a key part of the verification and impact monitoring studies proposed for the early stages of the proposed dredging operations (e.g. by helping to inform the design of monitoring activities and in the interpretation of the resultant measurements). An appropriate model-based predictive capability is likely to prove invaluable should environmental constraints (over and above those already anticipated) need to be placed on dredging operations. Furthermore the development of a well-calibrated and validated model-based predictive capability is likely to prove invaluable for future environmental impacts assessments of a similar nature or should it become necessary in the future to assess potential cumulative impacts of marine dredging in these waters.

SCOPE OF WORK

The Mining Licence Area (ML 170) proposed to be mined by Namibian Marine Phosphate (Pty) Ltd is located on the Namibian continental shelf approximately 60 km off the coast of Conception Bay. The area of the mining licence covers 2 233 km² within which there are three areas identified for exploitation: Sandpiper-1 (SP-1), Sandpiper-2 (SP-2) and Sandpiper-3 (SP-3). It is proposed to exploit each area systematically over time starting in SP-1. The mining licence would be granted for 20 years and the company proposes to mine an area of approximately 3 km² annually, i.e. an area of 60 km² over the period licenced.

The Ministry of Fisheries and Marine Resources, in its evaluation of the specialist assessment of possible negative impacts in the water column and sediments (undertaken by Dr Robin Carter – Lwandle, 2012), determined that that plume modelling should be undertaken. The purpose of this modelling would be to provide a more robust assessment of the nature and scale of potential impacts. This request was further emphasised during a peer review exercise by Dr M. O'Toole, who recommended that a preliminary numerical model be assembled using the data gathered by the project to date (the 90 day instrument mooring deployment). It is considered by Dr Robin Carter that the value of the insights gained from interpretation of prior assessments undertaken by Dr Trevor Probyn and the CSIR (2006) for DeBeers Marine along with a robust understanding of plume dynamics, will far out-weigh the value provided by any new modelling study. The De Beers mining project was located to the south of the NMP MLA in water depths of 90 to 130 m. The modelling study was project-specific and validated with *in-situ* observations.

Given the conflicting views of Dr Robin Carter and those of Dr M. O'Toole, together with the views of MFMR, Namibian Marine Phosphate (Pty) Ltd requires a position statement from an independent, qualified and respected scientist that provides clarity on what would be the best approach going forward. Consequently this review was commissioned by Namibian Marine Phosphate (Pty) Ltd that has the objective of obtaining an independent professional opinion on:

- the utility of such plume modelling in better informing the assessment of potential impacts on the water column and benthic environment associated with dredging in ML 170 and consequently;
- provide a recommendation on the best approach to an additional assessment of potential dredging plumes, ranging from an expert opinion (based on a qualitative interpretation of existing data) to a comprehensive modelling study.

The purpose of such an additional assessment (model-based or otherwise) would be to ***reduce any existing uncertainties in the specialist assessments to the extent that the reviewing authorities confidently would be able to make the relevant environmental decisions around the proposed project.*** Specifically the additional information generated should be sufficient to allow the authorities to confidently provide support the project and issue the relevant environmental authorisations as appropriate.

The specific terms of reference for this study therefore are as follows. The independent scientist (modeller) should by independent assessment:

- provide a definitive statement on the optimum approach to be taken to deal with residual uncertainties in the project;
- indicate the relative merits of the proposed approaches (ranging from the existing expert opinion based on a qualitative interpretation of existing data and information to a comprehensive modelling study or some combination thereof) in providing an optimal outcome in terms of the scientific information generated to better inform environmental decision-making around the

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proposed project (*i.e.* provide an understanding of the nature and likely extent of potential impacts and the reduction of existing uncertainties in this regard);

- provide an assessment of monitoring data and measurements that would be required by each of the approaches considered (e.g. for calibration, validation or the set-up of modelling scenarios so that this can be included in ongoing environmental management practices and monitoring required for the project).

If the assessment undertaken here determines that an approach comprising more than an expert opinion based on a qualitative interpretation of existing data and information (*i.e.* a model-based approach as suggested by Dr M. O' Toole and MFMR) is likely to add sufficient value, then a clear indication must be provided of which aspects of the assessment(s) will be significantly improved and the likely extent in the reduction of uncertainty around these aspects of the assessments(s) that is expected from such a modelling study. Furthermore should such a modelling study be indicated, the likely duration and cost of such a modelling study is to be provided.



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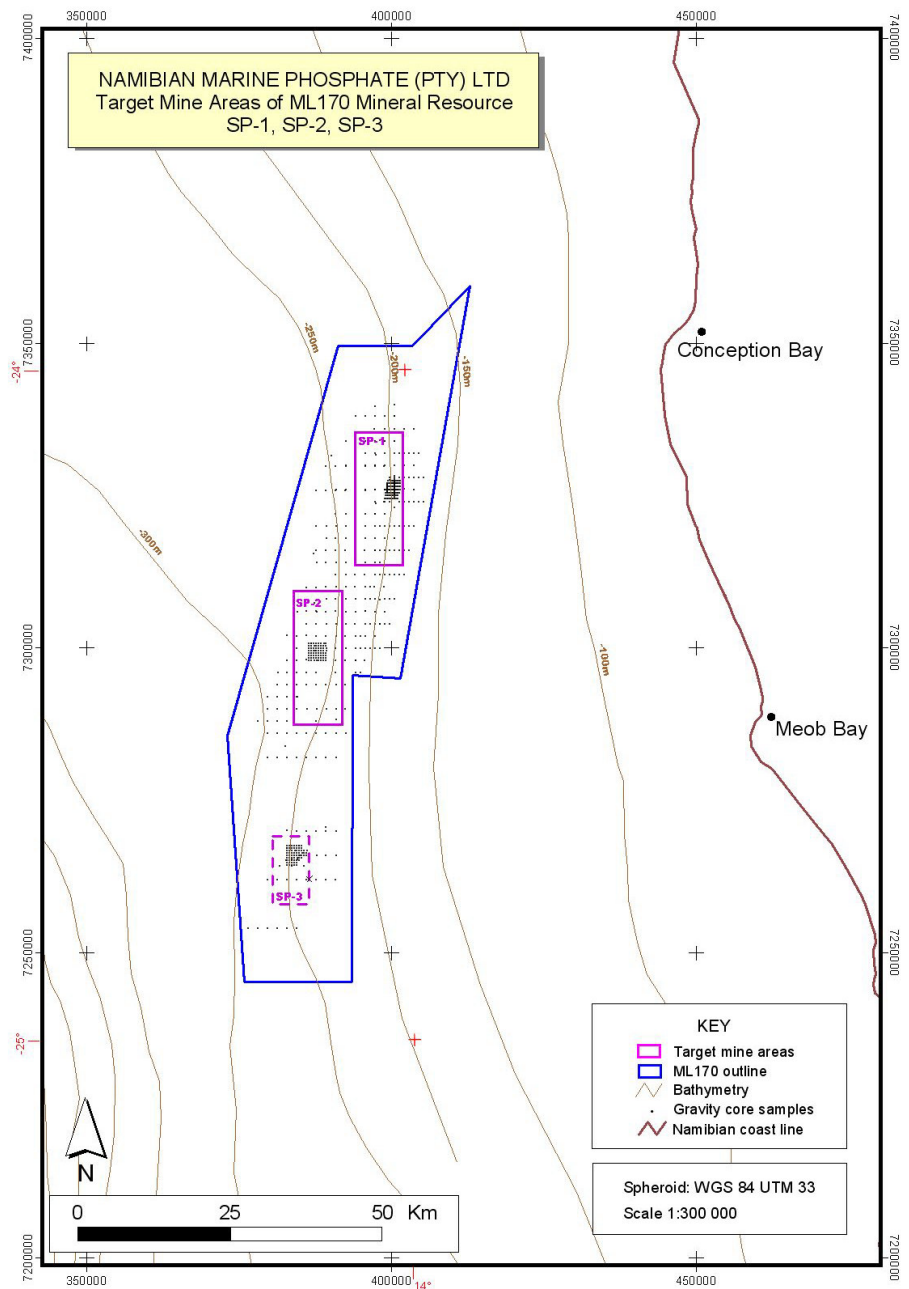
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1 INTRODUCTION

1.1 BACKGROUND

The Mining Licence Area (ML 170) proposed to be mined by Namibian Marine Phosphate (Pty) Ltd is located on the Namibian continental shelf approximately 60 km off the coast of Conception Bay. The area of the mining lease area (Figure 1.1) covers 2 233 km² within which there are three areas identified for exploitation: Sandpiper-1 (SP-1), Sandpiper-2 (SP-2) and Sandpiper-3 (SP-3). It is proposed to exploit each area systematically over time starting in SP-1. The mining licence would be granted for 20 years and the company proposes to mine an area of approximately 3 km² annually, which will lead to dredging an area of 60 km² over the period licenced.

Figure 1.1: The Mining Licence Area (ML 170) and the three areas that are proposed to be mined within the mining licence area.



The Ministry of Fisheries and Marine Resources, in its evaluation of the specialist assessment of possible negative impacts in the water column and sediments (undertaken by Dr Robin Carter – Lwandle, 2012), determined that that plume modelling should be undertaken. The purposes of this modelling would be to provide a more robust assessment of the nature and scale of potential impacts. This request was further emphasised during a peer review exercise by Dr M. O'Toole, who recommended that a preliminary numerical model be assembled using the data gathered by the project to date (the 90 day instrument mooring deployment). It is considered by Carter (Lwandle, 2012) that the value of the insights gained from interpretation of prior assessments undertaken by Dr Trevor Probyn and the CSIR (2006) for DeBeers Marine along with a robust understanding of plume dynamics, will far out-weigh the value provided by any new modelling study. The De Beers mining project was located to the south of the NMP MLA in water depths of 90 to 130 m. The modelling study was project-specific and validated with *in-situ* observations.

1.2 SCOPE OF WORK

Given the conflicting views of Dr Robin Carter and those of Dr M. O'Toole, together with the views of MFMR, Namibian Marine Phosphate (Pty) Ltd requires a position statement from an independent, qualified/competent and respected scientist that provides clarity on what would be the best approach going forward. Consequently Namibian Marine Phosphate (Pty) Ltd commissioned this review that has the objective of obtaining an independent professional opinion on:

- the *utility of such plume modelling in better informing the assessment of potential impact on the water column and benthic environment associated with dredging in ML 170*, and consequently;
- a recommendation on the best approach which could comprise an additional assessment of potential dredging plumes ranging from the *existing expert opinion (based on a qualitative interpretation of existing data and information)* to a comprehensive modelling study.

The purpose of such an additional assessment (model-based or otherwise) *would be to reduce any existing uncertainties in the specialist environmental impact assessments to the extent that the reviewing authorities would be able to confidently make the relevant environmental decisions around the proposed project*. Specifically the additional information generated should be sufficient to allow the authorities to confidently provide support for the project and issue the relevant environmental authorisations as appropriate.

