Numerical modelling of dredge plumes: a review

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WAMSI Dredging Science Node

Report

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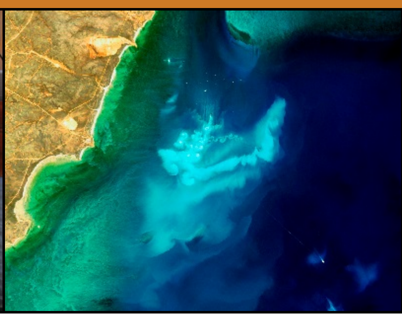

WAMSI Dredging Science Node

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.

Funding Sources

The $20million Dredging Science Node is delivering one of the largest single issue environmental research programs in Australia. This applied research is funded by **Woodside Energy, Chevron Australia, BHP Billiton and the WAMSI Partners** and designed to provide a significant and meaningful improvement in the certainty around the effects, and management, of dredging operations in Western Australia. Although focussed on port and coastal development in Western Australia, the outputs will also be broadly applicable across Australia and globally.

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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Front cover images (L-R)

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

Image 2: Profiling rosette with LISST, SBE-19plus, Hydroscat-6 and niskin bottles. (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 29/08/2010.

Image 4: Piston sediment corer being retrieved from deployment. (Source: Kevin Crane)

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Executive summary

The Environmental Impact Assessment (EIA) of proposed large-scale dredging operations in Western Australia, such as those associated with port and coastal infrastructure developments, is fundamentally based on impact predictions expressed spatially (EPA 2011). Quantifying and modelling the transport and fate of sediments released during dredging operations is essential to predicting the extent, severity and duration of environmental impacts. However, the key physical processes that control the extent, intensity and duration of sediment plumes generated from both the dredge site and dredge spoil grounds are complex and challenging to model. The rate of sediment deposition and resuspension by waves and currents varies across habitats and can lead to further dispersal. It is essential to predict sediment deposition and erosion rates, and bottom light availability in order to predict the likely impact on the benthic communities such as corals, seagrasses and sponges.

In this review, we synthesize the current knowledge on several key processes for sediment transport modelling, and standard practice of sediment transport modelling around the world with a particular focus on the applicability to tropical marine waters off north Western Australia, and tropical Australia more broadly. We also review a number of EIA modelling studies around tropical Australia associated with coastal infrastructure developments. We assess factors contributing to the accuracy in model predictions and the effectiveness of monitoring and managing the impacts during dredge operations. The key issues assessed are: (i) contemporary understanding, algorithms and parameters in sediment transport models; (ii) the process of testing and validating model predictions; and (iii) the required data for model parameter estimation and model validation. Emphasis is placed on the choice of parameters for modelling key processes for predicting the fate of dredge plumes, including flocculation, resuspension and deposition of the sediments generated through dredging.

Considerations for predicting and managing the impacts of dredging

Dredge plume simulation modelling exercises conducted for EIAs have been reviewed for tropical Australian marine environment. Prediction of dredge plume dispersal involves hydrodynamic and wave modelling, and sediment transport modelling. The accuracy of prediction depends on the quality of models and the complexity of the processes involved and the level of understanding of how these processes operate in the local context.

Relatively speaking, protocols for hydrodynamic and wave modelling have been well established, however, the following need to be considered:

- Temporal and spatial coverage of the model calibration and validation is often limited due to the lack of suitable data; when such data are available, model-data comparisons should cover both temporal and spatial ranges of available data so that different scales of key processes are resolved;
- Three dimensional models are preferable to two dimensional models so that the vertical and horizontal structures of the plumes are adequately simulated; and
- If the dredge plume is likely to travel to areas that are under the influence of large-scale currents, it is recommended to address such influence by either setting up nested models or appropriate open boundary conditions.

Compared to hydrodynamic and wave modelling, sediment transport modelling has many challenges due to more complex nature of sediment transport processes and lack of data, which is a huge obstacle for improving model predictions. Here are some major points to consider:

- Modelling non-cohesive sediments (sand) and cohesive sediments (mud) require different approaches. For example, different size classes of non-cohesive sediments often behave independently, but in cohesive sediments there are interactions between different size classes due to flocculation or resuspension processes. Since detailed modelling of this interaction is not practical in field conditions yet, including many particle size classes does not necessarily improve model predictions for cohesive sediments. We note that cohesive sediment transport modelling in scientific literature usually uses only a few particle classes.

- Sediment transport models are often not calibrated or validated due to the lack of relevant field data. This is understandable because dredging has not started at the EIA stage, but this produces large uncertainty when assessing the model's predictive skill. It would be a great step forward to require monitoring plans in EIAs to include model-data comparisons as part of the monitoring efforts, and for these data to be made generally available to inform subsequent modelling exercises.
- Parameterizations and parameter values used in sediment transport models are often not reported in EIA documentation leaving considerable uncertainty in assessing the model performance and inter-comparison with other models. We recommend that proponents be required to report model parameter values and parameterizations to enhance the ability of assessors and regulators to evaluate model performances.
- Currently, sediment transport modelling in EIA documents does not include ambient sediments. Understanding the dynamics of ambient sediments is important in determining overall impact of dredging, and trigger levels based on total SSC may be more practical because 'suspended sediment concentration (SSC) above ambient level' is not easy to quantify from monitoring data, especially in areas influenced by river outflows or during stormy conditions. Although conceptually there are potential benefits from including ambient sediments, in practice the issue of ambient sediment modelling needs to be carefully assessed in the future because it requires more data and poses a number of technical challenges.
- Assessing the long-term impact of dredging requires the modelling of extreme events (such as tropical cyclones and floods) and model performance can only be assessed through the collection of calibration and validation data for such events. In addition, the interaction between dredged and ambient sediments needs to be considered because the behaviour of mixed sediments would likely differ from that of the dredged sediments once dredged materials are dispersed and mixed with ambient sediments. For long-term impacts, approaches other than modelling, such as the analysis of sediment records and bed morphology, might be beneficial. Currently most EIAs do not address the long-term impact of dredging and spoil disposal.

Reducing the uncertainty of sediment transport modelling requires site-specific data and background research to understand key sediment transport processes, but the cost could be significant. Therefore, in order to improve predictive capacity in an efficient and effective manner, we need to prioritize the issues in a pragmatic way and systematically address them. The details are out of the scope of this review, but some important points are listed below:

- Uncertainty in sediment transport modelling *per se* should be compared to levels of uncertainty in the released mass of dredge spills (i.e. the far field source terms which are essential input data for sediment transport modelling), and uncertainty in the impacts of dredge plume to receptors. If the uncertainty in source terms is large, reducing uncertainty in sediment transport modelling may not affect the overall uncertainty significantly.
- Model results may be sensitive to some specific processes and model parameters while relatively insensitive to other processes and parameters. For example, if dredge spill occurs in deeper water where deposited sediments are unlikely to get re-suspended, then determining the mass released from the dredge spill and the settling velocity should be the priority, rather than the details of resuspension process.
- Improving model accuracy should be considered in the context of current science and financial costs. For example, settling velocity is essential for dredge plume modelling in any circumstances, and measuring settling velocity of particles/flocs in dredge plume can be done using existing technologies. On the other hand, cohesive sediment resuspension under surface wave forcing appears to be poorly understood and

not well represented in sediment transport models; hence improving this aspect would require long-term research. Note that Project 3 of this theme is addressing some aspects of sediment resuspension.

1. Introduction

Quantifying and modelling the transport and fate of sediments released during dredging operations is essential to predicting the environmental impact of large-scale port and coastal developments. Predicting zones of impact is an essential component of Environmental Impact Assessment (EIA) for proposed dredging operations (NAGD; Australian Government 2009). A spatially defined zoning pattern outlined in *Environmental Assessment Guideline for Marine Dredging Proposals* (EPA 2011) has been adopted by various regulatory authorities around Australia. The importance of managing the impact of dredging has been widely recognized by the government, industry and the public; a recent report has found greater awareness and compliance with environmental regulations across the ports in Northern Australia (RMC/Sprott 2014).

Numerical modelling is a vital tool for predicting potential environment impacts of dredging activities and dredge spoil disposal. However, the processes governing dredge plume generation and transport are complex and depend on many factors, which are often site- and substrate-specific. Many different hydrodynamic and sediment transport models are used by proponents, some are open source, but many are licensed models and the formulation and parameterizations of important processes are not always known. There are currently no industry standards for calibrating the models. Usually hydrodynamic models are calibrated with field measurements of currents, water levels and waves and capable of reproducing the dynamics in the study region. However, sediment transport models are not always calibrated and ways of calibration vary greatly, partly due to differences in quality and quantity of data. Therefore, large uncertainties in modelling results often exist.

