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WAMSI Dredging Science Node Theme 3 I Synthesis Report: Characterisation and prediction of dredge-generated sediment plume dynamics and fate

Chaojiao Sun[1,5], Ryan Lowe[2,5], Peter Fearns[3,5], Marco Ghisalberti[4,5], Paul Branson[1,4,5]

[1]CSIRO Ocean and Atmosphere, Perth, Western Australia, Australia

[2]School of Earth Sciences, UWA Oceans Institute and ARC Centre for Coral Reef Studies, The University of Western Australia, Crawley, Western Australia, Australia

[3]Department of Physics and Astronomy, Remote Sensing and Satellite Research Group, Science and Engineering, School of Science, Curtin University, Perth, Western Australia, Australia

[4] University of Western Australia, Oceans Graduate School, Crawley, Western Australia, Australia

[5] Western Australian Marine Science Institution (WAMSI), Perth, Western Australia, Australia

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WAMSI Dredging Science Node

The WAMSI Dredging Science Node is a strategic research initiative that evolved in response to uncertainties in the environmental impact assessment and management of large-scale dredging operations and coastal infrastructure developments. Its goal is to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging in Western Australia, delivered through a combination of reviews, field studies, laboratory experimentation, relationship testing and development of standardised protocols and guidance for impact prediction, monitoring and management.

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This remarkable **collaboration between industry, government and research** extends beyond the classical funder-provider model. End-users of science in regulator and conservation agencies, and consultant and industry groups are actively involved in the governance of the node, to ensure ongoing focus on applicable science and converting the outputs into fit-for-purpose and usable products. The governance structure includes clear delineation between end-user focussed scoping and the arms-length research activity to ensure it is independent, unbiased and defensible.

And critically, the trusted across-sector collaboration developed through the WAMSI model has allowed the sharing of hundreds of millions of dollars' worth of environmental monitoring data, much of it collected by environmental consultants on behalf of industry. By providing access to this usually **confidential data,** the **Industry Partners** are substantially enhancing WAMSI researchers' ability to determine the real-world impacts of dredging projects, and how they can best be managed. Rio Tinto's voluntary data contribution is particularly noteworthy, as it is not one of the funding contributors to the Node.

Funding and critical data

Critical data

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Corresponding author and Institution: Chaojiao Sun, chaojiao.sun@csiro.au

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Front cover images (L-R)

Image 1: Trailing Suction Hopper Dredge *Gateway* in operation during the Fremantle Port Inner Harbour and Channel Deepening Project. (Source: OEPA).

Image 2: Piston sediment corer being retrieved from deployment. (Source: Kevin Crane)

Image 3: Dredge Plume at Barrow Island. Image produced with data from the Japan Aerospace Exploration Agency (JAXA) Advanced Land Observing Satellite (ALOS) taken on 29 August 2010.

Image 4: Flume experiments using idealized roughness to assess how canopies modify sediment transport (image courtesy of UWA).

Contents

1 Introduction

Dredge plume modelling is often used in Environmental Impact Assessment (EIA) of large-scale port and coastal developments to quantify and model the transport and fate of sediments released during dredging operations. The modelling is used to describe the spatial extent and intensity of the 'pressure field' generated by dredging related activities, including how it develops and changes over time. The model results are frequently used in biological response models to predict the consequences of the estimated pressure field on the health of sensitive benthic communities and habitats such as coral reefs and seagrass meadows.

Whilst fundamental to the predictions of environmental impact, dredge plume modelling at the EIA stage is challenging due to limited availability of information such as model input data and detailed information of the dredging program is often not known. There are significant benefits to be gained by improving the modelling process such as providing more clarity around appropriate data requirements for model calibration and validation, which will provide greater accuracy in the modelling outputs. This will in turn provide proponents and regulators with greater confidence in the model to support better decision making.

The objectives of the WAMSI Dredging Science Node (DSN) Theme 3 are to provide insights and guidance on ways to improve the modelling and monitoring of passive dredging plumes to support the EIA and management of dredging programs, with a focus on the Pilbara region of Western Australia. By carefully designing a number of laboratory, field and numerical model investigations, Theme 3 has advanced the modelling and measurement (via remote sensing) of dredging generated plumes. Under an agreement with WAMSI, unprecedented access was granted to baseline, dredging and monitoring data from a major dredging project in the Pilbara region. Effort focused on modelling the dynamics and fate of total suspended solids (TSS) in the passive dredging plume, with the goal of identifying the most important processes and model parameters. Those processes include in-canopy sediment transport processes, the bed schematization and cohesive sediment transport model parameters. The utility of applying remote sensing techniques to monitor sediment plumes and establishing background conditions was also explored.

Importantly, the research program was undertaken to ensure the model output parameters and their representations and analyses, were compatible with the critical effects thresholds (e.g. 14 day running percentiles, daily light integral) that were being generated by the biological themes of the WAMSI DSN (see Themes 4 to 7).

2 State of knowledge prior to the WAMSI DSN

In the past decade there has been a significant increase in port developments across Western Australia, especially in sub-tropical and tropical north-western Australia. In 2011–12 alone, four proposals in the Pilbara region had a combined dredging volume of about 130 million m^3, which was significant by global standards. Since the released sediments can cause damage to marine habitats, most large-scale dredging proposals are subject to EIA as part of the approvals process. In Western Australia, the EIA process requires dredging proponents to make scientifically sound predictions of the likely extent, severity, and persistence of environmental impacts of the proposed activity under a spatially defined zoning pattern. Review of previous EIA studies demonstrated a clear lack of consistency in the approach to modelling, parameter estimation and reporting. Furthermore, prior to the DSN, objective understanding was lacking in areas such as: the accuracy of dredge plume transport and fate modelling; dredge plume remote sensing; and, transport processes over canopies.

2.1 Remote sensing of suspended sediment plumes

Review of remote sensing products that could be applied to dredge plume monitoring demonstrated that there was no region-specific algorithm for estimating TSS from remote sensing data. Further, there was no understanding of the expected accuracy of the more than 70 published MODIS and Landsat TSS algorithms if they were to be applied in waters of unknown optical characteristics.

2.2 Sediment transport processes over complex canopies

The seabed has generally been assumed to be smooth and not considered macroscopic roughness in the form of seagrass and coral canopies. As such the impact of the canopy on in-canopy sediment transport processes (deposition and resuspension) through modified hydrodynamics and bed shear stress had not been studied in detail. Sediment transport formulations developed for bare beds have never been tested in canopy systems.

2.3 Hydrodynamic and sediment transport modelling

It is generally accepted that hydrodynamic and wave models are mature and usually well calibrated and validated, but this is not the case with sediment transport models due to the more complex nature of sediment transport processes and lack of calibration and validation data. The current state of dredge plume modelling for EIA was identified by a literature review of dredge plume modelling practice (Sun et al 2016) and an expert workshop held in 2016 with key stakeholders (https://www.wamsi.org.au/news/better-predictions-dredge-plumes). It was found that there was no consistent approach in modelling and a suitable protocol or standard did not exist. There was no consistent method to calibrate and validate the models or to evaluate model skills. Further, there was a lack of understanding of sources of model uncertainty and knowledge gaps in appropriate model parameterisation, including which model parameters are most important, and the appropriate ranges for their values?