The specific terms of reference for this review therefore are as follows. The independent scientist (modeller) should by independent assessment:

- provide a *definitive statement on the optimum approach to be taken to deal with residual uncertainties* in the project;
- indicate the *relative merits of the proposed approaches* (the existing expert opinion based on a qualitative interpretation of existing data and information to a comprehensive modelling study or some combination thereof) in providing an optimal outcome in terms of the scientific information generated to better inform environmental decision-making around the proposed project (*i.e.* provide the requisite understanding of the nature and likely extent of potential impacts and the reduction of existing uncertainties in this regard);
- provide an assessment of *monitoring data and measurements* that would be required by each of the approaches considered (e.g. for calibration, validation or the set-up of modelling scenarios)

so that this can be included in ongoing environmental management practices and monitoring required for the project).

If this assessment undertaken here determines that an approach *comprising more than an expert opinion based on a qualitative interpretation of existing data and information* (i.e. a model-based approach as suggested by Dr M. O' Toole and MFMR) is likely to add sufficient value, then a clear indication must be provided of *which aspects of the assessment(s) will be significantly improved and the likely extent in the reduction of uncertainty around these aspects of the assessments(s) that can be expected from such a modelling study*. Furthermore should such a modelling study be indicated, the likely duration and cost of such a modelling study is to be provided.

1.3 REVIEW APPROACH

The approach taken in this review is first to summarise the key findings of the existing impact assessment studies and assess the uncertainties that remain with respect to each of the key findings (Section 2). An evaluation of those aspects of the assessments of plume behaviour, extent and duration assessments (i.e. physical and biogeochemical processes) needed to resolve the residual uncertainties in the environmental impact assessments, is given in Section 3. Here the robustness of the existing impact assessments is reviewed. A clear indication is given of the sources of uncertainty in the existing assessments and the uncertainties that will remain should these not be fully resolved in a modelling study.

In Section 4 a brief summary of existing modelling platforms and modelling expertise available for making the relevant assessments is provided. Given the *inherent capabilities* of the models and *existing data* to support such modelling activities, an assessment is made whether the proposed approaches to the modelling studies will be able to reduce significantly the residual uncertainties of concern in the existing specialist assessments. Two potential modelling approaches will be considered and their relative merits assessed in terms of their ability to reduce residual uncertainties in the assessments and their likely cost and duration.

Should the review indicate that such modelling studies are required and that the data available to undertake such modelling studies are insufficient to warrant a modelling study at this time, recommendations are made as to the nature of model that should be set up and the likely data requirements to support such modelling. An assessment of monitoring data and measurements that would be required for each of the proposed modelling approaches in terms of model calibration, validation and the setting up of modelling scenarios is included in Section 5. This information is required so that the relevant measurement activities can be included into ongoing environmental management programmes.

2 KEY FINDINGS OF THE RELEVANT EIA SPECIALIST STUDIES

The proposed dredging method will:

- Directly modify the seafloor in the dredged area;
- Redistribute fine sediments to the adjacent seabed;
- Modify benthic community structure in the mined area;
- Affect seawater quality through re-suspension of sediments at the dredge head and discharge of lean water from the dredger's hoppers, possibly modifying dissolved oxygen distribution through either relocating hypoxic water in the water column or exposing anoxic pore water in the sediments. This can also apply to methane, hydrogen sulphide and contaminants that may be held within the dredge area sediments;
- Import alien and/or noxious organisms into the region via ballast water discharges from the dredger on first entry to the project area;
- Possibly affect fish and fisheries;
- Possibly disturb marine mammals and seabirds; and
- Possibly compromise other ecological services such as eco-tourism etc.

The focus here is on potential water quality effects of dredging and risks associated with ballast water discharges (bullets 4 and 5 above) and to a lesser extent benthic impacts (bullets 1 to 3).

Water column impacts

The initial specialist report on potential water column impacts (Lwandle, 2012) comprised a desktop study that considered a number of potential impacts on the water column from the dredging activities. The eleven potential impacts considered were:

- Pollution from discharged vessel wastes;
- Ecosystem disruption by alien species discharged with ballast water;
- Organisms adversely affected by suspended sediments in the water column;
- Toxicity from released hydrogen sulphide in the water column;
- Reduction in dissolved oxygen in the upper water column from introduced anoxic bottom waters;
- Increased nutrients promote phytoplankton growth and ultimately reduce dissolved oxygen concentrations;
- Trace metals (cadmium and nickel) discharged with the overspill affect organisms in the water column;
- Benthic organisms are exposed to remobilised cadmium and nickel in the dredge areas on the seabed;
- Benthic and/or demersal organisms are exposed to an increased flux of dissolved H₂S into the lower water column;
- Benthic and/or demersal organisms are exposed to anoxic sediments and lowered oxygen levels on the seabed; and
- Removal of thiobacteria mats by dredging increases the flux of H₂S to the lower water column.

This assessment on the likely utility of plume modelling in reducing uncertainty in the assessed impacts, is limited to the impacts in the highlighted text box above. Plume modelling will not be able to improve assessment of the potential impacts listed in bullets 1 and 2 above. The impacts assessed in this review are summarised in Figure 2.1 below (adapted from Lwandle, 2012).

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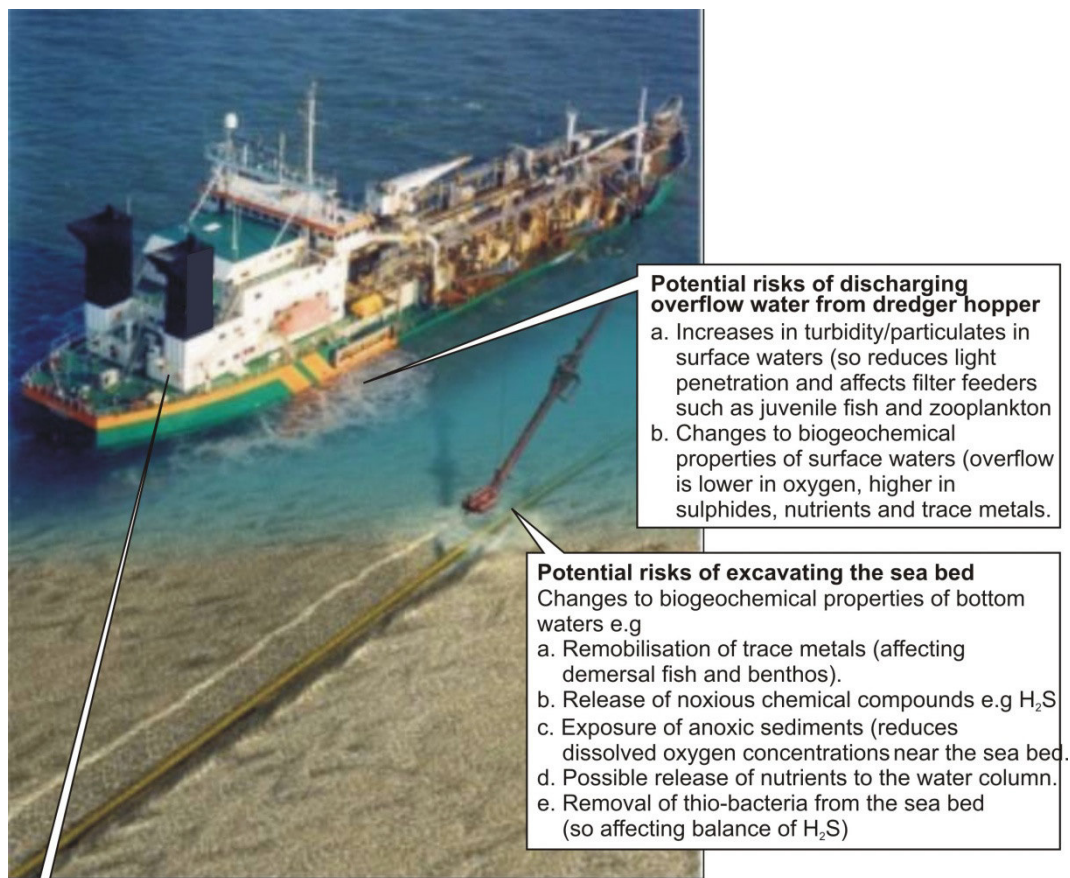


Figure 2.1: Risks to water quality from operation of a Trailer Suction Hopper Dredger at sea (adapted from Lwandle, 2012).

The water quality impact assessment (desktop) study concluded that, apart from the risk of ecosystem impacts from the introduction of alien species, all the others were of low significance or not of significance. A verification study was undertaken to reduce residual uncertainties in the initial impact assessments (Lwandle, 2014). Acknowledged limitations of the initial study are:

- while the impacts of the proposed dredging were assessed, it is not be possible to assess cumulative or additive effects of the dredging operations and other activities such as industrial fishing (demersal trawling), until the effect of these other activities are similarly quantified.
- the confidence levels awarded to the impact assessments show that there is some uncertainty about the biogeochemical properties of the sediments in the proposed dredging areas. This should be resolved by investigations specific to the dredging areas either prior to commencement of dredging or in its early/initial stages. Of particular relevance are the overspill plume characteristics and behaviour. Should investigations show that the impacts are more severe than predicted, then real-time controls on, for example, exceeding established thresholds for turbidity, dissolved oxygen, H_2S , etc. would need to be used to manage the dredging operations.

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The scope of the verification survey undertaken was based on key concerns raised by NatMIRC and other external reviewers of the NMP EIA report (2012) as abstracted below (Lwandle, 2014):

- The currents and circulation information in the EIA studies were primarily taken from regional scale circulation modelling and other published sources. There is uncertainty on the applicability of this to the proposed dredging area.
- Similarly, important features of the water column were generalised from regional and possibly outdated information; this needs to be focused on the dredging area.
- Sediment characteristics vary zonally and longitudinally on the Namibian continental shelf, *extrapolation from measurements to the north and south of the proposed dredging area may not be safe leading to uncertainty* on whether:
 - the adduced sediment particle size and sediment texture apply;
 - the sediment bed is resistant to suspension (sediment water content/porosity and presence/absence of armouring);
 - the *in situ* organic content (POM) and molar carbon/nitrogen (C/N) ratios are as predicted;
 - sediment pore water departs from Redfield ratios, specifically in terms of inorganic nitrogen and phosphate ratios;
 - sediment heavy metal contents are within the published guidelines for the region and whether those that are not are likely to be biologically available, and
 - the sediments are sulphidic or likely to release hydrogen sulphide (H₂S) during dredging?
- The available ancillary biological data presented (sediment meiofauna, macrofauna and presence/absence of thiobacteria and (thio) bacterial mats required refinement to add confidence to the impact assessments.