Over the years, it has been recognized that sediment release from different dredges are poorly understood and modelled. To address this issue, a research programme called TASS (Turbidity ASsessment Software) aims at the development and validation of a model to predict suspended sediment concentration as a result of dredging operations (overflow) as well as other dredger-related sources such as propeller wash (Spearman et al 2011). The research sought to identify all the mechanisms by which sediment is released during dredging and to develop models that predict the rates of release. Recognizing that data collected are often inconsistent and incomplete to assess sediment losses with different types of dredger working in different soil and rock conditions, HR Wallingford released in 2003 a document titled *Protocol for the Field Measurement of Sediment Release from Dredgers: A practical guide to measuring sediment release from dredging plant for calibration and verification of numerical models*. This document provides guidance on standard methods of measuring sediment release from dredging plant with the goal that the measurements can be used to calibrate the TASS models. It is the intention that, when calibrated by field measurements, the models can be used with reasonable confidence by all parties, including regulators and industry alike, to predict sediment release during dredging.

Attempts have been made to promote the use of best practices in numerical modelling, such as the Guidelines on the *Use of Hydrodynamic Numerical Modelling for Dredging Projects in the Great Barrier Reef Marine Park*, issued by the Great Barrier Reef Marine Park Authority (GBRMPA) in August 2012. This document provides general guidelines such as the requirement to apply three-dimensional (3D) hydrodynamic modelling of sediment plumes for assessment of potential impacts from dredging and sediment disposal activities in the Marine Park. It also provides minimum requirement for baseline data collection and range of particle sizes considered for sediment transport modelling. It also recommends appropriate model resolutions and output, including the requirement that the minimum resolution to model a dredge channel should be two cells within the width of the channel.

Through the WAMSI DSN Theme 3 project, we plan to provide detailed and specific guidance with regard to modelling physical and sediment transport processes in the tropical and subtropical Australia, including model calibration and set up and potential ranges of suitable parameters when possible. We have carried out desktop reviews of literature, including peer-reviewed journal articles and various ‘‘grey literature’’: technical reports, student theses, and environmental impact studies for securing government approvals that were submitted for EIA.

We aim to critically evaluate approaches in parameterizing important processes in hydrodynamic but especially in sediment transport. We will provide our recommendations on modelling and summarize best practice parameters and guidance in the final report.

1.1 Numerical models

We looked at the models used in the EIAs, whether or not they are open source, if they used scenarios or time series for simulations, whether or not they are nested, and how the models are calibrated. The models we reviewed include a dynamic plume model and several passive plume models.

1.2 Key processes

We investigated how resuspension/deposition and flocculation are handled in different studies, and how key processes are modelled, such as:

- number and type of sediment classes;
- settling velocity and flocculation ;
- critical shear stress for resuspension and deposition;
- wind;
- tides;
- large-scale ocean currents; and
- Eulerian or Lagrangian coordinate.

We find that there are wide range of options chosen, some ad-hoc, some are physics based.

1.3 Key input data

To successfully predict or hindcast plume dispersal with numerical models, we need a realistic range of parameter settings and data inputs to force the model. For hydrodynamic and wave models, we need input data such as local forcing (e.g. wind, pressure, water level, air-sea fluxes of heat and fresh water, and river discharge) and large-scale forcing from regional or global models (e.g. tides, waves, currents, temperature and salinity at model boundaries). For the sediment transport model, we need sediment spill rates from dredgers with the vertical distribution, particle size distribution, settling velocity, stress-resuspension relationship, sediment density and porosity. For the dynamic plume model input, a number of parameters are required, such as spill rates, sediment concentration and settling velocity of the overflow.

2. Methods

Desktop reviews were conducted of peer-reviewed scientific literature and grey literature, including but not limited to, EIA documents, student theses and technical reports, as well as information identified and made available through Theme 1 of the WAMSI Dredging Science Node.

3. Results

3.1 Numerical models

To predict the likely extent, severity, and persistence of environmental impacts by proposed dredging activity in a scientifically sound way requires the use of hydrodynamic, wave and sediment transport models to model dredge plume development and dispersal, in conjunction with water quality (ecological) thresholds for sensitive receptors such as corals, filter feeders, seagrasses and macroalgae. These model predictions guide the scale and scope of associated monitoring programs, providing assistance to proponents as to where to establish environmental monitoring and reference sites. Increasingly, modelling is also being used by dredging programs to forecast a few days in advance, so as to understand the potential consequence of various dredging scenarios and optimize the dredging programs to minimize environmental damage. Improving the accuracy in model predictions of dredge plume dispersal will improve public confidence in managing dredging impacts and reduce environmental monitoring costs. See Table 1 for some of the dredge plume modelling studies in the tropical Australia we examined in this review.

Sediment characteristics of dredge plumes, such as particle size and settling velocity distributions, depend on the source material being dredged, the type of dredge being used and the prevailing metocean conditions (note: 'metocean' is a term widely used for describing the physical conditions at a marine location, especially the wind, wave, current and tidal conditions. It is a combination of the terms "meteorological" and "oceanographic".). Here let us consider a Trailing Suction Hopper Dredger (TSHD), which is commonly used for dredging in Western Australia; the fate of dredged sediments is often described using three process models.

- Trailer Process Model: The dredge operation is such that it sucks up a water-sediment mixture from the seabed and pumps it into its hopper. The water-sediment mixture contains ~20% (volume) solids with the coarser material settling to the bottom of the hopper displacing the overlying water and finer sediments upwards. Filling of the hopper continues after the hopper is full, by letting the excess water and fine sediment overflow.
- Dynamic Plume Model: The sediment concentration in the overflow can be quite high and increases with time as the volume of sediment in the hopper increases. The high sediment concentration effectively increases the density of the overflow water which descends rapidly and is referred to as the dynamic plume. Here we briefly review one of the leading models for dynamic plume simulation.
- Passive Plume Model: The effects of sediment concentration on density decrease with time and distance from the dredge and ambient metocean conditions govern the plume dispersal. Possible sediment sources for the passive plume are sediment released directly into the water column, de-entrainment from the dynamic plume, propeller wash and from the draghead of the dredger on the seabed. The plume will be advected by tidal currents, wind driven currents and other larger scale circulation features. Turbulent diffusion and shear dispersion act to spread the plume while gravitational settling and resuspension processes are also important.

To predict passive plume dispersal, three separate models are needed: a hydrodynamic model, a sediment transport model, and a surface wave model that is required to simulate sediment resuspension under combined current and wave forcing. There are a number of modelling suites that include these three models; some are free open-source models, while others are licensed products. The licensed models require payment of significant license fees and usually do not grant the user access to the source code to allow modification and customization of the model, and there are often restrictions on passing the model onto a third party. Therefore the open-source models are preferred by this project.

Here we briefly review three open-source modelling suites: Regional Ocean Modelling System (ROMS), Delft3D, and Sparse Hydrodynamic Ocean Code (SHOC). We also provide a brief overview of a leading commercial modelling suite, the US Army Corps of Engineering's Coastal Modelling System suite. Some of the commonly used commercial models in Australia are the Danish Hydraulic Institute (DHI) MIKE modelling suite (http://worldwide.dhigroup.com), the Global Environmental Modelling Systems (GEMS) Coastal Ocean Model (GCOM3D) and the GEMS 3D Dredge Simulation Model (DREDGE3D) (http://www.gems-aus.com), and HYDROMAP (http://www.asascience.com/software/hydromap).

3.1.1 A dynamic plume model - the Turbidity ASsessment Software (TASS)

To improve the ability to predict sediment release during dredging, a software programme called TASS (Turbidity ASsessment Software) has been developed to predict sediment release and the initial dynamic behaviour of the sediment plumes (Spearman et al 2011). The TASS project has been motivated from the realization that the effects of dredgers are rather poorly estimated, often leading to unrealistic predictions of the development of turbidity plumes around dredging operations. Different types of dredging equipment are considered, including Grab (clamshell) dredgers, Backhoes, bucket (ladder) dredgers, cutter suction dredgers, and TSHDs. The focus of TASS is particularly on the TSHDs. TASS has been validated against field data in a variety of locations and site conditions along the North Sea coast. Additional measurement campaigns in tropical waters and validation of the software have been conducted to improve the robustness of TASS for sites around the world. The model has been found to reproduce both the nature of the overflow and the far-field plume realistically. The TASS model represents a useful tool for EIA studies associated with dredging plumes. The TASS project has been partly funded by the European EcoShape Foundation's *Building with Nature* innovation programme and it is envisaged that TASS will become available to the public in the near future once the validation and testing of the software is completed. However, at the time of writing this review, TASS was not available as open source software.