The review identified several key questions that must be tackled in a dredging plume project. There was no consensus on the conditions under which two-dimensional (2D) modelling would be sufficiently accurate to provide robust predictions of environmental impact. The passive sediment source characteristics were schematised in a widely varying manner with a range of different sediment sizes and estimated settling velocities, compounding uncertainty in the numerical model results. Most EIA studies only model the excess TSS produced by dredging. However, this complicates comparison with measured data and limits the capacity to evaluate the cumulative impact of dredging in combination with natural TSS dynamics. This in turn, results in difficulty in translating model outputs into ecologically relevant pressure fields, resulting in model outcomes that are difficult to interpret against ecological thresholds.

Consequently, the regulators have generally adopted a precautionary approach and the proponents have have applied overly conservative estimates of plume footprints (predicted plume footprints significantly larger than subsequent comparative observations). This approach has led to confirmed “good” environmental outcomes, however, the cost of monitoring program has been unnecessarily high and less informative.

3 Research Program

The focus areas of the Theme 3 research program were to develop better TSS algorithms for remote sensing, improve understanding of the modified sediment transport process over canopies, and carefully develop a model hindcast to investiage model sensitivity and assess ecological pressure field prediction.

3.1 Research Priorities

3.1.1 Remote sensing of suspended sediment plumes

Remote sensing can be used to provide data over large areas and in near real time. Remotely sensed chlorophyll-a and sea surface temperature data are routinely used for fisheries management. More recently remote sensing techniques have been used to provide information on the dynamics and extent of sediment plumes generated by dredging. However, to improve accuracy, mathematical algorithms designed to convert spectral data into suspended sediment concentrations need to be calibrated and validated to the local conditions. The priority of this project was to develop algorithms tuned to local conditions in the Pilbara region and provide a calibration and validation dataset for numerical modelling.

3.1.2 Sediment transport processes over complex canopies

Current practices in hydrodynamic and sediment transport modelling assume a smooth (bare) seabed comprised of sediment without canopies present. However, vegetation and coral reef canopies can significantly increase the roughness of the seabed and thus alter near-bed velocities and bed shear stresses. This modification of bed stress is expected to have significant implications for the processes of erosion and deposition in these environments, but this has not been rigorously tested. A high priority for Theme 3 research was to develop new transport formulations applicable to a broad range of bottom types building on 'conventional' knowledge of sediment transport over bare sandy beds. This was to be done using a combination of laboratory and field experiments to measure the influence of the canopy on near-bed flow, bed stress and sediment transport characteristics.

3.1.3 Hydrodynamic and sediment transport modelling

The modelling of dredging plume dispersion is necessarily complex due to the stochastic nature of the environment and physical processes associated with advection, diffusion, settlement and resuspension of sediment. The research priorities in the numerical modelling project were to evaluate empirical source term estimation techniques in a case study where validation data from a real dredging campaign was available, investigate the effects of 2D or three-dimensional (3D) modelling, investigate the sensitivity of key parameters used in sediment transport modelling, and demonstrate the concurrent modelling of natural and dredged sediments, and assess the number of sediment fractions required for passive dredging plume modelling. To support the numerical model development, a priority of the program was to conduct field investigations during a case study dredging project to validate the numerical model and develop remote sensing algorithms for TSS.

3.2 Research Projects

The WAMSI DSN Theme 3 research program was designed to provide knowledge to support improved and more efficient monitoring and modelling of passive plumes generated by dredging activities, including model outputs in units consistent with key indicators of pressure (to sensitive biota) identified in the subsequent themes. A number of inter-related projects were undertaken in three broad areas (1) Remote sensing of suspended sediment plumes, (2) Transport processes, (3) Numerical Modelling.

Prior to the commencement of the research projects, literature reviews were conducted for each of the three research areas to benchmark current understanding.

3.2.1 Remote sensing of suspended sediment plumes

Field samples of benthic sediments were re-suspended in laboratory conditions to compare and contrast the various optical scattering measurements obtained with a range of common *in situ* sensors. Results were used to assess the efficacy of the procedure to potentially support or replace extensive *in situ* field programs. Data from the investigation were used to inform the modelling study for the remote sensing algorithm analysis and used to quality control some of the instrument data from the field campaign.

Field data and modelling were used to develop and test a semi-analytical TSS algorithm. The TSS algorithm was applied to 10 years of MODIS data to determine baseline conditions and highlight deviations from the baseline caused by events such as dredging, river outflow and storms. The impact of the different spatial resolutions of different sensors on estimates of TSS concentration was also investigated.

3.2.2 Sediment transport processes over complex canopies

Field and laboratory (flume) studies were used to understand and predict the processes governing near bed sediment transport (including how dredged sediment is deposited and resuspended, with a particular focus on how sediment transport is modified by the canopies that are characteristic of sensitive coastal ecosystems such as coral reefs and seagrass meadows).

3.2.3 Hydrodynamic and sediment transport modelling

Hydrodynamics and wave models were set up using the best available bathymetry and metocean forcing, analysis of wave, currents and bed shear stress climate were undertaken, and the models were calibrated and validated. A two-part large field program was undertaken in 2013 and 2014 to collect environmental data for optical, hydrodynamic and sediment transport model calibration and validation during inshore and offshore dredging campaigns for a large dredging project off Onslow. Extensive analysis of electronic dredging logs was undertaken and source terms estimated for the hindcast dredging project. A range of analysis techniques and methods were applied to estimate source term characteristics using baseline and monitoring data. Model sensitivity to different parameters was tested, a hindcast of dredge plume evolution was produced, and ecologically relevant pressure fields were calculated.

4 Overview and synthesis of findings

This section sets out the key findings of the research program in the context of providing knowledge for improving the prediction and management of the physical effects of dredging related activities in the tropical waters of WA, with a particular focus on the Pilbara region.

Access to environmental monitoring and input data from a large dredging project near Onslow was fundamental to the success of the program and allowed a level of confidence to be placed on the interpretation of results that have not been available before. Significant effort was put into interrogating and analysing the data to prepare it for use. To complement these data, field work was undertaken during the dredging campaign to capture the different characteristics of dredge plumes during offshore and inshore dredging for use in numerical model calibration and validation, and remote sensing algorithm development. The field program provided important information on plume characteristics and established the relationship between turbidity and TSS, demonstrated the 3-dimensional structure of the dredge plume in shallow waters (< 10 m depth) and provided estimates of the in-situ settling velocity.