The verification study (Lwandle, 2014) was required to address the above issues, particularly:

- the characterisation of the prevailing currents and water column structure, and;
- the characterisation of the sediments in terms of the parameters listed above.

The characterisation of the prevailing currents and water column structure is important in determining the transport and fate (dispersion) of suspended sediments and other biogeochemical or potentially toxic components of concern, while the characterisation of the sediments largely is required to determine the initial loading of biogeochemical or potentially toxic components of concern (low oxygen water, H₂S, trace metals, etc.). The characterisation of the sediments and the nature of the initial loading of biogeochemical or potentially toxic components of concern also have relevance in terms of transformation processes that may affect the transport and fate assessments (i.e. provide insight into the non-conservative behaviour of the constituents of concern when undertaking the plume modelling transport and fate assessments).

The results of the verification study (Lwandle, 2014) are summarised below.

- Currents measured during two mooring periods (MSI, 2014 a,b) were as expected for the region displaying uniform north westward flow at the surface and varying poleward and equatorward flow in the bottom of the water column. Near seabed current velocities averaged 18 cm/s for poleward flow and 9 cm/s for equatorward flow. Peak flows recorded were approximately 30 cm/s. Profiling of the water column indicated a reasonably strong variability over 5 days in the upper mixed layer and thermocline depths. Clearly evident in these data were the effects of

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local wind mixing as well as advection of water masses into the region². Also reported were a general decrease in velocities with depth except for near the seabed where flows were relatively large. In this respect these data differ from those measured by the CSIR (2006) which indicated a general decrease in velocities with depth. Similar to the currents reported in CSIR (2006), the flows at depth often opposed those nearer the sea surface. The two measurement periods reported in the verification study also indicated quite different current regimes near the seabed, the earlier mooring indicating persistent southwards flow at depth (MSI, 2014 a) and the later mooring data more variable flow both northwards and southwards (MSI, 2014 b).

- The dominant water mass present in the area during the survey period was South Atlantic Central Water with origins in the Cape Basin and the Angolan continental shelf. The former was relatively oxic and the latter severely hypoxic. The upper mixed layer in the water column ranged in depth from 20 m to 30 m and was oxic. Below the relatively weakly developed thermocline oxygen concentrations declined with depth to very low (severe hypoxia) levels near the seafloor. The southwards flows near the seabed were associated with low dissolved oxygen concentrations while the northward flows at depth constituted “ventilation” events, suggesting that the dissolved oxygen concentrations at depth were generally higher in the second period when bottom flows were more variable with a much higher occurrence of northerly flows than the first period.
- Upper water column turbidity was low at <1 NTU. Mean turbidity near the seafloor was <3.5 NTU but episodically exceeded 350 NTU. The data indicate that these short term turbidity events were generated outside of the survey area and were being advected through it.
- The characteristics of the sediments may be summarized from Lwandle (2014) as follows:
 - Dissolved heavy metal concentrations in the water column were close to the analytical detection levels and nutrient concentrations agreed with those reported for the region. Nitrogen/phosphorus ratios were close to Redfield (17.7 vs 16.0).
 - Surficial sediments in the survey area were silty sand and the underlying sediments primarily silt. Average POM concentrations were 7.4% and molar C:N ratios 11.4 – 19.8. These indicate that the POM was refractory.
 - Inorganic nutrient concentrations in the sediment pore waters average 156 µg/l for nitrogen (ammonia + nitrite + nitrate-nitrogen) and 209 µg/l for phosphorus. This shows a considerable departure from the Redfield ratio and is attributed to phosphorus enrichment from the pelletal phosphorus ore. Sediment water content was low leading to minimal risk of modifications to the overlying water column nutrient distributions.
 - The range of measurements indicative of the oxidative state of the sediments showed that they were hypoxic. The presence of nitrate-nitrogen in the sediment pore water supports this as it converts to ammonia in anoxic conditions. AVS was below detection levels in the surficial sediments and averaged <2 mMol/kg in the subsurface layers. The absence of AVS is consistent with hypoxia as free sulphide is oxidized to sulphate (SO₄²⁻) in the presence of oxygen. This implies that sulphide fluxes would be low.
 - Surficial and subsurface sediments supported relatively high concentrations of the heavy metals arsenic, cadmium, chromium, copper and nickel. The bioavailability of these heavy metals was investigated by elutriation tests and negligible proportions

² The implication of this observation is that any detailed plume modelling would need to take into account both the wind-mixing as well as the effects of the advection of water masses into the area of interest.

entered the dissolved phase³. The low release of the metals into the dissolved phase indicates that although their natural concentrations exceeded the sediment quality guidelines for the region they do not represent a toxicity risk either *in situ* or following physical disturbance. This supports the assessment of toxicity risks in the EIA.

- The investigations into benthic meiofauna and macrofauna in the surficial sediments in the survey area showed that fauna were abundant in both size classes, consistent with a mainly hypoxic sediment environment and inconsistent with sulphidic sediments. The relative abundance of benthic macrofauna in the >1 000 µm size class is consistent with a stable sedimentary environment even though the overlying water body may undergo seasonal changes in terms of its oxygen content with varying contributions of Cape Basin and Tropical Atlantic Central Water.
- The investigation into sulphur bacteria indicated that sulphide fluxes were probably low as the large sulphate bacteria, namely from the genera *Thiomargarita*, *Beggiatoa* and *Thioploca*, which play a significant roles in the oxidation of H₂S, were absent from the bacterial assemblage. Smaller forms including *Thiobacillus* spp. with relatively lower growth rates were present; however, indicating that although estimated to be low (hydrogen) sulphide was present in the sediments.

The conclusion of the study was that the main findings of the initial impact assessment (Lwandle, 2012) are supported by the data gathered and analysed during this verification study. As a result, the level of confidence with which a number of the impacts are assessed has been increased. *The major findings of the verification survey confirmed that the majority of the impacts associated with the project are expected to be physical rather than biogeochemical as was described in the original assessment* (Lwandle, 2014). Specifically the characteristics of the sediments dredged were such that impacts associated with potential elevation in nutrients, the introduction of low dissolved oxygen waters and H₂S into the water column and the effects of the bioavailable component of trace metals released into the water are expected to be limited, particularly given the predictions that the extent of the plumes containing these constituents will be relatively constrained.

Subsequent more detailed reviews of these impact assessments (i.e. Lwandle, 2012 EIA, 2014) raised a number of potential residual uncertainties that needed to be resolved. The key aspects of these reviews are outlined in Section 3 of this report.

³ This is possibly due to their precipitation as insoluble sulphides as, although there was low AVS in the tested (subsurface) sediments, it was present well in excess of the simultaneously extracted metal (SEM) fraction. Iron was abundant in both of the sediment layers and scavenging of the metals from the dissolved phase by iron hydroxides and organic complexes is another possible sink

3 KEY ASPECTS OF UNCERTAINTY TO BE RESOLVED

The key impacts assessed as part of the Lwandle (2012 EIA) specialist study are listed in Table 3.1. The severity of the impacts is based on the intensity (e.g. concentration levels of the constituents of concern), the extent (plume dimensions) and the duration (occurrence and longevity of plumes) of the potential impacts being assessed. Also of relevance is the probability of the envisaged impact occurring. Clearly listed in the table are the confidence levels for the various impacts assessed. Added to the table are the likely aspects of uncertainty underlying the lower confidence levels where indicated. It is these uncertainties that needed either to be addressed in the verification studies, or additional modelling studies as suggested by MFMR, and one of the reviewers (Dr M. O' Toole). Upon completion of the verification studies (Lwandle, 2014) there was a re-rating of the impacts based on the findings of the verification study. These re-rated risks are listed in Table 3.2, which also contains the key residual uncertainties that remained after the verification study.

An early concern raised was the potential for large-scale systemic impacts. This particular issue has been addressed in a separate review (Cochrane, 2014). The conclusion from that review is that given the combination of the high uncertainty typically associated with projections by ecosystem models and the small area that will be impacted by the proposed dredging, it is unlikely that ecosystem modelling would expose any unexpected, highly significant threats that have not already been considered in the specialist studies. A caveat to this was that this conclusion may, however, not apply if the area to be impacted by the mining is of particular importance in the ecosystem or in the life cycle of one or more key species. It was, therefore, important that the nature and likely ecological role of the benthic substrate and biota be adequately understood. Based on the above, it is highly unlikely that ecosystem modelling would better inform decisions around the environmental approval of the proposed NMP mining project.

Similarly additional hydrodynamic or biogeochemical modelling suggested by reviewers of the EIA report is only indicated if it significantly reduces the uncertainty in these key aspects of the potential impact(s) under consideration. The key aspects of uncertainty in the assessments are:

- uncertainty in the initial loadings (i.e. bioavailability of trace metals, oxygen demand, etc);
- the transport and fate of the constituents of concern (i.e. plume dynamics and fate of constituents of concern contained within the plume). The transport and fate of the constituents of concern are determined by transformation processes (i.e. non-conservative behaviour of the various plume constituents of concern) and the advection and dispersion of these constituents (that are largely determined by horizontal flows and vertical mixing in the water column). Here the purpose is to provide a quantification of the extent and duration of the plumes containing constituent concentrations exceeding levels of concern in the environment;
- a quantification of the negative effects of the various vectors of impact.

The focus of this review is therefore on the transport and fate of the constituents of concern (*i.e.* the nature, extent and duration of the expected plumes associated with the proposed mining operations).

A review by Roychoudhury (2014) states that whether the biogeochemical dynamics and their impact to a large extent becomes significant, depends on the behaviour of the sediment plume generated during the dredging activity. *Should the plume be larger than anticipated, in addition to impacting the wider area, prolonged sustenance of the plume will make biogeochemical processes important within*

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the water column by modifying the redox status and mobilization of trace metals. For example, sulphide dynamics may become important under these conditions and will require a better understanding of oxygen consumption by the chemically reduced sediment reservoir. The sensitivity of biogeochemical processes and resultant potential impacts to an increased plume extent and duration (i.e. greater than assessed in Lwandle (2012 EIA, 2014)), is uncertain.

While all indications are that the initial loadings are such that they are unlikely to result in significant impacts (e.g. the volume of low oxygen waters, potential oxygen demand and bioavailable trace metals concentrations), the review by Professor Roychoudhury suggests that there exists a potential sensitivity that remains to be resolved should the plume extent be significantly different to that originally assessed (Lwandle, 2012 EIA, 2014). Consequently this review focusses on the likely plume extents and duration and whether these have been assessed correctly and/or could be better informed by additional modelling studies⁴.