3.1.2 Passive plume mode 1: Delft3D

The Delft3D model is developed by Deltares in the Netherlands (http://oss.deltares.nl/web/delft3d). Delft3D is a world-leading 3D modelling suite that investigates hydrodynamic, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. Delft3D is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community and coastal engineers for a diverse range of applications. It includes coupled modules for short wave propagation, far-field water quality, mid-field water quality, particle tracking, ecological modelling, and cohesive and non-cohesive sediment transport. There are over 1500 registered users of Delft3D worldwide in over 70 countries, and it has been applied to diverse marine environment around the world including Australia, at Port Hedland, Exmouth Gulf, Cockburn Sound (Fremantle Port Authority), Geographe Bay, Port Botany (Sydney), Port Philip Bay (Port of Melbourne), Murray River Mouth (South Australia), Cairns Navy Base (Queensland). There is an active internet forum including developers and users for exchanging ideas and asking questions.

Delft3D simulates the interaction of water, sediment, ecology and water quality in time and space. The suite is mostly used for the modelling of natural environments like coastal, river and estuarine areas, but it is equally suitable for more artificial environments like harbours, locks, etc. Delft3D consists of a number of well-tested and validated programmes, which are linked to and integrated with one another. These programmes are D-Flow, D-Morphology, D-Waves, D-Water Quality, D-Ecology, and D-Particle Tracking. The D-Flow, D-Morphology, and D-Waves, and D-Water Quality modules are all open-source.

3.1.3 Passive plume model 2: the Regional Ocean Modelling System (ROMS)

The Regional Ocean Modelling System (ROMS) is developed by the Rutgers University (http://www.myroms.org). It is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications. ROMS includes accurate and efficient physical and numerical algorithms and several coupled models for biogeochemical, bio-optical, sediment, and sea ice applications. It also includes several vertical mixing schemes, multiple levels of nesting and composed grids. The dynamical kernel of ROMS is comprised of four separate models including the nonlinear (NLM), tangent linear (TLM), representer tangent linear (RPM), and adjoint (ADM). There are several drivers to run each model (NLM, TLM, RPM, and ADM) separately and together. ROMS is open-source and there is an active internet modelling forum to exchange ideas.

3.1.4 Passive plume model 3: the Sparse Hydrodynamic Ocean Code (SHOC))

The Sparse Hydrodynamic Ocean Code (SHOC) is developed by CSIRO (see http://www.emg.cmar.csiro.au/www/en/emg/software/EMS/hydrodynamics.html). SHOC is a free surface primitive equation model using a curvilinear orthogonal grid in the horizontal and a choice of fixed 'z' coordinates or terrain following sigma coordinates in the vertical. The 'z' vertical coordinate system allows for wetting and drying. SHOC includes coupled modules for sediment transport and biogeochemistry. The sediment model simulates resuspension and deposition of fine particles in a vertically-resolved water column and sediment bed. The Biogeochemical model predicts water quality parameters in coupled ephibenthic, benthic and pelagic layers. The modelling suite has been tested and refined through numerous applications around the Australian coast.

The user interface has been developed to allow non-expert users to set up the model on arbitrary domains, although expert intervention may be required to resolve model difficulty associated with complex topography.

Table 1. A selection of existing modelling studies used in Environmental Impact Assessments in tropical and subtropical Australia.

Project Location	proponent	Approval date	status	Approved vol. M³	consultants	modelling
Abbot Point	NQBP	2015	pending	1.1	GHD	Mike 3; Mike 21
Anketell	API	2013	pending	19.2	Oceanica, AECOM, APASA, MScience, Worley Parsons	SWAN, HYDROMAP, SSFATE, DREDGEMAP
Cape Lambert A	Rio Tinto	2007	completed	2.5	SKM, GEMS, IMO, MScience	GCOM3D, SWAN, DREDGE3D
Cape Lambert B	Rio Tinto	2010	completed	14	SKM, GEMS, Oceanica	GCOM3D, SWAN, DREDGE3D
Dampier Port Upgrade	Hamersley Iron	2006	completed	3.4	SKM, MScience	SWAN, PLUMETRAK, GCOM3D
Gorgon	Chevron	2009	completed	7.6	RPS, GEMS, APASA	GCOM3D, SWAN, DREDGTRAK
Great Barrier Reef	GBRMPA	2013	completed	N/A	SKM, APASA	HYDROMAP
Darwin Harbour INPEX	INPEX, Browse	2012	completed	16.9	HR Wallingford, URS, GEO Oceans, NRETAS	TELEMAC-2D, Delft3D WAQ
Wheatstone Gas	Chevron	2011	completed	48	DHI, URS, SKM, MScience	Mike3 FM
Port Hedland Outer Harbour	BHP Billiton	2012	pending	42	SKM, APASA	HYDROMAP
Port Hedland South West Creek	PHPA	2011	completed	14.2	SKM, Worley Parsons, Cardno	Delft3D
Dampier Marine Services Facility	Dampier Port Authority	2011	completed	2.2	Worley Parsons, SKM, APASA	SWAN, SSFATE, HYDROMAP, DREDGEMAP
Pluto	Woodside	2007	completed	14	SKM, APASA, MScience, IMO	SWAN, HYDROMAP, SSFATE
Townsville Port Expansion Project	Port of Townsville	ongoing	pending	10	BMT WBM	TUFLOW-FV, SWAN
South of Embley	Rio Tinto, Alcan	ongoing	current	6.5	Worley Parsons	Mike 21
Gladstone Port Western Basin	Gladstone Port	2009	completed	42.3	GHD, BMT WBM, Worley Parsons, Aurecon, VisionEnvironment	TUFLOW-FV, SWAN

3.1.5 Passive plume model 4: the Coastal Modelling System (CMS) by US Army Corps of Engineers

The Coastal Modelling System (CMS) has been a research and development area of The Coastal Inlets Research Program (CIRP) at the United States Army Corps of Engineers - Engineering Research and Development Center (USACE-ERDC), Coastal and Hydraulics Laboratory (CHL) since 2006. It was built from a group of numerical models that have been under development since 2002 (Reed et al., 2011).

The system is a coordinated system of major multidimensional numerical models integrated to simulate waves, currents, water level, sediment transport, and morphology change in the coastal zone. Emphasis is on navigation channel performance and sediment exchanges between the inlet and adjacent beaches in the coastal zone. The CMS has been verified with field and laboratory data.

There are two major components in CMS: CMS-Flow and CMS-Wave. CMS-Flow is a finite-volume numerical engine which presently includes various two dimensional capabilities. Present features are: hydrodynamic (water levels and current flow), sediment transport (as bedload, suspended load, and total load dependent on various transport algorithms), morphology change, and salinity transport. The model is intended to be run on a project-scale, meaning the domain should only be on the order of 1-100 kms in length and width. The current CMS computational grid is a non-uniform Cartesian grid which is very easy to set up and offers some degree of refinement. In order to improve the refinement capability, a telescoping mesh will be introduced in SMS 11.0. The telescoping mesh, also referred to as quadtree mesh, offers local mesh refinement for the least amount of effort (both computationally and grid generation). Local refinement is achieved by subdividing a rectangular cell into 4 cells. The quadtree mesh can be arranged as block-structured or completely unstructured. Rectangular (or quadrilateral) meshes are more convenient for establishing high-order schemes and discretizing higher order spatial derivatives. The telescoping mesh offers most of the flexibility of the triangular unstructured mesh with the computational simplicity of the rectangular mesh.

CMS-Wave, formerly known as the Wave-Action Balance Equation Diffraction Model (WABED), is one of the principal components of the CMS. The model is a 2-D wave spectral transformation (phase-averaged) model. The term ''phase-averaged'' means the model does not resolve individual waves but rather simulates the propagation of wave energy expressed in terms of wave-action. It was originally built to represent theoretically developed approximations for both wave diffraction and reflection in a nearshore domain.

Four input files are required for a CMS-Wave simulation. Up to six optional input files may also be utilized depending on the processes being modelled and the selected model parameters. Depending on which options are selected for the simulation, CMS-Wave will generate from one to six output files.

CMS is a commercial product and the licensed user is provided with the executables of the model but no source code is given.

3.2 Key processes and parameters in fine sediment transport modelling

In this section, we review the current scientific understanding on key processes and the associated parameters in sediment transport modelling, namely flocculation, settling velocity, deposition, and resuspension. State-of-the-art sediment transport models do not necessarily include these processes explicitly; however, understanding these processes forms the basis for wise use of state-of-the-art models because these processes can be reflected in a way the model is set up and used. These key processes are mostly studied using inorganic mineral particles and natural sediments, and this review applies to both ambient sediments and dredged material.