4.1 Remote sensing of suspended sediment plumes

Project 3.2 used a combination of field measurements and controlled tank-based tests to measure relevant optical and physical parameters required for algorithm development and tuning, including nephelometric turbidity units (NTU), scattering and backscattering coefficients, particle size distribution (PSD) and acoustic scattering, to compare the efficacy of the in-situ and ex-situ approaches. The in-situ data were used to develop remote sensing algorithms applicable to MODIS, Landsat and WorldView-2 satellite data and develop a model of spectral attenuation of light in turbid waters as a function of TSS. This model has been applied to MODIS TSS data to produce maps of relative light intensity at the substrate which is important for predicting impacts to benthic primary producers. The physical data have also been used as inputs to help validate modelling of plume dynamics (see Sun et al. 2017).

4.1.1 Re-suspension of sediment samples

With consideration for the excessive cost and logistical effort involved in collecting high quality *in situ* optical measurements, we investigated the efficacy of collecting substrate samples for subsequent re-suspension and measurement in a controlled environment. Material from benthic sediment samples collected in the locale of the dredging and water sampling activities was re-suspended in laboratory conditions. The PSD’s derived from this tank-based activity consistently displayed bimodal characteristics, in contrast to the typical power law distribution PSD’s measured in the *in situ* water column. It is therefore advised that sample collection and re-suspension is not a reliable procedure for collecting optical data associated with a sediment sample. However, the data collected in the controlled environment did prove useful for informing quality control of some field-collected data.

4.1.2 Algorithm development

Field data and optical modelling were used to develop a Semi Analytical Sediment Model (SASM) which may be 'tuned' for use by different satellite-borne sensors. In this work the SASM was applied to MODIS, Landsat-8 (Figure 1) and WorldView2 data. The semi analytical form of algorithm was shown to be more robust than most empirically based TSS algorithms with respect to application across a wide range of water conditions. The field data showed that the vertical distribution of TSS is quite variable, and since optical remote sensing methods can only 'see' into the top few metres of the water column, attempting to estimate TSS concentration throughout the water column based on remote sensing methods is unlikely to produce results with high confidence.

4.1.3 TSS algorithm selection

This study identified more than 70 MODIS and Landsat TSS algorithms published in the past decade. An extensive optical modelling investigation compared all the algorithms to show a small number that are robust across a range of water types and showed the majority to be sensitive to water optical conditions. Thus, the selection of a TSS algorithm for a specific application must be undertaken with some degree of caution. Optimum results would be achieved by model tuning and *in situ* validation of the remotely sensed product.

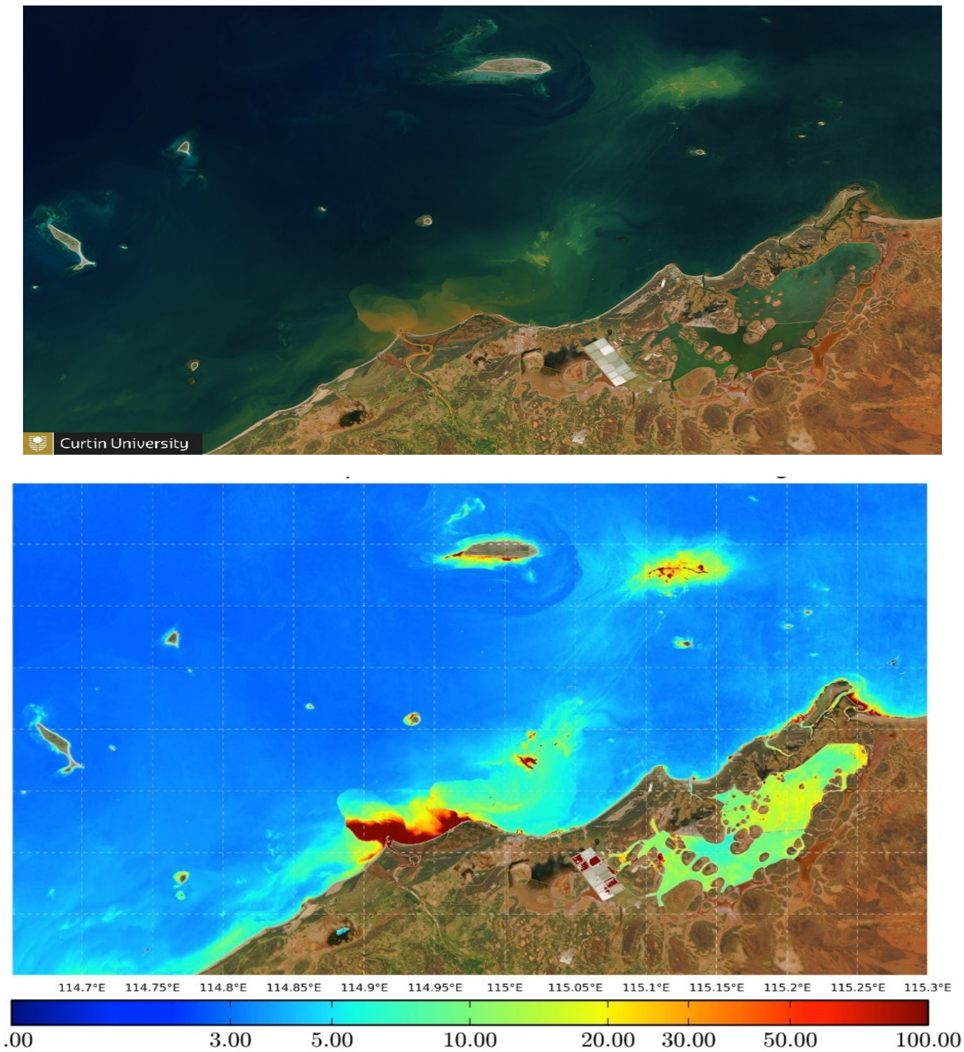
Spectral nature of light at depth. Vertical profile measurements of hyperspectral downwelling irradiance were used to develop a relationship between water column TSS and spectral light attenuation. Significant changes in spectral light quality were demonstrated for changes in TSS concentration. The spectral light attenuation model was used to calculate the total light quality and intensity of photosynthetically active radiation (PAR) at the substrate. Although the primary measure of light in relation to understanding impacts of turbid water on photosynthesising organisms is total PAR, changes in the spectral quality have been shown to have significant impact on the photosynthetic processes. The hyperspectral attenuation model is able to provide estimates of both the total PAR and the spectral quality.

4.1.4 Spatial Resolution

Remotely sensed TSS estimates are affected by the spatial distribution of TSS and the spatial resolution of the sensor used to obtain the image. The remotely sensed product may be considered to represent an average value over the spatial extent of the image pixel, although due to the non-linear relationship between ocean reflectance and the TSS concentration, the TSS product can only be considered an estimate. Higher spatial resolution sensors (e.g. WV2 and Landsat-8) produce higher maximum TSS values than lower spatial resolution sensors (e.g. MODIS), particularly as the spatial variability of *in situ* TSS increases. If remote sensing methods are to be applied to monitoring absolute values of TSS, consideration must be taken of the spatial resolution of the sensor and the spatial variability of the plume features being observed.