Should these initial or discharge concentrations (including initial non-conservative behaviour of the various biogeochemical parameters) be adequately determined, the most significant contribution of additional modelling studies will be a reduction in uncertainty due to a better characterisation on the extent and duration of the impacts, i.e. plume behaviour characterised in terms of its likely extent and the duration of its presence at concentrations of concern. Should the assertion that the only potential residual impacts of concern relate only to the physical impacts of dredge discharge plumes (i.e. turbidity effects in the water column and smothering at the seabed) then any proposed modelling study need only focus on the sediment plume behaviour, extent and durations.

As noted above, for an assessment of the plume dynamics to be robust:

- the *initial loadings* in terms of sediments and any associated potentially toxic or biogeochemical parameters/constituents of concern need to be adequately constrained. This includes the physical characterisation of the sediments being discharged, as well as the rate and duration of the discharge. This requires an adequate knowledge of the sediments being dredged (grain size, organic content, etc.). The nature of the sediments (proportion of fines) and the quantity being discharged (or the concentration of the discharge) may significantly affect *the initial (near-field) behaviour of the discharge plume*, resulting in a number of behaviours that may significantly affect the plume extent and duration.
- the assessment of the plume extent and duration (i.e. assessment of the advection and dispersion of constituents of concern) require that a number of processes are adequately resolved in either the available measurements or the hydrodynamic and/or water quality models used in the assessment. The most basic requirement is that the *currents distributions (both horizontal and vertical distributions)* are accurately measured or simulated in the models. In the NMP area this implies that tidal and wind-driven currents need to be measured or sufficiently accurately simulated in the available models. Given the offshore location and water depth at the proposed dredging sites, it is highly likely that the currents will be strongly influenced by large-scale flow features such as the upwelling fronts that occur in this region. Secondly, vertical mixing dynamics need to be known. These affect the vertical mixing of constituents of concern and also affect the settling rates of sediments, particularly in the upper

⁴ Should the biogeochemical processes prove to be important in determining the "initial loadings" or result in non-conservative behaviour of relevance to the plume modelling, such non-conservative behaviour and biogeochemical processes, in principle, could be included in the plume (i.e. transport and fate) modelling undertaken.

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mixed layer. These vertical mixing dynamics are difficult to measure and are either i) inferred from observations of concentrations of the constituents in the plume being assessed or ii) need to be sufficiently accurately simulated in the hydrodynamic and water quality models used for the assessments. These vertical mixing dynamics depend on turbulence introduced into the water column as well as the existing water column structure (i.e. stratification). The implication is that *the processes driving vertical mixing (e.g. the introduction of turbulence due winds, tides and waves), as well as horizontal inflows and/or atmospheric fluxes affecting water column structure* will need to be specified or sufficiently accurately simulated in any modelling study undertaken.

- Where *non-conservative behaviour of constituents* of concern is significant, this will need to be included in the assessment whether based on measurements of more detailed modelling of these biogeochemical processes.

Whether the environmental impacts assessments to date meet these requirements or whether additional modelling studies are required, is assessed below based on prevailing perceived residual uncertainties in the assessments (see Table 3.2). The residual uncertainties that may need to be resolved by modelling largely relate to the behaviour, extent and duration of sediment plumes (i.e. the near-field behaviour and far-field behaviour of the discharge plumes).

The assessment of risks in the water column (Lwandle, 2012 EIA) is based on an interpretation of previous modelling results for similar dredging scenarios, however for variable but significantly larger discharges and in shallower water depths (90 m to 130 m). It is important to note that the interpretation of the measurements and modelling outputs of the study (CSIR, 2006) used to reach the assessments in Lwandle (2012 EIA) made a few key assumptions, these being:

- that the flows in the CSIR (2006) study were accurately simulated and that these flows are representative of those prevailing at the deeper 200 m to 225 m ML 170 sites.
- the physical properties (grain size distributions, flocculated or unflocculated settling rates, etc.) of the material that was dredged was similar to that which will be dredged at the NMP operations site;
- the quantities being discharged (particularly the fines component) by the NMP dredging operations will be less than that assessed in the CSIR (2006) study. The fact that the overall sediment discharge rates for the CSIR (2006) study were approximately 4 times those anticipated for the NMP dredging suggest that this will remain true even if there is a significantly increased fines component in the NMP dredging discharges;
- The assumed initial plume behaviours in the CSIR (2006) study were correct and correctly accounted for in the modelling undertaken as part of that study;
- That these initial plume behaviours reported in the CSIR (2006) study are also applicable for the assessment of the proposed NMP dredging discharges

The desktop assessment of the proposed NMP dredging discharges (Lwandle, 2012 EIA) needed to interpret correctly and adapt the CSIR (2006) study outcomes to ensure a sufficiently robust assessment. This was largely achieved, however some minor issues may not have been fully resolved (see below). The robustness of the initial CSIR (2006) study as well as its interpretation to provide the Lwandle (2012 EIA) assessment of the proposed NMP dredging operations, is discussed below.

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Table 3.1: Impact Assessment summary table (Lwandle 2012 EIA)

Impact	1	2	3	4	5	6	7	8	9
Risk Area	Overspill discharge					Seabed dredging			
Nature of the impact	Turbid plume	H ₂ S toxicity at surface	Oxygen deficient water at surface	Nutrients added at surface	Trace-metal toxicity at surface	Trace-metal toxicity on seabed	H ₂ S toxicity on seabed	Lowered oxygen levels on seabed	Increase of H ₂ S flux.
Extent	Dredge area	Dredge area	Dredge area	Dredge area	Dredge area	Annual Mining Area	Dredge area	Annual Mining Area	Dredge area
Duration	Very short term	Short term	Very short term	Short term	Short term	Short term	Medium term	Medium term	Long term.
Intensity	No lasting effect	Minor effects	No lasting effect	No lasting effect	Minor effects	Minor effects	Moderate effects	Minor effects	Minor effects
Probability	Possible	Possible	Improbable	Possible	Possible	Possible	Possible	Possible	Improbable
Status	Negative	Negative	Negative	Neutral	Negative	Negative	Negative	Negative	Negative
Significance (no mitigation)	Low	Low	None	None	Low	Low	Low	Low	None
Mitigation	Built-in	None possible	n/a	None possible	None possible	None possible	None possible	Not possible	n/a
Significance (with mitigation)	Low	Low	None	None	Low	Low	Low	Low	None
Confidence level	High	Medium	High	Medium	Medium	Medium	Medium	High	Medium
Source(s) of residual uncertainty	Near-field behaviour (initial density/grain-sizes, settling rates) and far-field behaviour (currents, thermocline and mixing behaviour)	Initial H ₂ S concentrations and subsequent dynamics, dispersion (near-field behaviour, far-field behaviour (currents, thermocline and mixing))	Initial dissolved oxygen concentration & evolution of oxygen demand upon release, dispersion (near-field behaviour, far-field behaviour (currents, thermocline and mixing behaviour)	Initial nutrient concentrations & consequences of elevated nutrients, (near-field behaviour, far-field behaviour (currents, thermocline and mixing behaviour)	Initial trace metal concentrations (near-field behaviour & far-field behaviour (currents, thermocline and mixing behaviour)	Initial trace metal concentrations and bio-availability, far-field behaviour (currents and mixing behaviour)	Initial H ₂ S concentrations at source & far-field behaviour (currents and mixing behaviour)	Initial trace metal concentrations and their bio-availability & far-field behaviour (currents and mixing behaviour)	Time taken for Thio-bacterial mats to re-establish

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Table 3.2: Re-rated impact assessment table after the verification studies (Lwandle 2014)

Impact	1	2	3	4	5	6	7	8	9
Risk Area	Overspill discharge					Seabed dredging			
Nature of the impact	Turbid plume	H ₂ S toxicity at surface	Oxygen deficient water at surface	Nutrients added at surface	Trace-metal toxicity at surface	Trace-metal toxicity on seabed	H ₂ S toxicity on seabed	Lowered oxygen levels on seabed	Increase of H ₂ S flux.
Extent	Dredge area	Dredge area	Dredge area	Dredge area	Dredge area	Annual Mining Area	Dredge area	Annual Mining Area	Dredge area
Duration	Very short term	Short term	Very short term	Short term	Short term	Short term	Medium term	Medium term	Medium term
Intensity	No lasting effect	Minor effects	No lasting effect	No lasting effect	Minor effects	Minor effects	Minor effects	Minor effects	Minor effects
Probability	Possible	Possible	Improbable	Possible	Possible	Possible	Possible	Possible	Improbable
Status	Negative	Negative	Negative	Neutral	Negative	Negative	Negative	Negative	Negative
Significance (no mitigation)	Low	Low	None	None	Low	Low	Low	Low	Low
Mitigation	Built-in	None possible	n/a	None possible	None possible	None possible	None possible	Not possible	n/a
Significance (with mitigation)	Low	Low	None	None	Low	Low	Low	Low	Low
Re-Rated Confidence level	High	High	High	High	High	High	High	High	High
Reason for re-rating		Mine site sediment property data indicate low H ₂ S presence, pyrite sulphide will have low solubility		Mine site sediment pore water volumes are low	Mine area Heavy metals have low solubility and bioavailability, trophic transfers are attenuated at primary consumer level	Mine area Heavy metals have low solubility and bioavailability, dredging should not increase exposures	Mine site sediment property data indicate low H ₂ S presence	POM in sediments is refractory	Mine site sediment property data indicate low H ₂ S presence and release from iron pyrites should be low.

Seemingly the modelling studies undertaken in the CSIR (2006) study were sufficiently calibrated and validated for the purpose of assessing the dredge plumes from the dredging activities being assessed. The calibration and validation of the modelling results in Figure 9.4 of the CSIR (2006) study confirm that this is the case for the near-bottom currents (for ADCP currents measured at depths of 72 m and 85 m in an approximate 101 m water depth). However, the ADCP current measurements reported in the study (albeit for a very short time period - 8 March 2006 to 14 March 2006) indicate that there exists significant vertical shear in the measured currents with the deeper currents (> 35 m water depth) often opposing those measured higher up in the water column and near the sea surface. While the calibration and verification of the model is assumed to be correct, the CSIR (2006) study provides no evidence that these vertical shears in current flows indeed were adequately simulated in the model.