It is customary to define non-cohesive sediment particles (e.g. sand) and cohesive sediment particles (e.g. mud or 'fines') based on particle size. Clay, silt, and sand are defined based on particle size, with common thresholds of 2-4 and 62-63 (μm), depending on definition (e.g. the φ scale or ISO 14688). The International Organization for Standardization (ISO) standards for geotechnical investigation and testing, ISO 14688-1 and ISO 14688-2, define clay as less than 2 μm, silt between 2 and 63 μm, and sand between 63 μm and 2 mm. Sand is non-cohesive, whereas mud or 'fines', which are clay plus silt, is considered cohesive, although only clay provides physicochemical cohesion. However, note that sediment beds are often classified based on overall behaviour of the bed instead of particle composition. For example, a muddy bed with a small fraction of sand is often classified as a cohesive bed because of its consolidation and resuspension behaviours (see subsection 3.2.4). A recent review of cohesive sediment transport from a civil engineering perspective is given by Mehta and McAnally (2008).

In this review, we focus on cohesive sediments for three reasons. Firstly, cohesive sediments are more relevant to environmental impact of dredging than non-cohesive sediments because fine particles attenuate light more efficiently and carry more hydrophobic contaminants adsorbed onto the surface. Secondly, in comparison to non-cohesive sediment particles, cohesive sediment particles travel longer distance due to slower settling and higher susceptibility of fresh sediment to resuspension. Thirdly, it appears that dynamics of cohesive sediments is less well understood in tropical Australian environment than in the temperate regions of the northern hemisphere.

The aims of this section are as follows:

- To provide a summary of current scientific understanding of the key processes;
- To compare the scientific understanding with current practice with a particular focus on tropical Australia where possible;
- To assess cohesive sediment transport models which are inherently much less accurate compared to hydrodynamic and wave models. Some important reasons are that 1) some processes, such as resuspension under surface wave forcing, are simply not well understood; 2) cohesive sediments are strongly affected by temporally varying biological activity; and 3) cohesive sediments from different sources, such as ambient suspended sediments, sediments supplied by flood events, consolidated sediments resuspended by cyclones, and dredged material, behave in different ways; and
- To review calibration of cohesive sediment transport model using field data.

3.2.1 Flocculation

The differences between non-cohesive and cohesive sediments originate from inter-particle attraction, which causes aggregation of sediment particles and strengthening of the sediment bed. This aggregation process is commonly called 'flocculation' and the resulting aggregates 'flocs'. However, it should also be noted that some researchers classify the aggregation process into coagulation and flocculation (e.g. Winterwerp and van Kesteren 2004; Grabnowski et al. 2011). Coagulation occurs due to electrochemical attraction, such as electrostatic and Van der Waals forces. For example, clay particles tend to be dispersed in fresh water because of negative charges on the surface, but they tend to form aggregates in salt water because cations (positively charged ions) tend to neutralize the repulsive force. Flocculation occurs due to adhesion, or attraction provided often by organic matter. Sticky mucus produced by bacteria and phytoplankton, called extracellular polymeric substances (EPS), is known to promote flocculation by forming biofilms around mineral particles (Eisma 1986; Ayukai and Wolanski, 1997; Van der Lee, 2000; Droppo 2004) or by forming transparent exopolymeric particles (TEP; e.g. Passow 2002). (Although it appears technically incorrect, it is common to refer to sediments attracted by both cohesion and adhesion as 'cohesive' sediment.)

Although flocculation is not explicitly modelled in state-of-the-art three-dimensional (3D) sediment transport models, understanding flocculation is important because it modifies the settling velocity (see next subsection) and dictates the way we set up cohesive particle size classes in the models.

Flocs are aggregates made up of loosely bound particles called primary particles. Primary particles can be mineral particles, living phytoplankton, phytoplankton skeletons, or small strong flocs (microflocs) if they make up larger fragile flocs (macroflocs) (Eisma 1986). The size of primary particles is typically of the order of a few µm, whereas flocs can reach several mm containing millions of primary particles. Flocs have porous structure and smaller apparent density (mass divided by floc volume) compared to the primary particles. Flocs are often fragile, and can be broken up by traditional sampling and analysis techniques because of shear in pumps, orifices (e.g. in the Coulter counter), pipettes, outlet of the Niskin bottles, and possibly because of collision with a solid surface (Gibbs 1981, 1982a,b; Gibbs and Konwar 1983; Eisma 1986; Kranenburg 1999). Therefore, the best measurement strategy is to observe *in situ* particles using submerged cameras or video systems (e.g. Suzuki and Kato 1953; Eisma et al. 1996), and using *in situ* particle size analysers, such as LISST (Mikkelsen and Pejrup 2001).

Flocs made up of primarily mineral particles with the same composition and a narrow size range (i.e. monodisperse) are known to have approximately self-similar or fractal structure, i.e. the structure looks the same if you zoom in or zoom out (although this is naturally limited by the size of a floc and the primary particles) (e.g. Krone 1963; Kranenburg 1994). The tightness of packing is quantified by the fractal dimension nf (ranges between

1 and 3). If the characteristic size of a floc and the primary particles is Lf and Lp, respectively, the number of primary particles in the floc is proportional to (Lf/Lp)nf. Note that nf ≈3 for tightly packed particles (e.g. cubic structure like crystals) and nf ≈1 for stringy structure. The fractal dimension of flocs varies typically between 1.8 and 2.2 (e.g. Kajihara 1971; Hawley 1982; Winterwerp and van Kesteren 2004), although it can be as small as 1.4 for porous marine snow (Alldredge and Gotschalk 1988). The self-similarity or fractal structure is useful to obtain various dependences between important variables not only for flocs but also for fluid mud and sediment bed (Krone 1963; Kranenburg 1994, 1999). It is known that the fractal dimension depends on the processes forming the flocs (Jiang and Logan 1991), but currently it is impossible to predict it (Kranenburg 1999).

The key physical factors governing flocculation are turbulent shear and particle concentration, because they control the frequency of particle collision and the strength of shear that can tear flocs apart (Dyer 1989). If flocs are exposed to a certain level of turbulent shear for a long time, the particle size distribution (PSD) of flocs reaches the equilibrium (Tambo and Watanabe 1979; Spicer and Pratsinis 1996). The maximum floc size is approximately given by the Kolmogorov scale (Parker et al. 1972; van Leussen 1997; Verney et al. 2011), which is the smallest length scale of turbulence, typically a few 100 µm to a few mm in coastal waters. Flocculation time, or the time it takes for flocs to reach the equilibrium, decreases with increasing turbulence intensity (or decreasing Kolmogorov scale) and increasing particle concentration. Flocculation time in estuaries and shallow seas ranges from minutes to more than a day (Winterwerp and van Kesteren 2004). Since flocs eventually settle to the sediment bed, the time available for flocculation is limited and flocs do not necessarily reach the equilibrium, particularly in shallow water. Therefore, flocs much smaller than the equlibrium size are often observed under calm conditions (Winterwerp 2002; Winterwerp et al. 2006).

For flocs in monodisperse suspension, the kinetics of flocculation can be simulated using the so-called population balance equation or coagulation equation, which describes the evolution of floc PSD as a result of aggregation and break-up (e.g. McCave 1984; Burd and Jackson 2009). For typical flocs observed in estuaries and oceans, aggregation occurs due to turbulent shear increasing collision frequency (i.e. number of collisions per unit volume and time; Saffman and Turner 1956), and differential settling (i.e. fast-sinking large particles hitting slow-sinking smaller particle; Lick et al. 1993; Stolzenbach and Elimelech 1994). Although there are some laboratory studies of floc breakup (Parker et al. 1972; Matsuo and Unno 1981; Pandya and Spielman 1982), the process is not well understood and is hence formulated empirically (Spicer and Pratsinis 1996; McAnally and Mehta 2000; Verney et al. 2011). For monodisperse suspension, simulations based on the population balance equation produce realistic PSD, although it requires a rather large number of cohesive sediment particle classes and small time step (Spicer and Pratsinis 1996; Verney et al. 2011). These limitations led to simplified models that simulate only floc size instead of the complete PSD (Winterwerp 1998, 2002; Winterwerp et al. 2006; Maerz et al. 2011). Simplified floc models have been applied to field conditions in vertical one-dimensional models (Winterwerp 2002; Winterwerp et al. 2006; Son and Hsu 2011). To our knowledge, there is no published work that applied a full floc population model to field conditions.