4.1.5 Time series and anomaly analysis

Remote sensing data were shown to be useful in determining historical and baseline TSS conditions for the entire Pilbara region. Historical data were able to be used to identify anomalous TSS events linked to storms, enhanced river outflow, dredging activities and resuspension of sediments in the dredge spoil ground. Analysis of wind speed and TSS showed no significant correlation for wind speeds less than 7 ms^{-1}. For wind speeds greater than 8 ms^{-1} the correlation was greatest for a lag of 3 days, suggesting winds need to be extended in time to have a significant effect and that re-suspended TSS takes 3 days to build to a maximum. The anomaly analysis proved useful in highlighting the zone of influence of the dredge activities and the spoil ground (see Figure 1).



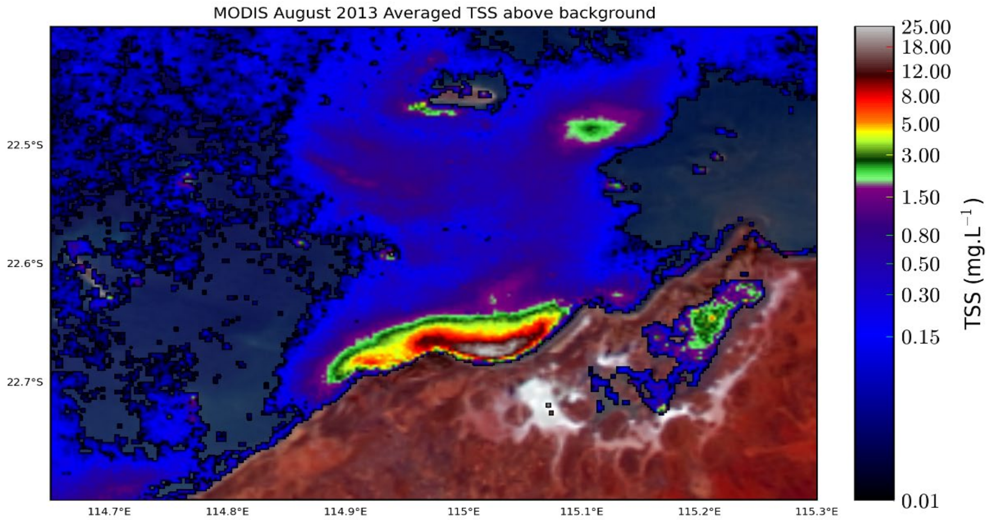


Figure 1. Top: Landsat true colour image for 23 May 2014 showing turbid water associated with outflow from the Ashburton River, dredging operations and the turbid water at the location of the spoil ground. Bottom: TSS derived from Landsat 8 data for the same date as the true colour image Figure 2. TSS anomaly image for August 2013. MODIS TSS data were used to determine a 10-year baseline level. The anomaly image shows the difference between monthly mean TSS for 2013 and the baseline TSS level. The spoil ground, river outflow and dredge region are distinct.

4.2 Sediment transport processes over complex canopies

4.2.1 Conventional models

Conventional sediment transport models were found to break down dramatically in coastal ecosystems with large bottom roughness (canopies) present. These models typically either (1) ignore the flow attenuation provided by the canopy or (2) assign an enhanced bed stress to canopy regions (to diminish the flow), a correction which ultimately enhances sediment erosion (relative to adjacent regions without canopies). Both of these errors can result in massive over-prediction of the capacity for sediment to be mobilised within the canopy, and thus significantly underestimate the potential impact from dredging activities.

4.2.2 Hydrodynamic driver of sediment transport in canopies

To accurately predict the deposition and resuspension of sediment in canopy systems, the in-canopy (i.e. near-bed) velocity is the flow measure that most needs to be quantified. Laboratory experiments demonstrate robust predictive capacity for the near-bed velocity under both current- and wave-dominated conditions. Furthermore, thresholds for the onset of sediment motion in canopy systems can be described in terms of this near-bed velocity. Once this velocity threshold is exceeded, canopies that experience sediment deposition become regions of sediment remobilisation. Importantly, these threshold near-bed velocities in canopies are shown to substantially breakdown when applying conventional bare bed models.

4.2.3 Effect of canopies on hydrodynamics

The effect of the canopy flow attenuation, which causes the in-canopy velocity to be significantly less (by up to an order of magnitude) than that in the absence of the canopy, is two-fold. Firstly, suspended sediment concentrations in real canopies are seen to be significantly less than those in adjacent bare bed areas, indicative of the capacity for canopies to create strongly depositional environments. Secondly, when the canopy flow attenuation is not accounted for, predictions of sediment resuspension in canopy environments are in clear disagreement with field observations.

4.2.4 Development of new models for canopy environments

Key parameters of the near-bed flow that govern rates of sediment remobilisation in canopy environments (in particular the bed stress, described through the bed shear velocity, u_*) are also described in terms of the near-bed velocity. The physical link between the near-bed flow and sediment transport in canopy systems has allowed the prediction of rates of sediment mobilisation in canopy environments and comparison against detailed measurements in both the laboratory and the field. Indeed, bed stress estimates that account for the reduced near-bed flow vastly improve the relationship between the predicted and observed grain sizes in suspension. In a complex flow environment with mean currents, swell waves and low-frequency wave motions, regions of rapid sediment suspension (and high suspended sediment concentrations) can be readily predicted through consideration of the canopy impact on the near-bed flow and, in turn, the impact on local bed stresses.

Overall, by consideration and prediction of the in-canopy flow, this project provides a new capacity for the prediction of regions that are most prone to rapid rates of deposition of sediment in a dredging plume. In particular, dense canopies in low-flow environments (where the near-bed velocity or stress will often fall below the threshold value) are most at risk of rapid rates of sediment deposition. The timescale of removal of deposited sediment from these systems will be governed by rates of sediment mobilization during high-flow periods.

4.3 Hydrodynamic and sediment transport modelling

The goal of the numerical modelling project was to improve the prediction of the transport and fate of dredge-generated sediments and translation of dredge plume model results into ecological pressure fields. The project sought to develop an improved understanding of key physical processes that control the extent, intensity and duration of sediment plumes by improving the modelling of the dynamics and fate of total suspended solids (TSS) in the passive dredge plumes. The study included an extensive review of past EIA studies and re-modelled a recently completed capital dredging project in the Pilbara region (a hindcast) with the benefit of access to all the collected data.

A particular challenge in the modelling of far field dredging plumes is the translation of model output into ecologically relevant pressure parameters that are measurable in the field. Model output needs to be provided in a way that is resolvable and comparable to field measurements. This is particularly challenging where there is significant spatial variability in natural sediment dynamics within a project area, making the selection of appropriate reference sites difficult. In addition to the temporal variability in TSS, forcing due to differences in meteorological conditions often confound the use of baseline data.