Given that the currents measured in the CSIR (2006) study:

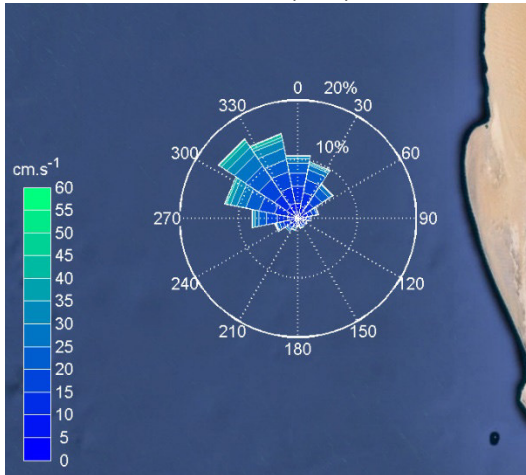
- were measured in a *ca.* 110 m water depth as opposed to those for the NMP verification study (MSI, 2014a, 2014b) that were measured in a water depth exceeding 190 m, and;
- were measured in a different season from those measured for the NMP verification study, i.e. a late summer to autumn period (8 Mar 2006 to 4 May 2006) as opposed to the currents measured for the NMP verification study that were measured in winter to early spring (8 June to 26 July 2013 and 2 August to 13 September 2013);
- the two data sets are surprisingly similar in that both have northward or north-westerly surface flows and southerly or south-easterly flows at depth. This is perhaps not unsurprising and modelling studies in the region indicate that the poleward undercurrent, to a greater or lesser extent, is likely to be present at both of these locations (Veitch, 2010). The surface flows in the data measured by the CSIR in an approximately 110 m water depth (Figure 3.1) are slightly larger than those measured in the NMP verification study (Figure 3.2) while the flows near the seabed are slightly weaker for the current measured in a 110 m water depth.

The Lwandle (2012 EIA) assessment estimates the initial concentration of muddy sand mixture of sediments discharged will be of the order of 18 g/l, suggesting that the near-field behaviour in at intermediate concentrations in the overspill are expected to behave in 'transition mode'; as defined by Winterwerp (2002) where the discharged plume is subject to both density currents and mixing. *This initial near-field behaviour is important in determining the initial plume dynamics and the spread and persistence of sediment, particularly in the upper mixed layer.* The lower these initial sediment concentrations the greater the proportion of the sediments discharged that will mix into upper mixed layer. However the lower these initial concentrations, the lower will be this loading of the water column. Provided that the CSIR (2006) study consistently took into account the range of possible initial discharge or near-field behaviours for the various initial discharge concentrations (which it claims to do), the interpretation of the results of the CSIR will remain relevant to the assessment of the plume dynamics reported in Lwandle (2014).

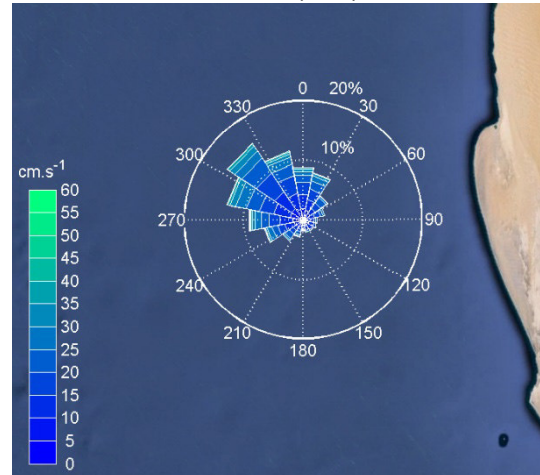
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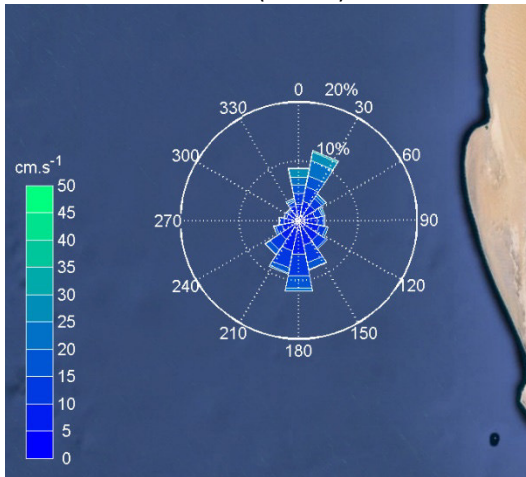
NEAR SURFACE CURRENTS (-7 m)



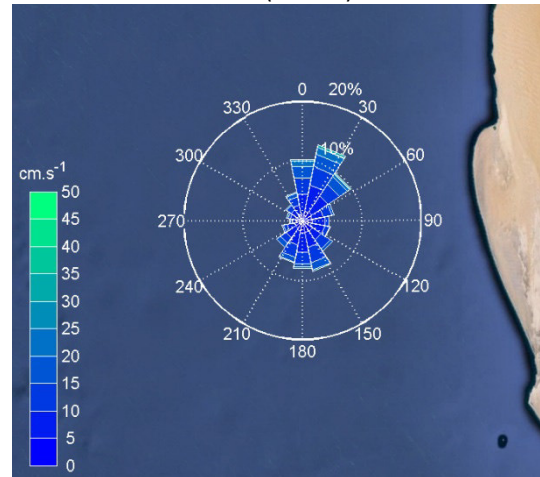
NEAR SURFACE CURRENTS (-9 m)



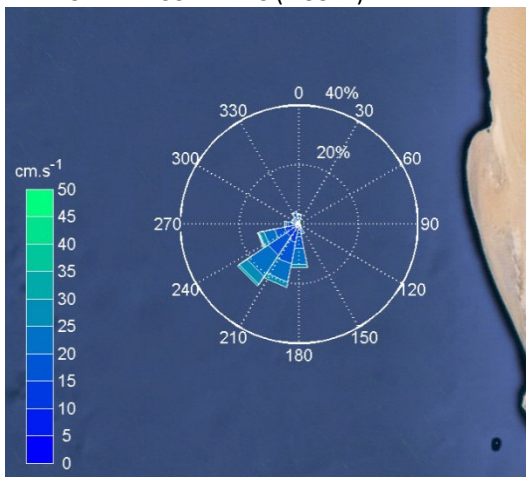
MID WATER CURRENTS (-148 m)



MID WATER CURRENTS (-142 m)



NEAR SEABED CURRENTS (-193 m)



NEAR SEABED CURRENTS (-188 m)

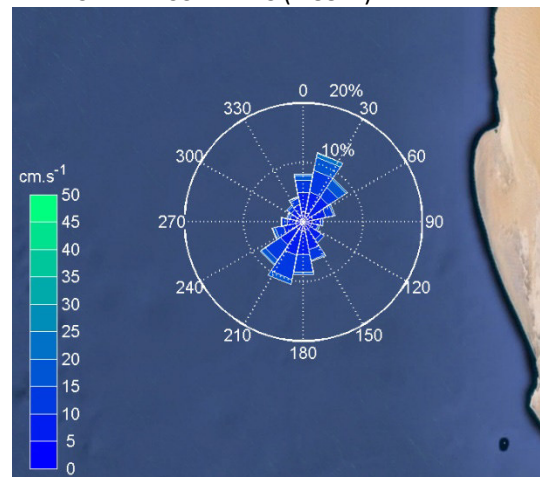


Figure 3.1: Summary plots of current speed and directions during P1: 8 June – 26 July 2013 (left panel) and P2: 2 August – 13 September 2013 (right panel) at the near surface, mid water and near the seabed, collected from the oceanographic mooring located at 24° 08' 18.96" S, 14° 01' 32.88" E. Note the different scale in the lower left panel

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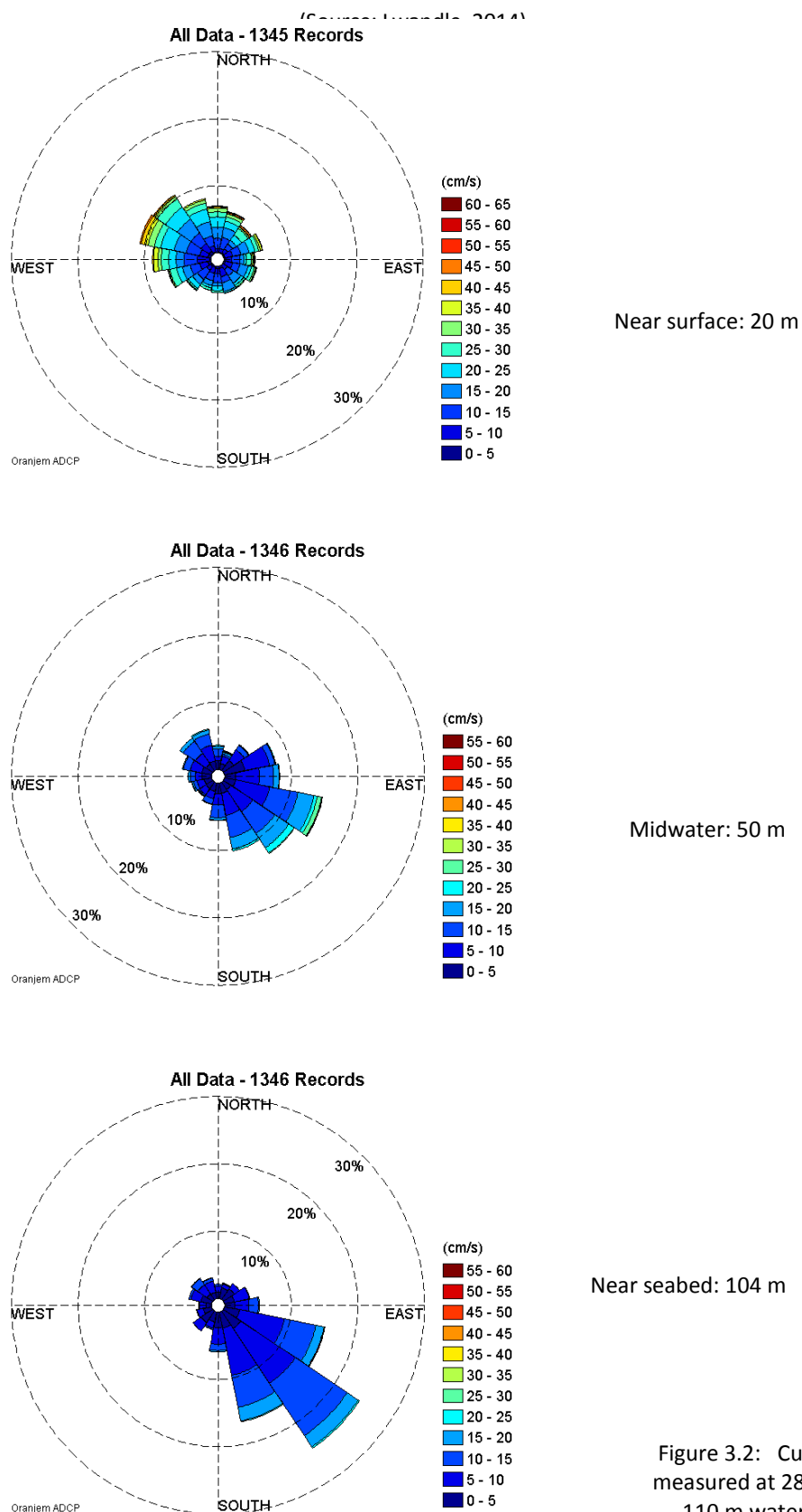


Figure 3.2: Current roses for data measured at 28.6192S; 16.1028E in 110 m water depth (from the CSIR (2006) study).