Application of simplified floc models to field conditions is successful in some cases (Winterwerp 2002; Winterwerp et al. 2006), but not so in other cases (Son and Hsu 2011). This at least suggests that the models require careful calibration to each case (Son and Hsu 2011). This is not so surprising considering that field conditions are much more complex than monodisperse suspensions, because *in situ* primary particles consist of mineral particles with different sizes, phytoplankton, and bacteria; even the presence of sand particles changes floc characteristics significantly (Manning et al. 2010).

The state-of-the-art floc population modelling shows that including interactions between cohesive particle size classes (aggregation and break-up) is not yet practical in 3D modelling applied to field conditions. This means that, when and where flocculation is important, it is not practical to use many cohesive particle size classes. This is in contrast to modelling of non-cohesive particles, in which many particle size classes can be used thanks to the independent behaviour of different size classes. This poses a severe limitation when we deal with particles from different sources, such as sediment particles suspended in the ambient condition, sediments brought by floods, sediment re-suspended under cyclonic conditions, and dredged material, because one sediment class usually has one set of fixed model parameters. In practice, the number of particle size classes must be chosen based on field observation; using several particle size classes (e.g. slow and fast settling cohesive particles or micro- and macroflocs) can be useful in reproducing observed sediment dynamics (e.g. Sanford 1994).

In the tropical marine environments around Australia, suspended sediment concentration (SSC) is typically low and flocculation within the water column might not be as important as more turbid waters studied in the Northern Hemisphere (but it can be important upon deposition to the sediment bed, where particles are interconnected). However, flocculation could be important in river plumes (Wolanski and Spagnol 2003) and dredge plumes that are dominated by smaller particles. For example, from the Port Hedland SW Creek dredging project, geotechnical data showed that more than 50% of the fines (< 63 µm) in the dredging area are less than 2 µm in particle size (Worley Parsons 2009; SKM 2010). Flocs in a dredge plume may form within a hopper during dredging or transport, within the overflow, and within the density current after dumping, which provides high-concentration and moderate turbulence. Wolanski et al. (1992) reported flocculation in a density current from dredge spoil dumping in Cleveland Bay. Although not from Australia, Smith and Friedrich (2011) showed that flocs with 200 µm diameter and <1200 kg m^3 density represented 50% to 80% of total suspended mass in a dredge plume from a TSHD. In a lime (calcium carbonate, $CaCO_3$) dredge plume, Mikkelsen and Perjrup (2000) also reported that the observed peak in PSD at about 100 µm is due to flocculation of primary particles that have nearly flat PSD between 2 to 50 µm.

The flocculation process greatly affects optical properties of suspended sediments. For example, turbidity measurements are known to be strongly dependent not only on the SSC but also on the size distribution (e.g. Baker and Lavelle, 1984; Conner and De Visser 1992; Gibbs and Wolanski, 1992; Benns and Pilgrim, 1994). This also has implications for the estimation of SSC from satellite observation.

3.2.2 Settling Velocity

A key parameter in sediment plume modelling is sediment fractions (classes) and associated settling velocities. For cohesive sediments, flocculation can increase particle size and settling velocity by several orders of magnitude (Kranck, 1975, 1981; Pejrup, 1988; Eisma, 1993; Mikkelsen and Pejrup, 1998); however, the increase of the settling velocity is lower than would be expected for individual particles with the same size because flocs have lower density than individual particles due to the porous structure (e.g. Gibbs, 1985; Fennessy et al., 1994; Ten Brinke, 1994). In this review we discuss the applicability of the Stokes law and make recommendations on best practice for estimating settling velocity, while paying attention to the context of tropical Australia marine environment. A survey of current practice is presented in Table 2. We have found the current practice mostly falls into two categories: (1) simply the Stokes law while acknowledging the fact that *in situ* settling velocity could be considerably higher; or (2) a somewhat arbitrary minimum settling velocity for fine particles (this minimum settling velocity is set to be higher than predicted by the Stokes law) to try to account for the effect of flocculation of fine particles (e.g. Aarninkhof and Luijendijk, 2009).

A routinely used formula for estimating particle settling velocity is the Stokes law, which is based on the assumptions that: (1) the flow is highly viscous, (2) the particles are impermeable, and (3) the shapes of particles are spherical. The Stokes law predicts that the friction (more generally drag force) on the particles exerted by the fluid is,

$$F_d = 6\pi\mu w_s d \qquad (1)$$

where w_s is the settling velocity, d the particle diameter, and µ the dynamic viscosity.

The forces acting on the spherical particles are buoyancy force F_b, drag of the fluid on the sphere F_d, and gravity force F_g,

$$F_b + F_d = F_g \qquad (2)$$

Since the volume of a sphere is $V = \frac{4}{3}\pi r^3$, where r is the radius of the sphere, $r = d/2$, the gravity force is thus

$$F_g = mg = \frac{4}{3}\pi r^3 \rho_p g \tag{3}$$

where g is the gravitational acceleration, $\rho_p$the particle density. The buoyancy force due to displacement of the fluid by the particle is

$$F_b = \rho_w V g = \frac{4}{3}\pi r^3 \rho_w g \tag{4}$$

where ρ_w is the water density. The balance of the forces on the sphere (2) could then be written as

$$\frac{4}{3}\pi r^3 \rho_w g + 6\pi\mu w_s d = \frac{4}{3}\pi r^3 \rho_p g \tag{5}$$

The particle settling velocity according to the Stokes law is thus,

$$w_s = \frac{(\rho_p - \rho_w) g d^2}{18\mu} \tag{6}$$

While the Stokes law is straightforward, the underlying assumptions are often violated in reality. Flocculation changes apparent density of particles (ρ_p). Furthermore, the Stokes law is only valid for highly viscous flow. To compare the inertial and viscous forces, a dimensionless parameter known as the Reynolds number is defined as

$$Re_p = \frac{w_s d}{\upsilon} \tag{7}$$

where υ is the kinematic viscosity. Highly viscous flow is represented by a small particle Reynolds number $\mathrm{Re_p}$ (usually $\mathrm{Re_p}$ < 1). If $\mathrm{Re_p}$ is not small, the drag coefficient CD will be

$$C_D = \frac{F}{\frac{1}{2}\rho\pi w_s^2 d^2}, \tag{8}$$

while the Stokes law is equivalent of prescribing the spherical drag coefficient as

$$C_D = \frac{24}{Re_p} \tag{9}$$

Smith and Friedrichs (2011) reviewed the state-of-art formulation of settling velocity estimates. When the particle Reynolds number $\mathrm{Re_p}$ is not small, the most common empirical approximations to spherical drag coefficients are the Schiller-Naumann drag coefficient for Re_p < 800, which was attributed to Schiller and Naumann (1933) by Raudkivi (1998),

$$C_D = \frac{24}{Re_p}(1 + 0.150 Re_p^{0.687}) \tag{10}$$

Soulsby (1997) derived an explicit empirical formula for settling velocity that closely follows the Shiller-Naumann drag coefficient formula,

$$w_s = \frac{\nu}{d}\left(\sqrt{10.36^2 + 1.049 D_*^3} - 10.36\right) \tag{11}$$

where $D_* = [g\left(\frac{\rho_p}{\rho_w} - 1\right)\nu^2\,]^{1/3} d$. The empirical constants are derived from field experiments with sand.

Because of the fragility of flocs, the best way to measure settling velocity of cohesive sediments is *in situ* measurements (see Mantovanelli and Ridd (2006) for a review of different *in situ* devices). Currently common methods are the LISST and submersible cameras and video systems. Using a LISST-100, Mikkelsen and Pejrup (2000) showed that in a lime (calcium carbonate, $CaCO^3$) dredging plume, the lime particles flocculate and their size increases, but their mean density decreases correspondingly, such that settling velocity increases by a factor of 1.7. The time-scale of flocculation is found to be within the order of 50 minutes, in good agreement with modelling results in Winterwerp (2002). The LISST-Settling Tube (LISST-ST) is a relatively new instrument that measures both *in situ* particle size and settling velocity distribution of suspended sediment, and has been used in fresh water (e.g. Wijngaarden and Roberti, 2002), laboratories (e.g. Pedocchi and Garcia, 2006), and coastal oceans (e.g. Agrawal and Pottsmith, 2000). Under some conditions, ADV measurements can also provide estimates of settling velocity (Kawanisi and Yokosi 1997; Fugate and Friedlichs 2002, 2003). The Owen tube and its variants were common until the mid 1990's, but they are seldom used for research purposes today because it breaks up flocs upon sampling and does not provide reliable particle size information (see e.g. Dyer et al. 1996).