Effort was focused on identifying the most important processes and model parameters, in particular, the bed schematization and cohesive sediment transport model parameters. A broad range of data was analysed to define the sediment transport model parameters and processes. Hydrodynamic and wave models were set up using the best available bathymetry and metocean forcing for the region. The models were calibrated and validated against available wave and current data and bed shear stress climatology analysed. A sediment transport model was set up using source terms derived from the analysis of dredging logs, and sediment characteristics were based on analysis of baseline and monitoring data. Model sensitivity to different parameters was analysed and model parameters that are important, difficult to establish, or interdependent were identified. A hindcast of dredge plume evolution was produced. Once calibrated, the model was applied to assess the relative contributions of both the ambient and dredging fine sediment fractions with ecologically relevant pressure fields calculated.

The carefully calibrated hindcast model was used to (1) improve the estimation of source terms for the passive far-field model; (2) identify and improve the estimates of important sediment transport model parameters; and (3) demonstrate some statistical means of calculating ecologically relevant pressure fields.

4.3.1 Model calibration parameters

Detailed sensitivity analysis of the sediment transport model parameters highlighted the complexity in modelling cohesive sediment transport due to numerous sensitive and interdependent parameters. The final model parameter set and configuration was identified through an extensive set of model simulations that was compared qualitatively and quantitatively against observations of TSS, including near-surface TSS derived from remote sensing data from MODIS, and near-bed TSS derived from the *in situ* monitoring instruments. Examples of the resulting model calibration parameters from the case study are provided in Table 1 and Table 2.

Table 1. Example overview of key wave and hydrodynamic model processes and parameters from the numerical modelling study.

Description	Value/model applied	Justification
White capping model	Westhuysen (2007)	Improved modelled wave height of locally generated seas on the shelf
Wave bottom friction model	Collins (1972)	Commonly applied bed friction model
Wave bottom friction coefficient	0.015	Model default value for mixed sand seabed, confirmed through model sensitivity analysis
Hydrodynamic bottom roughness formulation	White-Colebrook (z0)	Standard roughness formulation for 3D models
Bottom roughness coefficient	0.001 m	Based on model sensitivity analysis and calibration
Horizontal eddy viscosity coefficient	5 m^2/s	Based on model sensitivity analysis
Vertical turbulence closure model	k- ε	Commonly applied turbulence closure model applied in shallow coastal seas
Model for bottom shear stress due to waves and currents	van Rijn (2007)	Successfully applied in previous studies

Table 2. Example overview of key sediment transport model parameters from the numerical modelling study

Description	Value applied	Justification
Horizontal eddy diffusivity	0.5 m^2/s	Based on model sensitivity analysis
Background vertical eddy diffusivity	1.00E-6 m^2/s	Model default value, modelled eddy diffusivity (from k- ε mode) typically one to two orders of magnitude larger
Fluff layer 0th-order erosion parameter (M_2)	2.00E-5 m^2/s	Manually calibrated based on sensitivity analysis and numerous model calibration simulations
Fluff layer 1st-order erosion parameter (M_1)	1.00E-4 m^2/s	
Fluff layer critical shear stress threshold for erosion ($\tau_{cr,f}$)	0.15 N/m^2	
Burial fraction on deposition (α)	0.15	
Settling velocity (w_s) – dredging fines	0.2 mm/s	Established based on analysis of measured data (sediment traps and LISST data) and model sensitivity analysis
Settling velocity (w_s) – natural fines	0.5 mm/s	
Buffer layer critical shear stress threshold for erosion ($\tau_{cr,e}$)	1.0 N/m^2	Manually calibrated based on sensitivity analysis and numerous model calibration simulations
Buffer layer erosion parameter (M_0)	2.00E-5 m^2/s	
Buffer layer thickness (d_0)	0.05 m	Manually calibrated based on sensitivity analysis and numerous model calibration simulations. Consistent with typical scale of active transport layer for mixed sand beds

4.3.2 3D modelling

A frequent question encountered during the modelling of passive dredging plumes is if a 3D model is needed, or if the circulation and plume dispersion can be considered quasi-two dimensional such that 2D modelling is sufficient. This study identified that even in very shallow water strong vertical gradients in TSS and sub-surface plumes were observed in both field data and model results. In order to make use of both remotely sensed (near surface) and *in situ* (near bed) TSS in the model calibration it was necessary to utilise a 3D model due to the vertical gradients in TSS. This is particularly important for the sediment resuspension process which establishes a near-bed peak in TSS. Furthermore, a secondary circulation that was established due to wind stress was better resolved in the 3D model compared to the 2D model, and this is consistent with recent analytical arguments that suggest the fundamental assumptions of quasi-two dimensionality in shallow seas break down (Cushman-Roisin & Deleersnijder 2019).

4.3.3 Source term estimation

Detailed analysis of dredging logs established the location and timing for over 22,000 separate dredging plumes across eight different operational modes utilised during the dredging campaign. An established empirical source term model was utilised to estimate the fine sediment flux introduced into the water column for each of the plumes. The spatially and temporally varying source terms were validated to ensure mass closure of the fine sediment budget available in the excavation, consistent with the assumed parameterisation of source terms utilised in the empirical model. The crucial calibration parameters to ensure mass closure were the duration of the dredging and placement phases of the dredging cycle. Based on comparison with the measured data, in particular at sites close to the dredging, the empirical model was found to be a reasonable approach to the estimation of source terms.

4.3.4 Number of sediment fractions and settling velocities

The approach of using a single fine sediment fraction for the dredged material and a single fine sediment for the ambient sediment made it feasible to carry out extensive model simulations, enhancing the effectiveness of the investigation of model parameter sensitivity. The approach reproduced the initial plume settling and resuspension processes well but was not able to maintain a low background TSS concentration of ~2 mg/L that was observed across the shelf.

4.3.5 The fluff layer

It was not possible to reproduce the resuspension of easily erodible freshly deposited dredging material on the inner shelf without the use of a fluff layer model such as the one in van Kessel et al. (2010). Due to the depth of the inner shelf and protection from swell energy by the broad shelf and numerous offshore islands, the inner shelf is a comparatively low shear stress environment. Without the use of the more easily erodible fluff layer it was not possible to reproduce the observed resuspension dynamics of freshly deposited dredging fines on the inner shelf (lower bed shear stress) at the same time as resuspension in the nearshore (higher bed shear stress). The inclusion of the fluff layer model introduces several additional interdependent parameters to the formulations for cohesive sediment transport which presents an additional challenge for model calibration. An alternative approach would be to utilise a spatially variable bed shear stress threshold based on the seabed particle size distribution as was applied in Dufois (2018).

4.3.6 Benefits of modelling ambient sediment

Whilst the modelling of the ambient TSS dynamics presents a significant challenge for modelling practitioners, there are significant benefits to all stakeholders involved:

- Dredging proponents are able to better establish the magnitude of dredging impacts relative to natural processes, which is particularly relevant in naturally high TSS environments
- The cumulative impact of dredging and natural TSS on benthic ecology can be assessed
- The model can be utilised more effectively in an operational context for proactively managing ecological pressure during the dredge campaign
- Model output can be directly compared to monitoring data
- The near-bed light climate and associated ecological pressure of light reduction can be readily modelled
- It advances the scientific understanding of the TSS dynamics of the systems being modelled and their relative exposure to waves, tides, cyclones and runoff
- In the numerical modelling study, modelling the ambient sediment enabled successful simulation of TSS dynamics across the majority of the system influenced by passive dredging plumes. The modelling of both ambient and dredging TSS was critical to adequately assess the combined pressure on the benthic light climate and habitat.