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The sediment loadings used in the CSIR (2006) study were highly variable, nevertheless the estimated plume dimensions used in the Lwandle (2012 EIA) assessment (a plume dimension of 1 500 m long by 800 m wide with suspended sediment concentrations within this plume ranging between >20 mg/ℓ but <100 mg/ℓ) were based on plume dimensions reported in CSIR (2006) for mining operations in southern Namibia having a overspill discharge rate approximately 4 times higher than that estimated for the proposed NMP dredging project. While the sediment grain sizes are likely to differ between the two projects, the differences in initial loadings are such that the estimates of plume dimensions from the CSIR (2006) are likely to remain conservative *in terms of the initial sediment loadings*.

While the current speed distributions near the surface and near the seabed are similar for the CSIR (2006) data measured in a 110 m water depth and data measured in an approximate water depth of 200 m in ML 170, *the difference in water depths will significantly change the time taken for sediments to reach the seabed at these two sites*. The discharges for the proposed NMP dredging will take place in water depths of 200 m to 225 m. The implication is that the plumes from the proposed NMP dredging activities will take approximately twice as long to reach the seabed than estimated for the CSIR (2006) study. This does not however imply that the plume dimensions will be twice as large as those reported in the CSIR (2006) study. *The actual dimensions of the plume depend on the concentration contour(s) selected to represent the outer dimensions of the plume, which in turn depends on the initial loadings from the waters being discharged to the marine environment*.

A further uncertainty when assessing sediment plume extent and duration is *the accurate specification of the settling rate of the various sediment fractions being discharged*. Assumed settling rates affect significantly the estimates of plume dimension, particularly in modelling studies. The Lwandle (2012 EIA) assessment suggest that all things being equal (to the CSIR (2006) study) that the sediments discharged at the deeper ML 170 dredging site will settle within approximately 2 hours. This implies a settling rate of approximately 20 mm/s which seems very high. A significant factor in this seemingly high settling rate most probably is the initial behaviour of the discharged material which may have acted as a negatively buoyant plume and rapidly flowed directly downwards in convective descent through the receiving water column. This assumed behaviour i.e. rapid descent of the plume) is predicated on an initially high concentration of sediment in the discharge, particularly fines, which may not necessarily be the case for the NMP dredging project.

For the assessment of dredger plumes generated in the proposed Sandpiper Project dredging area (Lwandle, 2012 EIA) a lower sedimentation rate of 1.6 mm/s was applied. (This lower sedimentation rate is based on average settling rates reported in the CSIR (2006) study.) The use of this sedimentation rate suggested a duration of approximately 3 hours being required for the settling sediments to transit the upper mixed layer and approximately 33 hours to sink to the base of the water column. Assuming uni-directional current magnitudes of approximately 0.1 m/s, the sediments will travel some 10 to 12 km before reaching the seabed. Consistent with the measurements and hydrodynamic modelling in the CSIR (2006) study, sediment concentrations within the plumes in the Lwandle (2012 EIA) assessment were predicted to be <100 mg/ℓ. It should be noted that in the CSIR (2006) study concentrations of 100 mg/ℓ were predicted to extend as far as 10 km from the dredge area, however exceedances for >50% of the time were limited to within 2 km of dredging. Concentrations >20 mg/ℓ could extend over an area of approximately 10 km². While the assumed low settling rates of 1.6 mm/s would suggest more extensive plume dimension than the assumed plume dimensions (of 1 500 m long by 800 m wide with suspended sediment concentrations in the plume ranging between >20 mg/ℓ but <100 mg/ℓ) in the Lwandle (2012 EIA)

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study, these assumed dimensions presumably were based on the median exceedances of 100 mg/ℓ not exceeding a distance of 2 km from the discharges.

Based on the above observations, it is *possible that the actual plume dimensions may exceed the dimensions assumed in the Lwandle (2012 EIA) assessment*. It should also be noted that, in the Lwandle (2012 EIA) assessment, the plume dimensions were based on the expected total suspended solids (TSS) concentration in the water column. These concentrations, because of the settling of sediments over time, are likely to be lower in the plume for sediments than for a conservative tracer or toxic constituent that is dissolved in the water column. However none of the constituents of concern (dissolved oxygen, H₂S or trace metals) are likely to display truly conservative behaviour and are likely to show some degree of decay (e.g. uptake of Cd by phytoplankton, oxygenation of upper mixed layer waters, etc.). This suggests that the plume dimensions determined from the distribution of a conservative tracer also are likely to overestimate the true situation. Finally, it should also be noted that the waters containing the dissolved toxic components or changed biogeochemical components of concern are likely to show similar near-field behaviour as sediment-laden waters being discharged from the dredger, suggesting a similar (at least initially) plume behaviour (and dimension) to that of the sediment laden water being discharged.

In summary, the two key metrics of relevance in terms of plume dynamics are the extent of the plume and the persistence (or duration) of the plume. The duration of the plume potentially has implications for biogeochemical transformation processes that may result in ecological impacts (e.g. oxygen demand and/or toxicity in the upper water column).

Based on this review of the initial impact assessment (Lwandle, 2012 EIA) and subsequent verification study (Lwandle, 2014) it is *possible that the actual plume dimensions may exceed dimensions assumed in the Lwandle (2012 EIA) assessment (i.e. plume dimensions may be up to 2 to 5 times larger than indicated)*. However, the implication of these potentially increased plume dimensions for the overall impact assessment and subsequent environmental decision-making is limited. It is not certain that the plume dimensions will exceed those indicated in the Lwandle (2012 EIA) study, however should this be the case, the extent of the plumes reported in the impact assessment tables may increase from being limited to the “Immediate Dredge Area” to affecting possibly the “Annual Mining Area”. It is not expected that the extent of the impact would increase to such an extent that it affects the “Specific Mining Site” (see Table 3.3 below for the definition of the impact extents and durations).

Should the potential biogeochemical impacts be limited in their intensity as is indicated by the studies to date and the reviews of these studies, it is only the turbidity and possibly the sediment deposition on the seabed that remain impacts of potential concern. It also should be noted that for a given sediment discharge, an increased plume extent necessarily implies lower turbidity levels over a larger area. *Given that the plume extent is typically defined in terms of turbidity or TSS values exceeding a given threshold, more widespread dispersion of TSS may not significantly change the dimensions of a turbidity plume s defined in terms of TSS values exceeding thresholds of concern.*

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Table 3.3: Impact criteria used to assess extent and duration (Lwandle, 2012 EIA).

Impact Criteria:						
Extent	Dredge Area Per vessel immediate cycle i.e. approximately 66,000m ² or 6.6 ha	Annual Mining Area Up to 3 km ²	Specific Mine Site (SP1 or SP2) each is 22x8 km or 176 km ²	Local 25-50 km or 2,000km ² -8,000 km ²	Regional 50-100 km or 8,000km ² – 30,000 km ²	National 100 km to EEZ (200 nautical miles) ⁵ 100 to 370 km, or >30,000 km ²
Duration	Very Short Term 3 days	Short term 3 days – 1 year	Medium term 1 - 5 years	Long term 5 – 20 years	Permanent > 20 years (life of mine)	

4 HYDRODYNAMIC AND WATER QUALITY MODELLING

For a stand-alone modelling study to reduce uncertainties associated with the existing assessments based on measurements and the interpretation thereof or prior modelling results in the region, certain pre-conditions need to be met in terms of available data and the functionality of the model(s) to be used. These uncertainties and requirements are listed in Table 4.1 below.

4.1 APPROACHES TO THE HYDRODYNAMIC AND WATER QUALITY MODELLING

Two modelling approaches may be used to address residual uncertainties, most of which is related to the plume dimension and duration. The first comprises a comprehensive modelling study with an interior high-resolution nested domain relying on the larger-scale model to provide the conditions at the boundary of the nested model. The second is a high resolution model only, with the conditions at the open boundary provided by measurements. The advantages and pitfalls of the two modelling approaches are discussed in detail below.

4.1.1 Modelling Approach 1: Large-scale model with nested high resolution domain

In this approach a large-scale model will be used to generate the requisite open boundary conditions for a high resolution nested domain used to simulate plume dynamics, extent and duration. The nested model domain, in turn, would be used to provide high resolution simulations of the dredge plumes. The advantages of such an approach is that it is unlikely to be constrained by the need for on-going availability of measured data to specify the boundary conditions for the nested high resolution model. This approach also allows for a better understanding of the regional ocean dynamics which may be of use for similar or more extensive modelling assessments in the region. However there are considerable disadvantages to such an approach. It is likely to be computationally very expensive, and likely to take 8 to 12 months to complete. Furthermore there is a significant

⁵ 1 nautical mile = 1,85 kilometres

likelihood that the large-scale model, while able to simulate key features in the region (e.g. Veitch *et al.*, 2010), will not be able to produce representative boundary conditions on the spatial and temporal scales required for the nested high-resolution model being used to assess plume behaviour, extents and durations. *Such a modelling study is not recommended due to the time that will be required to complete it, the probable high costs of such an exercise and the very real risk that such an approach that it may not manage to further constrain any of the key uncertainties in the existing environmental impact assessment specialist studies.* However should extensive verification studies of the impacts of the dredging be undertaken, it would be beneficial to attempt such a modelling study as it will provide a greater understanding of the hydrodynamic and biogeochemical dynamics in the region and also provide a platform for undertaking other high resolution assessments of one or more similar projects in the region.

4.1.2 Modelling Approach 2: High resolution model using measured data at the open boundaries

This comprises a more simple modelling approach and mirrors that used to assess the consequences of drill cuttings disposal on the Natal Bight offshore of KwaZulu-Natal, South Africa (Morant *et al.*, 1998). This approach was taken to overcome similar constraints to those likely to be experienced when undertaking a modelling assessment of the NMP dredging operations, namely that presently no predictive modelling platform exists that can reliably predict the hydrodynamic flows and water column parameters required to specify the open boundary conditions for a high resolution plume modelling study in the proposed dredging area. The approach proposed is to utilise the measured data to specify the requisite open boundary conditions for such a high resolution model (see Figures 4.1 and 4.2). The data required to run such a model include current measurements (presently available for a 90 day period), representative offshore wind data (ideally weather buoy measurements however NCEP data or a similar wind product are likely to be adequate), atmospheric fluxes (which can mostly be derived from NCEP data fields) and water column profile data. The latter may be difficult to obtain and therefore may need to be specified as a seasonal profile to which the interior domain of the model is relaxed over a period of time. Fortunately such data only serve to constrain mostly the vertical mixing in the model and only have a more limited effect on the current distributions in a model set up in this manner.