It has been widely recognized that flocculation effects must be included in sediment transport models to properly assess environmental impacts in estuarine and coastal systems (Milligan and Hill, 1998; Mikkelsen and Pejrup, 2000; Winterwerp, 2002). Many settling velocity formulae that include the effects of flocculation have been proposed. Winterwerp (1998, 2002) proposed an implicit, fractal-based expression for settling velocity of flocs including the Schiller–Naumann drag coefficient:

$$w_s = \frac{\theta g}{18\mu}(\rho_0 - \rho_w) d_0^{3-n_f} \frac{D_f^{n_f-1}}{1+0.15Re_p^{0.687}} \quad (12)$$

where θ is a particle shape factor (1 for spherical particles), ρ_0 the primary particle density, d_0 the primary particle diameter, D_f the floc diameter, n_f the fractal dimension, and Re_p the floc Reynolds number.

Smith and Friedrichs (2011) found that measured settling velocities from their field experiment agreed well with fractal-based estimates of settling velocities (Winterwerp 1998, 2002) for individual particle classes, but agreed poorly when the total suspended sediments were only described with one fractal dimension number. Thus, Smith and Friedrichs recommended identifying several fractal dimensions in the suspended sediments.

In a recent study using data collected in the Northern European estuaries (as reported in Manning and Dyer 2007), Soulsby et al. (2013) proposed new formulae that compute settling velocity of flocs using the turbulent kinetic energy dissipation rate (ϵ) and the overall concentration of suspended particulate matter (SPM). This is an empirical approach without trying to model the dynamics of flocculation, but based on established research that the maximum floc size is proportional to the Kolmogorov microscale (e.g. Van Leussen, 1988; Elimelich et al., 1995l Winterwerp 1999; Verney et al., 2010; Cuthbertson et al., 2010). Their simplified approach uses two floc classes: small, dense microflocs ($d < 160\ \mu m$) and large, sparse macroflocs ($d > 160\ \mu m$) to estimate the settling velocities and mass settling rate for natural flocculated estuarine mud. The settling velocity of microflocs and macroflocs is derived based on assumptions of two-floc populations in equilibrium with the flow. The settling velocities are related to floc size and density via the Kolmogorov microscale as a function of turbulent shear stress and sediment concentration, including height dependence and floc-density-dependence. The settling velocity is calculated using turbulent kinetic dissipation rate (ϵ) which is routinely calculated in the $k - \epsilon$ turbulence closure scheme (where k is the turbulent kinetic energy) of hydrodynamic/sediment transport models.

There are a number of assumptions made by Soulsby et al. (2013) which are briefly summarized below.

- Flocs are formed from primary particles of clay flakes, silt and sand grains, and organic debris.
- Two classes can be used to describe the floc population: microflocs (made up of a loose aggregate of primary particles) and macroflocs (made up of a loose aggregate of microflocs). The separation of microflocs and macroflocs is set at 160 μm empirically.
- The equilibrium size and settling velocity of microflocs are only dependent on the turbulent shear stress (this assumes aggregation and break-up of microflocs are only controlled by turbulent shear).
- The equilibrium size and settling velocity of macroflocs are determined by the turbulent shear stress and the overall concentration of suspended particulate matter (SPM).
- The relative concentrations of microflocs and macroflocs are determined only by the SPM concentration.

- The floc population is treated as being in quasi-equilibrium as the timescales of floc formation and break-up are small enough in a tidal estuarine flow.

The settling velocity for macroflocs is

$$w_{sM} = B_M\left(\bar{S}_{e\mu} - 1\right) \left(\frac{\epsilon \bar{d}_\mu^4}{\nu^3}\right)^{0.166} g c^{2.672k} \left(\frac{\nu}{\varepsilon}\right)^{1/2} exp\left[-\left(\frac{u_{*sM}}{u_* \xi^{1/2}}\right)^N\right] \quad (13)$$

where B_M, k, u_{*sM} and N are optimizable coefficients, $\xi = 1 - z/h$, z is height above the bed, h is water depth, $S_{e\mu} = \rho_{e\mu}/\rho$, $s = \rho_s/\rho$, ρ_s is the mineral density of the primary particles, d_1 is the (notional) diameter of the primary particles, c is the dimensionless SPM concentration, , $c = SPM/\rho$, and β_μ is a dimensionless coefficient. A set of standard values are taken: $s = 2.6368, d_1 = 10^{-5}m, \bar{S}_{e\mu} = 1.15, \text{and } \bar{d}_\mu = 10^{-4}m$, The four coefficients (B_M, k, u_{*sM}, N) were optimized against the measurements of macrofloc settling velocity in the dataset from Manning and Dyer (2007) by minimizing the squared errors between model-predicted settling velocity (13) and observed settling velocity. The optimized values are: $u_{*sM} = 0.067\ ms^{-1}, \mathrm{B}_M = 0.860, k = 0.0825, \text{and } N = 0.463$.

The settling velocity for microflocs is

$$w_{s\mu} = B_\mu(\bar{S} - 1) \left(\frac{\epsilon \bar{d}_1^4}{\nu^3}\right)^{0.39} g\left(\frac{\nu}{\varepsilon}\right)^{1/2} exp\left[-\left(\frac{u_{*s\mu}}{u_* \xi^{1/2}}\right)^n\right] \quad (14)$$

where $B_\mu, u_{*s\mu}$ and n are optimizable coefficients, which were optimized against the measurements of microfloc settling velocity in the dataset from Manning and Dyer (2007) by minimizing the squared errors between model-predicted settling velocity (13) and observed settling velocity. The optimized values are: $u_{*s\mu} = 0.025\ ms^{-1}, \mathrm{B}_\mu = 0.363, \text{and } n = 0.66$. In models where turbulent kinetic energy dissipation rate ϵ is not available, the settling velocity can still be calculated from observed shear stress if the flow is treated as quasi-steady and uniform horizontally (only varies with depth), by assuming turbulent kinetic energy dissipation rate ϵ equals turbulent production rate by large eddies, which can be estimated using measured shear stress $\tau(z)$ at a certain height above the bed, see equation (2) in Soulsby et al. (2013). The settling velocities of macroflocs and microflocs in uniform steady flows are represented by equations (10) and (11) in Soulsby et al. (2013).

One advantage of the formulae of Soulsby et al. (2013) is that the settling velocity is calculated using turbulent kinetic dissipation rate (ϵ) which is readily available in the $k - \epsilon$ turbulence closure scheme of flow/sediment transport models. In other models when the flow could be treated as quasi-steady and uniform horizontally, a similar set of equations for settling velocities could be applied. Another advantage is that each class is represented by a single size. The formulae perform remarkably well in the Northern European estuaries. It will be beneficial to test them with *in situ* field measurement of flocs and settling velocity in the tropical Australian marine environment and if they are valid or could be adapted for the Australian tropical marine environment, it will improve the settling velocity estimation of flocs and prediction of dredge plume dispersion and fate.

Based on our literature review, we would like to caution against the practice of deriving settling velocity based on laboratory analysis of sediment core data or water samples alone, as the dredged material would likely be different from the natural suspended particles, and the particle size distribution analysed by applying dispersant to water samples will overestimate the existence of fines in the plume as the flocs are likely to be broken up by the process. If practical, *in situ* measurement of particle sizes and settling velocity should be carried out and validated against various formulae to find the most suitable one. If not practical, then sensitivity analysis with different settling velocity formulation should be carried out and presented to provide an uncertainty estimate of plume dispersal predictions.

3.2.3 Deposition

Deposition and resuspension provide the bottom boundary condition in sediment transport modelling. A flux boundary condition is used for cohesive sediments because they are generally not in equilibrium in the vertical direction due to slow settling; different boundary condition can be used for (non-cohesive) sand in shallow water because such equilibrium is reached quickly (c.f., the Rouse profile).

For non-cohesive sediments, the deposition rate is commonly written as

$$D = w_s C \tag{15a}$$

However, the deposition rate of cohesive sediments is often parameterized as

$$D = w_s C \left(1 - \frac{\tau_b}{\tau_d}\right) \tag{15b}$$

where τ_b is the bottom shear stress, and τ_d is the critical shear stress for deposition, and w_s is the settling velocity outside of the bottom boundary layer. This parameterization has been attributed to Krone (1962). There is a general agreement that the existence of flocs is a major reason for different depositional behaviour between non-cohesive and cohesive sediments (e.g. Kusuda et al. 1982; Mehta 1988; Verbeek et al. 1993; McAnally and Mehta 2002). For example, a traditional explanation for the existence of critical shear for deposition is that weak flocs are broken up by strong shear near the bed and cannot deposit on the bed (e.g. Partheniades et al. 1968; Mehta 1988; Krone 1993). Since state-of-the-art sediment transport models do not resolve the bottom boundary layer, the resulting change of deposition rate is parameterized in (15b) using the parameters available in the model.