4.3.7 Ecological pressure field prediction

A particular challenge in assessing the environmental impact of dredging is in translation of modelled far-field dredging plumes into pressure parameters that are measurable in the field and account for the combined effect of both ambient and dredging pressure. The DSN Theme 4 research found strong relationships between coral mortality and a number of water quality indicators during dredging management near Barrow Island. The thresholds established for coral health and mortality in a clear water environment (Fisher et al. 2017) are applied to the calibrated passive plume model results to demonstrate how model results could be translated into ecologically relevant pressure fields. It is important to note that the numerical modelling study does not consider the benthic habitats present across the study site and, in that sense, the estimated pressure fields are not indicators of the pressure fields realised during the dredging campaign.

The numerical modelling study highlighted the difficulty in applying thresholds developed for different regions and where there is significant variability in the ambient TSS climatology. The numerical modelling of ambient sediment dynamics provides the opportunity to utilise the model to assess absolute thresholds that combine the potential stress from both natural and dredging disturbance. Examining the spatial distribution of the TSS and light probability distributions can assist in identifying the regions where the greatest dredging pressure relative to natural pressure is experienced and this can assist in the selection of impact and reference monitoring sites.

5 Implications for management

5.1 Remote sensing of suspended sediment plumes

5.1.1 Pre-development surveys

Analysis of historical remote sensing data can provide information on baseline water conditions, an understanding of the natural variability in water conditions, including seasonal patterns, spatial distribution of turbidity features (for example, the extent of impact of river outflows on water clarity), and evidence of re-suspension due to storms and cyclones.

If historical *in situ* TSS data are available for a region of interest, these may be used to assess the accuracy of remotely sensed products. Note that the selection of an appropriate TSS algorithm is supported by knowledge of the expected local water conditions. We recommend pre-development surveys include collection of ocean surface spectral reflectance and co-incident TSS measurements.

5.1.2 Impact prediction

Remote sensing can provide a historical perspective and near real-time observations of water conditions. Remote sensing does not include a predictive capability, however remote sensing data do provide excellent spatial and temporal data to help validate the outputs of dredge plume modelling.

5.1.3 Monitoring

Remote sensing can provide near real-time monitoring of turbid plumes generated by dredging or other activities. In its simplest form, a true colour image can provide undeniable evidence of the surface extent of plumes. By processing the remotely sensed data with a suitable algorithm, estimates of water column TSS concentration may be inferred. Further processing may provide estimates of the intensity of the light field at the substrate.

Moderate resolution sensors, such as MODIS, capture data daily. High resolution sensors, such as Landsat 8, are less frequent, but with continuous developments in space-based remote sensing the re-visit frequency is improving (approximately 5 days for the Sentinel series). Geostationary satellites such as Himawari-8 can provide images at high temporal resolution (e.g. 10-minute intervals).It is important to understand that the depth at which remote sensing instruments can 'see' into the water column is limited to a few metres, or a few centimetres in extremely turbid conditions. Inferring the total water column TSS load from remotely sensed 'surface estimates' is limited by the ability to predict the vertical TSS distribution profile.

We recommend ongoing collection of TSS data throughout the monitoring period to help validate the remote sensing products, to add confidence to the remote sensing products, and to potentially improve the remote sensing products, including retrospective remote sensing data used for determining background conditions.

5.1.4 Management

Remote sensing data can provide undeniable evidence of the extent and duration of dredge plumes near the sea surface. In particular, high resolution sensors can be used to produce high quality images that aid in understanding many aspects of the dredge operations.

The remote sensing TSS products have an associated uncertainty, but we expect the relative concentrations spatially and temporally to be comparable. As such, extreme events or exceedances can be identified by considering statistically significant deviations from a baseline condition and this information can inform adaptive management strategies that aim to minimise dredging pressures in sensitive areas.

Analysis of spatial and temporal patterns in remotely sensed data, such as anomalies in TSS relative to a background conditions, can provide supporting evidence to help define the realised zone of influence of a dredge plume.

5.2 Sediment transport processes over complex canopies

5.2.1 Pre-development Surveys

Accurately quantifying the characteristics of benthic habitats prior to dredging operations is essential for predicting local rates of sediment deposition and the resuspension of sediment deposits. The simplest set of surveys should provide basic identification and spatial extent of key benthic habitats (e.g. seagrass meadows, coral reefs and rocky reef habitats).

There can be substantial variability in sediment grain properties (shape, porosity, density, etc.) that can substantially influence sediment transport (i.e. through modifications to the settling velocity). Direct measurement of (i) settling velocities using a settling tube and (ii) grain density is desirable. Typically hydrodynamic monitoring programs focus on observing relatively deep water movements; however, to correctly predict the hydrodynamics within potentially impacted benthic ecosystems requires direct measurements of the shallow water hydrodynamic processes. This hydrodynamic information is needed to develop more accurate reef-scale hydrodynamic models that are essential for predicting the expected spatial pattern of dredging impacts across individual reef systems.

5.2.2 Impact Prediction

Accounting for the additional bottom roughness is critical to obtain robust hydrodynamic model predictions of the ambient currents and waves within these benthic ecosystems (including resolving the strong spatial variability that arises from habitat variability), which in turn can have a major influence on sediment transport predictions. Information from habitat surveys should be incorporated into hydrodynamic model predictions and models should be rigorously validated with hydrodynamic observations in the pre-development stage.

The application of conventional modelling approaches will greatly underestimate the sediment deposition that occurs in benthic canopies. It is recommended that the formulations developed here to estimate the reduction of bed shear stresses and sediment transport (see Report 3.3) be considered for incorporation in sediment transport models used to predict the fate and transport of dredged sediments.

Canopy systems whose values of the bed shear stress are below the thresholds established in Report 3.3 are most at risk of experiencing significant deposition. This is most likely to occur when current speeds are low, waves are small, and the canopy is tall and dense. Canopies that are predicted to fall below this threshold for a significant fraction of their exposure time to the dredging plume are those most at risk of harmful effects from the deposition of dredging-derived sediments.

Given the expected enhancement of sediment deposition in benthic ecosystems with large bottom roughness, monitoring efforts during dredging operations should consider having near real-time *in situ* measurements of rates of sediment deposition across a number of potentially impacted habitat types (even if in relatively close proximity), rather than simply focusing on distributing these sites in space. This monitoring would provide an early warning mechanism if there were substantial discrepancies in modelled versus observed depositions and increase confidence that the effect of the bottom roughness is correctly being accounted for in earlier impact prediction modelling.

5.2.3 Post-assessment

In the event that a benthic ecosystem such as a seagrass meadow or coral reef becomes impacted by a dredging event, the same general approaches and models used to predict sediment deposition apply to prediction of resuspension of the deposited material. The roughness characteristics of the benthos (especially in seagrass and macroalgae canopies), may however, have changed significantly due to mortality.