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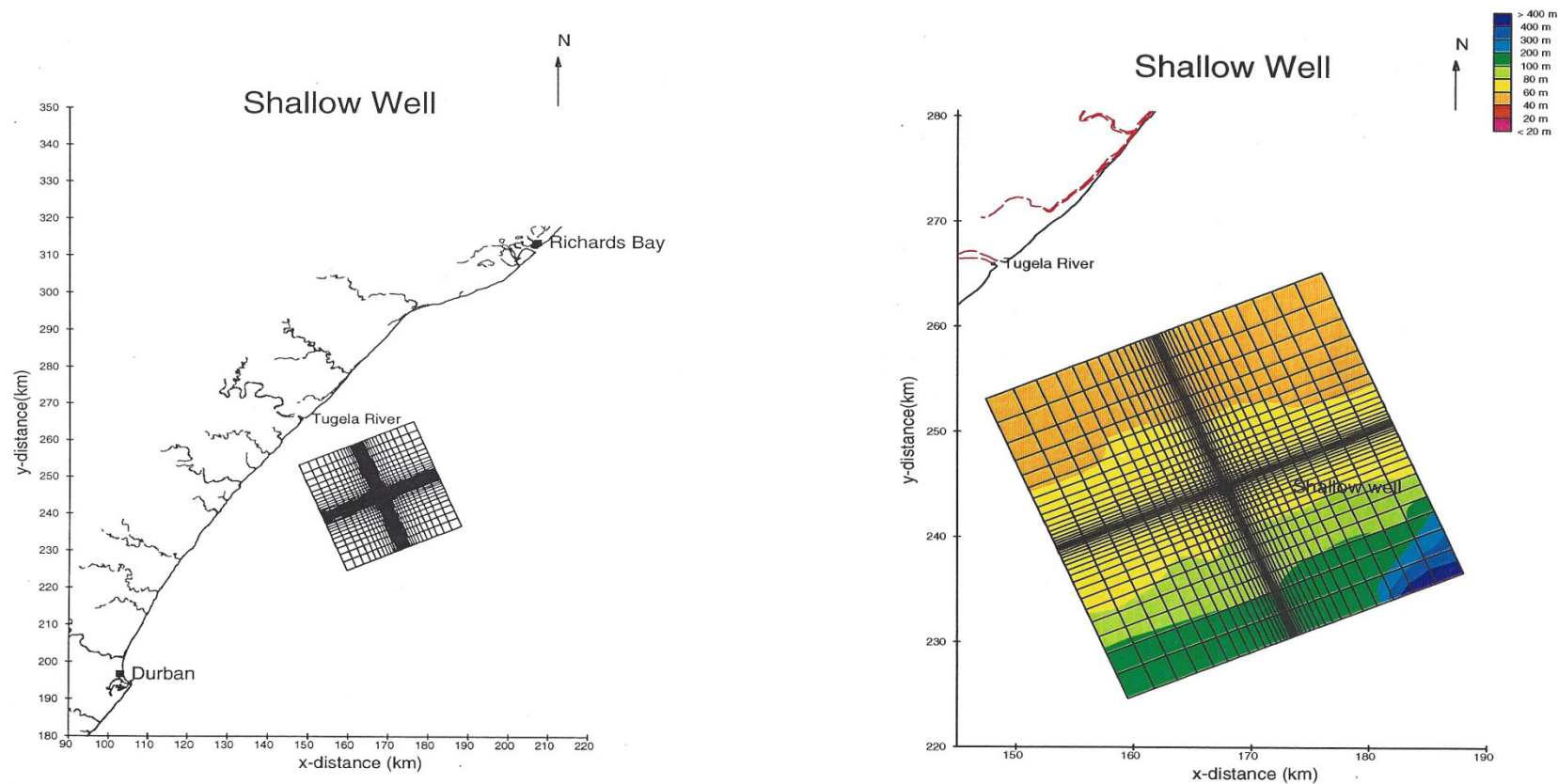


Figure 4.1: High resolution drill cuttings disposal simulation offshore of KwaZulu-Natal using Modelling Approach 2

(Source: Morant *et al.*, 1998).

A constraint of this more simple approach is that the model simulations will not include significant horizontal shears in flows and that the plume dynamics and information on their extent will be constrained by the size of the high resolution model domain (likely to be limited to an approximate 15 km x 15 km domain). **Perhaps the biggest potential constraint is that the model simulation periods constrained by the availability of measured data** (i.e. current and to a lesser extent water column structure measurements for the full periods that the model simulations are undertaken). However the advantages of such a modelling approach is that is cost-effective, can be executed within a reasonable time-frame of 3 months or less and **the simulated environment in the high resolution model domain will certainly will be representative of environmental conditions prevailing at the dredging location** (thus removing a significant source of uncertainty in the predicted plume behaviour, extent and duration).

This modelling approach, in principle, will be able to better constrain the estimates of the plume dimension and duration. Should it be of interest, estimates of the deposition patterns of the discharged sediments on the seabed also can be produced by the model (see Figure 4.2). Certainly this type of modelling will allow one to explore explicitly the sensitivity of the plume predictions to uncertainties in initial loadings, plume dynamics and effective settling rates of the sediments, as well as possible changes in the rates of dredging and nature of material being dredged.

Should there be uncertainties in biogeochemical processes in the plume, it is possible to extend the modelling to include such processes, however this will required that these biogeochemical processes are adequately parameterised and included in the modelling platforms. There will also then be al requirement for additional measurements such as ambient concentrations of dissolved oxygen as well as other relevant biogeochemical parameters. Presently the indication is that the biogeochemical effects of concern are sufficiently constrained and that such biogeochemical modelling will not be required.

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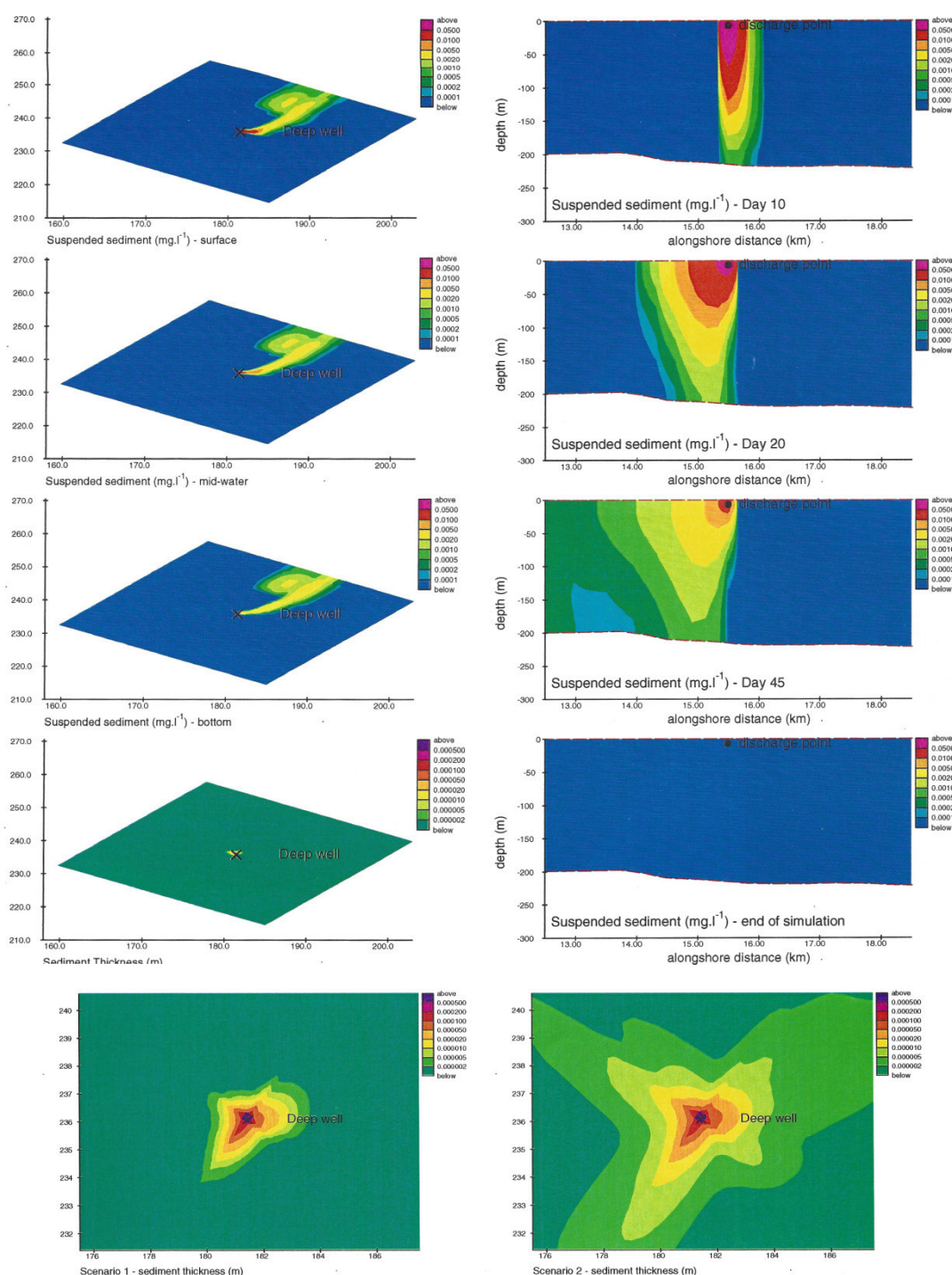


Figure 4.2: Sample of outputs (high resolution drill cuttings disposal simulation offshore of KwaZulu-Natal) from a modelling study using Modelling Approach 2

(Source: Morant *et al.*, 1998).

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Table 4.1: Comparative assessment of required information and model functionality for the two proposed modelling approaches.

Source of Uncertainty	Required information/ model functionality	Modelling Option 1 Large-scale model with nested high resolution domain	Modelling Option 2 High resolution model using measured data at the open boundaries	Comment
Initial discharge sediment concentrations	Adequate information on the material to be dredged in terms of grain size distribution, dredging rates. etc.	This is not a modelling issue <i>per se</i> . It just requires an adequate specification of the material to be dredged (that presently exists) and an adequate description of proposed dredging operations (technology, nature of overspill, dredging rates, etc.)		If this information is not available or inadequate this will negate the value of modelling in providing quantitative estimates of plume behaviour and characteristics
Initial behaviour of the discharge plume (e.g. convective descent, mixing into upper mixed layer or transitional behaviour)	Accurate assessment of initial discharge conditions (discharge velocity, depth of discharge below the sea surface, Initial discharge sediment concentrations and grain sizes)	Based on an accurate assessment of initial discharge conditions (discharge velocity, depth of discharge below the sea surface, initial discharge sediment concentrations and grain sizes), initial plume behaviours will need to be parameterised using software such as STFATE using the categorisation process contained in Winterwerp (2002).		If this initial plume behaviour is not adequately characterised and incorporated into the modelling, errors in the prediction of plume behaviour could be significant, resulting in errors of an estimated approximately 30 to 50% in the plume extent and duration in various parts of the water column.
Initial concentrations of biogeochemical parameters of concern	Adequate information on the material to be dredged in terms grain size distributions, dredging rates, etc. Adequate understanding/ quantification of relevant biogeochemical processes.	Whatever the process in obtaining the relevant information, the initial concentrations can be specified in the relevant modelling platform, e.g. Deltares Water Quality model (or similar) software	Whatever the process in obtaining the relevant information, the initial concentrations can be specified in the relevant modelling platform, e.g. Deltares Water Quality model (or similar) software.	It is not clear whether some of the larger-scale modelling platforms proposed for use in Modelling Option 1 will have the necessary functionality to model the parameters of concern. The nested domain therefore will need to comprise a modelling platform that is suited to this purpose, i.e. a platform such as the Deltares Water Quality model (or similar) software has the necessary functionality.