There are two paradigms regarding deposition and resuspension of cohesive sediments (e.g. Parchure and Mehta 1985; Winterwerp and van Kesteren 2004; Ha and Maa 2009). The net mass flux into or out of the bed is determined by the balance between deposition and resuspension:

$$J = E - D \tag{16}$$

where J is the vertical mass flux, E is the resuspension rate, and D is the deposition rate (we consider resuspension in the next subsection). The first paradigm assumes mutually exclusive deposition and resuspension; in other words, deposition only occurs below a critical shear stress for deposition τ_d (as in (15b)), resuspension only occurs above a critical shear stress for resuspension τ_c (see next subsection), and no deposition or resuspension occurs in between. The second paradigm assumes simultaneous deposition and resuspension; in other words, deposition occurs continuously (as in (15a)), and resuspension occurs independently from deposition either with or without critical shear stress for resuspension. The popular view on cohesive sediment deposition has been swinging between the two paradigms. Einstein and Krone (1962) assumed continuous deposition and mentioned that critical shear stress for deposition reflects the effects of resuspension. However, later laboratory studies supported exclusive deposition and resuspension (e.g. Partheniades et al. 1968; Mehta and Partheniades 1975; Parchure and Mehta 1985). Exclusive deposition and resuspension was a more common assumption between the late 60’s and early 90’s, although it has been questioned many times (e.g. Lick 1982; Sanford and Halka 1993; Lau and Krishnappan 1994). In particular, field observations from tidal systems often show co-varying bottom shear stress and SSC, and Sanford and Halka (1993) argued that it is impossible to model this behaviour with (15b). McCave and Swift (1976) also estimated that the deviation of deposition rate from (15a) is small in deep seas. Recently, Winterwerp and van Kesteren (2004) reanalysed early laboratory data, and argued that critical shear stress for deposition actually reflects consolidation and resuspension behaviours of the bed, advocating simultaneous deposition and resuspension. Currently, continuous deposition (15a) appears more popular in sediment transport models (e.g. Sanford 2008; Le Hir et al. 2011; van Kessel et al. 2011), although the discussion is still on-going (Ha and Maa 2009).

We do not intend to judge which deposition parameterization is correct; however, for the purpose of sediment transport modelling, we would like to draw attention to the following points.

Table 2. Summary of sediment particle classes and settling velocities used in Environmental Impact Assessments in tropical Australia.

Project	**sediment class**	**representative particle size (µm)**	**settling velocity (mm s^{-1})**	**note**	**reference**
Abbot Point	clay	2	0.050	for clay, 0.050 m s^{-1} instead of 0.004 m s^{-1} from Stokes law	GHD (2012)
	fine silt	8	0.057		
	medium silt	23	0.475		
	coarse silt	45	1.817		
	fine Sand	94	7.93		
Anketell Point	clay	<7	settlement rates following Teeter (2001)		APASA (2010)
	fine silt	8-35			
	coarse silt	36-74			
	fine sand	75-130			
	coarse sand	>130			
Browse	not mentioned	not mentioned	not mentioned	from 3 core samples	DoSD, WA (2010)
Cape Lambert A	29 classes	0.4-2000	0.0001236-3172	settling velocities from Geraldton (clearly based on Stokes law)	GEMS (2007)
Cape Lambert B	25 classes	1-10000	0.0008-78937.5	from 19 core samples using Sedigraph	GEMS (2008a)
Dampier Port Upgrade	20 classes	5 µm increments below 100 µm	not specified	settling velocity from Dampier Port Authority	GEMS (2004)
Dampier Marine Facility	clay	<7	Settlement rates following Teeter (2001)		APASA (2009a)
	fine silt	8-35			
	coarse silt	36-74			
	fine sand	75-130			
	coarse sand	>130			
Gorgon	not mentioned	not mentioned	not mentioned	particle size distribution (and settling velocities?) from Geraldton	GEMS (2005)
Great Barrier Reef Dredge material management study	clay	<7	0.8	settling velocities are minimum values	SKM/APASA (2013)
	fine silt	7-35	2.3		
	coarse silt	35-75	3.8		
	fine sand	75-130	10.6		
	coarse sand	>130	100		

Project	**sediment class**	**representative particle size (µm)**	**settling velocity (mm s⁻¹)**	**note**	**reference**
Ichthys	fines fine sand medium sand	<75 75-200 >200	not mentioned		HR Wallingford (2010)
Pluto	clay to medium silt coarse silt very fine to fine sand fine to medium sand medium sand coarse sand	30 70 100 200 500 1000	not specified	particle settling velocities are calculated using Stokes' law and through the complex processes of flocculation	APASA (2008)
Port Hedland Outer Harbour	clay fine silt coarse silt fine sand coarse sand	0-7 7-35 35-75 75-130 >130	not specified	sinking rates of clay and fine silt-sized particles are enhanced at increased concentrations	APASA (2009b)
Port Hedland RGP5	27 classes?	0.2-2000	0.000031-3090	from core samples	GEMS (2008b)
Port Hedland SW Creek	clay fine silt Silt	2 8 43	0.004 0.06 1.7		Cardno (2010)
Wheatstone	6 fractions	not mentioned	0.03 0.24 0.39 0.48 0.68 1.0		DHI (2010)

It is important to take into account the existing arbitrariness in separating the deposition and resuspension rates, when looking at existing data and analysing experimental and field data (e.g. in order to estimate model parameters). For example, available data in most laboratory and field experiments provide the total mass flux (e.g. resuspension rate minus deposition rate), and a different assumption on deposition rates results in different resuspension rates (and vice versa). Therefore, model parameters should be chosen based on data that are consistent with the deposition and resuspension parameterizations used in the model.

We expect that critical shear stress for deposition is sensitive to many physical, chemical, and biological parameters, which is the case for critical shear stress for resuspension (see next subsection). Therefore, it should ideally be determined using *in situ* particles and sediment beds. However, critical shear stress for deposition is often determined in laboratory experiments using artificial beds, and field-based estimates are limited (e.g. Wolanski and Spagnol 2003; Andersen et al. 2007). This makes applying (15b) to field conditions difficult.

From a modelling view point, (15a) is advantageous because it often explains field data better (Sanford and Halka 1993) and non-cohesive and cohesive sediments can be treated in the same way (Le Hir et al. 2011). However, the difference between (15a) and (15b) could be important for hydrodynamic modelling because a layer of high SSC near the bed, which develops with (15b) under depositional conditions, may reduce bottom friction and turbulent mixing (though such effects are usually not included in sediment transport models). It should also be noted that the existence (or absence) of exchange flux between the water column and the sediment bed is essential for some problems, such as transport of contaminants adsorbed onto cohesive sediments.

3.2.4 Resuspension

Resuspension or erosion is a process in which sediment particles on the bed is suspended by the flow above the bed. (In this review, the terms ‘resuspension’ and ‘erosion’ are used interchangeably.) Erodibility of cohesive sediments, or susceptibility of the sediment to erosion (opposite of bed strength or bed stability), is commonly expressed as a relationship between bottom shear stress and resuspension rate. Common forms of such a relationship used in sediment transport models (Gularte et al. 1980; Parchure and Mehta 1985) are

$$E = E_0(\tau_b/\tau_c - 1)^n \tag{17a}$$

$$E = M(\tau_b - \tau_c)^n \tag{17b}$$

and

$$E = \varepsilon_f exp\{\alpha(\tau_b - \tau_c)^\beta\}, \tag{17c}$$

where E is the resuspension rate (kg m^{-2}s^{-1}), τ_b is the bottom shear stress (N m^{-2}), and τ_c, E_0, M, n, α, β, and ε_f are model parameters. The first two parameterizations (17a,b) are essentially the same (using the conversion $E_0 = M{\tau_c}^n$); we prefer to use (17b) because it includes the case $\tau_c = 0$. These parameterizations (with $n = 1$) are often attributed to Partheniades (1965) and Ariathurai (1974), but it is probably more correct to attribute it to Kandiah (1974) (Krone 1999; van Prooijen and Winterwerp 2010). τ_c is the critical shear stress (N m^{-2}), defined as shear stress at which significant resuspension occurs. Critical shear stress is often used as a proxy of erodibility, but it should be noted that what is ‘significant’ resuspension is subjective, and it makes quantitative comparison of the parameter difficult (Partheniades 1965; Lavelle and Mofjeld 1987; Tolhurst et al. 2000a). It is also worth noting that many studies do not assume the existence of critical shear stress, and that resuspension rate is more important than critical shear stress for modelling purposes because it is the variable appearing in the budget of suspended sediments. Therefore, we consider all the parameters in (17) represent the erodibility. These parameters from selected literature are summarized in Table 3. The table shows:

- there are at least an order of magnitude differences in the resuspension model parameters;
- critical shear stress is often reported but not the rest of the parameters;
- critical shear stress is typically 0.01-0.1 (Pa) for a fluff layer and 0.05-4 (Pa) for a consolidated layer; and

- different forms of stress-resuspension relationships often explain data to a similar degree (see Fit 1 and 2 in Table 3; e.g. for Amos et al. 1992).