There can be a strong feedback loop between seagrass density, suspended sediment concentrations and light levels. Therefore, accounting for how these canopies modify suspended sediment concentrations and the light climate can be an important factor to consider when assessing the likelihood of recovery. The resilience of seagrass meadows under chronic exposure to dredging plumes would, in part, be regulated by this feedback loop and must be considered.

5.3 Hydrodynamic and sediment transport modelling

There is an urgent need to build a database and a parameter library for dredge plume modelling: to provide a starting point for setting up the model; guidance on valid ranges of model parameters; validation data for hindcast; and data to validate basic assumptions for source term estimation (see Theme 2 report). Input data and subsequent validation data of EIA modelling should also be made public. This will provide a key evidence base for modelling practitioners to estimate source term fractions using datasets gathered in similar circumstances and to choose from a reasonable range of parameter values from the parameter library.

To improve inter-model comparison and future learning from existing studies, we strongly recommend key model processes and parameters be reported as the examples shown in Report 3.4. A rationale for the chosen parameter values should be provided in the proponents EIA documentation – even if it is simply model default values.

5.3.1 Pre-development surveys

Bathymetry and ambient sediments must be mapped and described to sufficient detail given that these inputs will determine the accuracy of the hydrodynamic/wave model and availability of fines in the system. Baseline collection of natural sediment cover is important for developing spatial maps of natural fine sediment availability.

Detailed sediment characteristics should be investigated *in situ* to determine settling velocities and density of natural sediments (similar to the requirements of project 3.3); this should include characterisation of the relationship between TSS and turbidity across a range of natural forcing conditions.

Wave and currents measurements should be obtained both in deep water and shallow water regions, which are likely forced by different mechanisms.

Terrestrial sediment sources may be important and would require baseline data collection if significant natural sediment sources are located close to dredging.

5.3.2 Impact prediction

Ecological pressure field prediction and modelling of ambient sediment dynamics

It is problematic to apply water quality guideline values/thresholds derived from other regions or locations due to the significant variability in TSS dynamics that may be present between sites. In addition, significant spatial variability in TSS can be present within a site due to variations in depth, exposure (to winds and waves) and sediment availability. The modelling of ambient sediment dynamics in the dredging plume model significantly improves the utility of model predictions and comparison against baseline data. Through modelling both the ambient and dredging suspended solids, model results can be directly compared to monitoring data and the tolerance limits of the biota. When the ambient sediment dynamics are validated and model error well characterised, shifts in the cumulative probability distribution of modelled TSS at each point can be examined, which could be a more robust approach to characterisation of the pressure field rather than single thresholds at the sites. Furthermore, in order to assess the combined impact of both ambient and dredging TSS it is essential to resolve the ambient TSS. **It is strongly recommended that the modelling of ambient suspended solids dynamics be undertaken as part of the EIA process.** The modelling of the ambient suspended solids dynamics also assists in establishing the reasonable range of a number of critical model parameters associated with resuspension and the se- bed schematisation. In addition, it assists in establishing the relative contribution of dredging to TSS.

Improved reporting of model parameters and assumptions.

An extensive review of previous EIA modelling studies highlighted significant inconsistency in the reporting of model parameters and assumptions. **It is recommended that key model parameters and formulations be a basic reporting requirement for all EIA dredge plume modelling studies. It is also recommended that a brief justification for the selected model formulation or value is provided to build knowledge of reasonable parameter values and to identify those that have undergone significant sensitivity analysis and calibration.**

Often model default values have been subjected to extensive testing and may be appropriate in many contexts.

Establishment of a data reference library for EIA dredge plume modelling.

When setting up and validating dredge plume models, modelling practitioners would have a good starting point if they are able to access past datasets gathered in similar circumstances and knowledge of a reasonable range of parameter values that have been documented from earlier studies. **It is recommended that a data library for EIA dredge plume modelling be established by requiring all EIA studies to submit modelling data as part of the approval process, including input data, calibration and subsequent validation data, along with key parameter values.** The data library will provide benefits to both the practitioners and regulators by informing valid ranges of model parameters, sample model input and validation data for hindcast studies, and data to assess basic assumptions for source term estimation. The data reference library will provide a key knowledge base for future studies and increased consistency between EIA assessments.

Estimation of source terms and reporting.

The Becker et al. (2015) model was applied in this case study and the modelled source terms appeared to be reasonable for the placement of dredge material at the spoil ground. However, the source terms in the nearshore dredging area based on the Becker model appeared to be underestimated, a region which was predominantly dredged with a CSD. Whilst the upper limit of the suggested reasonable range for cutter head stir up was utilised in the case study, due to the shallow depth an additional source term due to ancillary vessel operation and propeller wash should have been included. The Becker model accounts for the fines available in the excavated mass, however a source term due to ancillary operations/propeller wash does not form part of this mass balance and should be considered separately.

The estimation of source terms based on empirical models is appropriate at the EIA stage, such as the Becker model, with the caveat outlined above. The Becker model is based on accounting for the fines available in the excavated mass, and relies on a number of empirical parameters to distribute the available fines throughout the dredging process. Whilst some of these parameters can be estimated from more detailed models, many parameters remain empirical and need to be estimated using professional judgement and experience. For this reason, **it is strongly recommended that the source term parameters and assumptions utilised during EIA are reported, validated with a plume characterisation exercise and recorded in a database for future use.**

Number of sediment fractions and settling velocities.

At a minimum, five sediment fractions are likely to be sufficient in many systems to model the combined effects of dredging and ambient fine sediment loads**. It is recommended that the following sediment fractions be utilised for far-field dredging plume models where fine sediment is the primary source of suspended solids: one sand fraction in the buffer layer, with four sediment fractions for fine material: two fractions for natural sediments, two for dredged material.** Due to difficulty in accounting for flocculation and uncertainty around suspended sediment particle densities, the appropriate parameter to use to describe each fine fraction is the settling velocity, not particle size, although the class of particles are useful references.

For the modelling of the fine sediment fractions in the passive plume the order of magnitude for settling velocity is typically between 0.01 to 2 mm/s, with a lower settling velocity (in the order of 0.01 mm/s) to reproduce the background TSS concentration and a higher settling velocity (nominally in the range 0.1 to 1 mm/s) used to reproduce the magnitude of resuspension events. Higher settling velocities (> 2 mm/s) are typically only relevant very close to dredging sources where large particle and strong flocculation is present due to the high sediment concentration. In this region the influence of density effects in the dynamic plume are greater and are not adequately modelled in a far-field model.