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Source of Uncertainty	Required information/ model functionality	Modelling Option 1 Large-scale model with nested high resolution domain	Modelling Option 2 High resolution model using measured data at the open boundaries	Comment
Advection and dispersion of constituents of relevance	Adequate specification of currents (both horizontal and vertical) variability through the water column. This requires that large-scale flows (upwelling fronts, under-currents, etc.), wind-driven, tidally and wave-driven flows be adequately simulated. This also will require that water column structure is accurately simulated.	The large-scale model with need to simulate the large-scale flows required at the open boundary of the nested high resolution model. The large-scale model simulations will require appropriate input time series such as winds and atmospheric fluxes, etc. If not undertaken as a research project some of these data may need to be purchased.	<p>The model will require the ongoing specification of current velocities profiles with depth at the open boundaries for the periods simulated. These will be provided by the existing (or future) measurements.</p> <p>Given that the model is dependent on the ongoing specification of open boundary conditions, it will not be possible to run model simulations when such data are not measured.</p>	The flows and water column structure simulated in the large-scale model may not adequately represent the actual situation at the open boundaries of the nested model and therefore would not be adequate for specifying times series of relevance at the nested model boundaries. Of particular concern would be that the large-scale modelling does not adequately represent the location of upwelling fronts and the spatial characteristics of poleward undercurrent which is likely to lead to currents and water column parameters being specified at the nested model that are not representative of conditions that prevail in the area of interest.
	Quantification of vertical mixing processes that depend on turbulence introduced into the water column (by wind waves and tides) as well as the existing water column structure (i.e. stratification) that in turn requires accurate simulation or specification of (large-scale) horizontal inflows	The large-scale model with need to simulate the water column structure and large-scale flows (affecting water column structure in the nested model) required at the open boundary of the nested high resolution model. The large-scale model simulations will require appropriate input	The model will require the ongoing specification of wind, waves, tides, atmospheric fluxes and profiles of water column structure profiles with depth at the open boundaries for the periods simulated. These will be provided by the existing (or future) measurements. Given that	see comment above

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Source of Uncertainty	Required information/ model functionality	Modelling Option 1 Large-scale model with nested high resolution domain	Modelling Option 2 High resolution model using measured data at the open boundaries	Comment
	and/or atmospheric fluxes affecting water column structure.	time series such as winds and atmospheric fluxes, etc. If not undertaken as a research project some of these data may need to be purchased.	the model is dependent on the on-going specification of open boundary conditions, it will not be possible to run model simulations when such data are not measured.	
Changes in sediment concentrations due to the settling of sediments through the water column.	Accurate specification of settling rates. This requires a good understanding of sediment grain size distributions, likely flocculation behaviour and to a lesser extent water column parameters such as salinity and temperature.	The settling rates specified in the model will be based on theoretical considerations and/or published data for the sediment being discharged.		This remains a key uncertainty in the modelling studies. The approach generally undertaken to address this key uncertainty is to undertake a number of simulations to determine the model sensitivity to these model parameterisations. This necessarily will result in a range of plume extents and durations that will need to be included in the assessments.
Changes in concentrations of biogeochemical parameters and toxic constituents of concern (e.g. low oxygen water, oxygen demand, changes in trace metal bioavailability, etc.) due to biogeochemical transformations.	Sufficient understanding of biogeochemical processes and the incorporation of this (process) knowledge into the modelling platform.	Where relevant the process models determining the evolution of the relevant parameters will need to be included in the relevant modelling platform, e.g. Deltares Water Quality model (or similar) software. It is anticipated that most, if not all of these process models will be able to be included in the Deltares Water Quality software considered to be	Where relevant the process models determining the evolution of the relevant parameters will need to be included in the modelling platform, e.g. Deltares Water Quality model (or similar) software. It is anticipated that most, if not all, of these process models will be able to be included in the Deltares Water Quality software considered to be most	While it is envisaged that the Deltares Water Quality software or similar DHI software considered for use in the high resolution domain will have the necessary functionality, this is unlikely to be the case for the large-scale modelling platforms likely to be used for this modelling study (e.g. ROMS). The implications for the coupling of the large-scale modelling platforms to the nested domains is uncertain, however it is likely that any limitations in this regard can be

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Source of Uncertainty	Required information/ model functionality	Modelling Option 1 Large-scale model with nested high resolution domain	Modelling Option 2 High resolution model using measured data at the open boundaries	Comment
		most suitable for the proposed study. It is however not clear that the large-scale modelling platforms likely to be used for this modelling study (e.g. ROMS) presently have the necessary functionality to address the biogeochemical process modelling required here	suitable for the proposed study.	overcome given sufficient time.
Availability of data to calibrate and validate the models	Requirement for model calibration/verification data	This approach will require large scale calibration data such a satellite temperature fields and hydrographic data (historical) and well as a degree of expert opinion to calibrate and validate the large-scale model. Specifically the model would need to represent the known large-scale oceanographic features of the region such as the offshore location of upwelling fronts and the poleward undercurrent. For the nested model this approach requires current profiles to calibrate the hydrodynamic parameters. Additional data	This approach requires current profiles to calibrate the hydrodynamic parameters. Additional data on the water column structure will help to constrain/calibrate the mixing dynamics in the model.	The Modelling Option 2 will require a number of large-scale data sets as well as some expert opinion to ensure that the model is generating the relevant hydrodynamics fields and mixing dynamics. In a strict sense, the data used to calibrate the nested high-resolution model (or the model envisaged for Modelling Option 1) should provide adequate data for the model calibrations as it is only the large-scale model outputs utilised at the boundary of the nested model that are of relevance. However the larger-scale calibration data would help to diagnose/understand the model limitations should the data generated for the nested model boundaries not

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Source of Uncertainty	Required information/ model functionality	Modelling Option 1 Large-scale model with nested high resolution domain	Modelling Option 2 High resolution model using measured data at the open boundaries	Comment
		on the water column structure will help to constrain/calibrate the mixing dynamics in the model.		adequately represent the measured calibration data.
Availability of data time series required to run the models	Requirement for on-going time series to run the models.	<p>The large-scale model simulations will require appropriate input time series such as winds and atmospheric fluxes, etc.</p> <p>However the nested model will not require the specification of flows and water column structure as these will be available from the large-scale model.</p>	This approach requires current profiles, wind & atmospheric flux time series and specification of water column structure at the model boundaries. The latter may be difficult to obtain and therefore may need to be specified as a seasonal profile to which the interior domain of the model is relaxed over a period of time.	The benefit of Modelling Option 2 is that the data required to run the large-scale model is likely to be available in the long-term (<i>i.e.</i> from global products) thus avoiding the limitation of Modelling Approach 1 where the model simulations can only take place is the requisite time series measurements are made specifically for the modelling study.

4.2 MEASUREMENTS REQUIRED TO SUPPORT MODELLING STUDIES

The measurements required to support the modelling studies are similar to those that will be required to assess plume dynamics and resultant impacts should it be chosen to make these assessments on measurements alone.

Specific requirements will include:

- Initial sediment concentrations and discharge parameters such as discharge volumes, flow rates, grain size distributions
- Initial concentrations of biogeochemical parameters of concern;
- Current meter measurements for the proposed simulation periods.
- Wind and atmospheric flux data (which can be obtained from global data sets such as NCEP data should it not be able to measure these using an offshore weather station);
- Water column structure measurements and water quality data, however should such data not be available, seasonal profiles based on historical data will be used.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSION

Based on this review of the initial impact assessment (Lwandle, 2012 EIA) and subsequent verification study (Lwandle, 2014) it is *possible (but not certain) that the actual plume dimensions may exceed the dimensions assumed in the Lwandle (2012 EIA) assessment* (i.e. plume dimensions may be up to 2 to 5 times larger than indicated). However, the implication of these potentially increased plume dimensions for the overall impact assessment and subsequent environmental decision-making is limited. Should the plume dimensions exceed those estimated in the Lwandle (2012 EIA) study, the extent of the plume reported in the impact assessment tables of this study may increase from being limited to the “Immediate Dredge Area” to affecting possibly the “Annual Mining Area”. It is not expected that this change in the extent of the impact would be such that it affected the “Specific Mining Site”. Therefore it is not expected that these possible, but modest, changes in the impacted area will materially affect the environmental decision-making surrounding this project.

5.2 RECOMMENDATIONS

The proposed Modelling approach 2 is viable in terms of cost, duration of the study and likely outcomes. Such modelling indeed will constrain some of the uncertainties remaining in the assessments around plume extents and durations (e.g. associated with uncertainties in sediments loads, sediment characteristics, settling rates, etc.) and also better characterise the sensitivity of the impact assessments to possible changes in the rates of dredging and nature of material being dredged. However, as indicated above, any changes in the estimated extent of the impacted area indicated by the modelling, are expected to be modest and unlikely to affect substantially the environmental decision-making surrounding this project.

The modelling will provide a more explicit means (than the existing assessments) of constraining the uncertainties (listed above) and providing greater confidence in the assessed impacts based on the plume behaviour extents and duration. . Should this be a priority, a modelling study should be undertaken using Modelling Approach 2, despite the fact that the outcomes of such modelling are unlikely to materially change the significance of assessed impacts.

Should such modelling not be undertaken prior to the commencement of dredging operations, it is recommended that modelling form a key part of the verification and impact monitoring studies proposed for the early stages of the proposed dredging operations (e.g. by helping to inform the design of monitoring activities and in the interpretation of the resultant measurements). . An appropriate model-based predictive capability is likely to prove invaluable should environmental constraints (over and above those already anticipated) need to be placed on dredging operations.

Furthermore the development of a well-calibrated and validated model-based predictive capability is likely to prove invaluable for future environmental impact assessments of a similar nature or should it become necessary in the future to assess potential cumulative impacts of marine dredging in these waters.

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