It is recognised that the use of additional sediment fractions increases the complexity and uncertainty in the model and model parameters, and establishing the mass distribution of the source terms across the sediment fractions is a challenging problem. **It is recommended that the number of sediment fractions be kept to a minimum so that greater effort is focussed on establishing appropriate model parameters.**

3D modelling

It is increasingly apparent that three-dimensional modelling is necessary to correctly resolve wind driven circulation in shallow water. In addition, in locations where the primary driver of resuspension is wave stirring, strong vertical gradients in TSS can be present, and these were observed both in the model and in field collected data. **It is recommended that three-dimensional numerical modelling be undertaken unless the two dimensionality of the flow and passive plume can be clearly demonstrated.** Three-dimensional modelling will become increasingly important with the growing use of remote sensing techniques for model validation and operational monitoring.

Calibration/validation of the model

It is recommended that model calibration and validation is performed on relevant variables, such as residual currents and TSS and near-bed light, instead of water levels. It is often more important (from an ecological perspective) to reproduce the cumulative probability distribution of a parameter rather than capture individual events. As such a quantile-quantile plot can be more informative than a typical scatter plot, in particular where small errors in the phase of an event (i.e. dredging plume release or resuspension) can significantly affect a scatter plot or model skill calculation.

Dynamic Plume

Where high protection value ecological systems are present in close proximity (< ~2 km) to the dredging sources, it is necessary to consider the impacts of the dynamic plume. Whilst not addressed in detail in this study, further research is required to advance dynamic plume modelling in order to better predict the extent and thickness of dynamic plumes at the seabed in a computationally efficient manner that can be applied during an EIA study. **It is noted that significant advancements in the modelling of the dynamic plume associated with hopper overflow have been achieved in de Wit (2014), and the parametric model developed in that work is appropriate for informing the estimation of overflow source terms.**

Data assimilation

Data assimilation may be a viable approach to improve the representation of the cumulative probability distribution of natural TSS, in particular as the prevalence of geostationary satellites to estimate TSS becomes more widespread which reduces the problem of tidal aliasing.

5.3.3 Monitoring

In past dredging monitoring programs monitoring sites have typically been located at a significant distance from dredging activities. It is strongly recommended that monitoring sites also be placed close to the dredging where passive plumes are able to be observed. This monitoring data can greatly assist in model validation and for comparison against model predictions. The modelling outcomes from the EIA stage are inherently uncertain due to the limited available information, as additional information becomes available through monitoring it is strongly recommended that EIA predictions are evaluated, and operational modelling and proactive management practices be adopted.

5.3.4 Post-assessment

Validation of the model results as the dredging campaign progresses and on its completion is recommended to enable learnings to be gained and valuable data to be added to the modelling database to benefit future EIA studies.

6 Residual knowledge gaps

6.1 Remote sensing of suspended sediment plumes

Different conditions impact the measurement of the spectral data and different measurement methods can produce different results. Further, different optical characteristics of ambient and dredged sediment can make algorithms site specific. Hence there is no single algorithm that works for all water types and all sensors. The relationship between reflectance and TSS is non-linear. Sensors essentially measures an "average" reflectance over a pixel, which cannot be scaled directly to an equivalent average TSS. If the water is quite uniform over a large area (non-plume), then all sensors measure the same average reflectance, and thereby measure the same TSS. However, if the water is highly variable spatially (in a turbid plume), then the average reflectances of different sensors should be the same, but the derived average TSS will be different. There are other factors that may impact remote sensing of suspended sediment plumes over space and time, such as: atmospheric correction which is often different for different sensors, and overpass times, which are different for different satellites.

6.2 Sediment transport processes over complex canopies

Bed shear stress in vegetated canopies

The presence of seabed canopies can significantly alter the shear stress imparted on the bed within the canopy. Work undertaken as part of the DSN Theme 3 has developed a new model to predict the reduction in bed shear stress caused by the presence of the canopy which significantly alters the in-canopy sediment fluxes compared to bare sediment beds. Future model development should be considered to incorporate these effects in the context of cohesive sediment dynamics and additional characterisation of the seabed canopies undertaken to provide input parameters.

6.3 Hydrodynamic and sediment transport modelling

6.3.1 Fluff layer model parameters

The use of a fluff layer model was essential in the Wheatstone Project case study to reproduce the resuspension of freshly deposited, more easily eroded dredging fines on the inner shelf, due to the large range in shear stress forcing across the shelf. It is difficult to systematically establish the model parameters required by a fluff layer model due to the complex interaction of numerous parameters. The choice and combination of model parameters have a significant influence on the mass distribution at the seabed and resuspension processes. **Further research is required to identify reasonable model parameter combinations and seabed schematisations for the broad range of coastal systems present across Western Australia.**

6.3.2 Sediment transport model parameter estimation

Interdependence of model parameters, particularly in the cohesive sediment transport models makes model sensitivity analysis, parameter estimation and calibration challenging. **Further research into model parameter estimation techniques for sediment transport models is required.** Such approaches require improvements in the scalability and computational efficiency of hydrodynamic and sediment transport models to make effective use of the growth in computational capacity and parallelisation.

6.3.3 Best case and worst-case scenarios

The establishment of 'best case' and 'worst case' scenarios remains a challenge for EIA. Whilst assessment of the metocean conditions of the site remains a critical step in appropriately defining likely current and wave forcing scenarios, **further research is required to investigate the application of input reduction techniques commonly applied in morphological models to passive dredging plume models.** Whilst best- and worst-case scenarios must be developed within the context of the specific details of the dredging site and program, the likelihood of significant resuspension events should be assessed against the cumulative deposition likely associated with the full dredging program.

6.3.4 Dynamic Plume

Where high protection value ecological systems are present in close proximity (< ~2 km) to the dredging activities, it is necessary to consider the impacts of the dynamic plume. Whilst not addressed in detail in this study, **further research is required to advance dynamic plume modelling in order to better predict the extent and thickness of dynamic plumes at the seabed in a computationally efficient manner that can be applied during an EIA**

study. It is noted that significant advancements in the modelling of the dynamic plume associated with hopper overflow have been achieved in de Wit (2014), and the parametric model developed in that work is appropriate for informing the estimation of overflow source terms.

6.3.5 Initialising ambient sediments at the seabed

The accuracy of the ambient TSS model is strongly influenced by the availability of fine sediment at the seabed. A reasonable approach to estimate the sediment distribution at the bed is to undertake a so-called 'warm up' simulation of sufficient duration so that the modelled availability of fines at the seabed reaches some dynamic equilibrium with the modelled bed shear stress forcing. Depending on the system this can take a significant period of model time (up to several model years) which requires that natural sediment fluxes into the model domain be adequately resolved. **It is recommended that baseline data collection include additional spatial sampling in surficial sediment particle size distributions when there is significant ambient sediment at the project site.** This data collection would assist in establishing the initial conditions for sediment cover and could be informed by the numerical modelling to span the range in bed shear stress climatology and natural sediment supply.

6.3.6 Wind forcing that resolves sea/land breeze

The accuracy of wind forcing is critical for estimating the residual currents and locally generated seas. **It was found that local wind effects are important (i.e. land and sea breezes) in some locations in this case study.** The development of high-resolution meteorological models that resolve sea breeze or assimilate local meteorological station wind data will be beneficial for providing appropriate mesoscale and local forcing.

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