Some reasons for the last point are that scatter in the data is large, and that the parameters in (17) vary with depth as explained below, which can be more important than the details of the formulation. In the following, we will see how these model parameters are obtained, why they are not constrained well, and why they have to be regarded as tuning parameters (adjusted on a case-by-case basis so that the model could reproduce the observations) in sediment transport modelling. Since resuspension of cohesive sediments is a complex process, this review starts from the simplest case and moves towards complex *in situ* sediments. We focus on physical processes of resuspension because we expect that physical processes are more important than biological processes for freshly deposited dredged materials. The situation is different for ambient and natural sediment beds, which are strongly affected by biological processes; see Grabowski et al. (2011) for a review of physical, chemical, and biological factors governing resuspension.

The differences between non-cohesive and cohesive sediments are best illustrated by the simplest cohesive sediment bed, consisting of one type of mineral particles with narrow size distribution (e.g. Roberts et al. 1998, 2003). Large particles behave in a non-cohesive manner; they get resuspended particle by particle, and the particle size and density are the major governing factors (e.g. Soulsby 1997). On the other hand, small particles behave in a cohesive manner, and may form two types of sediment bed depending on the sediment composition (e.g. Otsubo and Muraoka, 1988; Roberts et al. 1998). The first type does not have a well-defined sediment-water interface, and the bed flows under shear. Resuspension occurs as entrainment of fluid mud, and often formulations different from (17a-c) are used (see e.g. Odd and Cooper 1989; Kranenburg and Winterwerp 1997; Winterwerp and van Kasteren 2004). The second type has a clear sediment-water interface, and resuspension tends to occur in aggregates or chunks without flow of the bed. Equations 17 a, b, c are primarily developed for this type, though (17a, b) is also applied to fluid mud (Maa and Mehta 1986; Mehta 1996). Bulk density (or equivalently water content or porosity for particles of single mineral type) becomes a more important factor than particle size. The resuspension rates also vary with salinity and temperature (Gularte et al. 1980). Note that Eqs. (17a-c) are given for the total resuspension rate for all the size classes. Limited studies (e.g. Roberts et al. 2003) suggest no bedload and no sorting for the resuspension of cohesive sediments (i.e. particle size distribution of resuspended particles are the same as those of the surficial sediment).

Consolidation is an important process that differentiates non-cohesive and cohesive sediments. Non-cohesive sediments consolidate very quickly and form a bed of approximately constant erodibility with depth. On the other hand, cohesive sediments consolidate very slowly, and the erodibility varies with depth (and time). This leads to different resuspension behaviours even with the same sediment composition and under the same shear stress. For example, under constant shear stress, the resuspension rate decreases with time if the erodibility decreases with depth (e.g. deposited bed made from suspension), but the resuspension rate remains constant if the erodibility is constant with depth (e.g. remoulded bed). These idealized behaviours are called Type I and Type II behaviours, respectively (Amos et al. 1992; Sanford and Maa 2001). Type I behaviour is further divided into resuspension of a fragile 'fluff layer', or a layer consisting of unconsolidated mud, flocs, and fecal pellets on the surface (Type Ia), and that of the underlying consolidated bed (Type Ib). If a soft cohesive sediment bed is subject to sustained shear stress, compaction due to bed deformation can decrease the erodibility (Kusuda 1984; Panagiotopoulos et al. 1997). On the other hand, pore pressure fluctuation due to surface waves can increase erodibility and fluidize the bed (Maa and Mehta 1986; Mehta 1996).

Traditionally, non-cohesive and cohesive sediments are treated separately, but recent studies highlighted the importance of interaction between the two (Mitchener and Torfs 1996; Panagiotopoulos et al. 1997; van Ledden et al. 2004; Dickhudt et al. 2011). These studies show that a mixed sediment bed shows transition between non-cohesive or cohesive behaviours between mud fraction of 30-50% (Panagiotopoulos et al. 1997; Le Hir et al. 2008) or clay fraction of 5-10% (Panagiotopoulos et al. 1997; van Ledden et al. 2004; Law et al. 2008). Adding mud to sandy bed decreases the erodibility, but the effects of sand on muddy bed is not clear (Williamson and Ockenden 1993; Mitchener and Torfs 1996; Le Hir et al. 2008). Mixed beds also introduces a new phenomenon called bed armouring (e.g. Wiberg et al. 1994), in which less erodible surficial sediments prevent erosion of the underlying more erodible layer. Limited studies (e.g. Law et al. 2008) suggest that finer components get preferentially resuspended for non-cohesive (sandy) beds, but no preferential resuspension occurs for cohesive beds. There are also suggestions that, unlike flocs made of mineral particles, natural flocs are resistant to near-bottom shear and can be transported as bedload (Thomsen and Gust 2000; Roberts et al. 2003). There are recent models that deal with sand-mud mixture and/or bed armouring (e.g. Le Hir et al. 2011; van Kessel et al. 2011).

The situation becomes much more complex once we consider different types of sediments, interstitial water, and biological activity. Erodibility of cohesive sediments with the same particle size and bulk density can vary by orders of magnitude depending on other physicochemical factors, such as mineral composition, Cation exchange capacity (CEC), sodium adsorption ratio (SAR), pH, ionic composition, and quantity and type of organic matter (Ariathurai and Arulanandan 1978; Otsubo and Muraoka, 1988; Lick et al. 2004; Winterwerp and van Kesteren 2004). Biological activity can stabilize or destabilize sediments (Black et al. 2002; Grabowski et al. 2011). For example, bacteria and diatoms stabilize the surficial sediment by excreting EPS and forming bio-films, whereas movement and grazing of crustaceans, bivalves, and polychaetes mixes the upper sediment (typically surficial sediment of the order of 10 cm; Boudreau 1998), a process called bioturbation. Biological processes can cause large temporal and spatial variability of the erodibility (e.g. Widdows et al. 2000; Amos et al. 2004). Artificial sediment beds in laboratories are useful to understand basic physics of cohesive sediment resuspension under controlled environment; however, the limitation of this approach has long been recognized for erodibility of *in situ* sediments, because sediment consolidation depends on the history of deposition and disturbance, such as ambient currents and waves, storm and flood events, and because reproducing the various effects of biological activity in laboratory is difficult (e.g. Black et al. 2002; Grabowski et al. 2011).

The importance of undisturbed sediments led to development of many *in situ* devices to measure cohesive sediment erodibility (see Black and Paterson 1997 for a review). These devices typically apply stress that is larger than field conditions to erode *in situ* sediments. These devices have an advantage of providing vertical profiles of erodibility (parameters in (17)), but they have disadvantages that the deployment becomes difficult with increasing water depth (hence measurements are often done on tidal flats), and that the 'fluff layer' gets resuspended when the device is lowered to the bottom or when the device is filled with water (Black and Paterson 1997; Widdows et al. 2007). Unfortunately, later comparison studies found that the resuspension rates from different *in situ* devices vary by orders of magnitude (Tolhurst et al. 2000a; Amos et al. 2004; Widdows et al. 2007). Possible causes of the discrepancy include different methods to exert force to the sediment bed (Widdows et al. 2007), inconsistent experimental procedures (Tolhurst et al. 2000a), inconsistent data analysis methods (Sanford 2006; Widdows et al. 2007), and possibly different assumption on deposition rate. Actually, inconsistent data analysis method is also a problem with laboratory experiments (e.g. definition of critical shear stress as mentioned earlier), as well field data analysis described below. Another option to measure cohesive sediment erodibility is laboratory experiments using *in situ* sediments. Transporting sediments could destroy the sediment structure and change the resuspension parameters by an order of magnitude (Tolhurst et al. 2000b), but carefully transported sediments can yield results comparable to the field (Widdows et al. 2000).

Due to current uncertainty of *in situ* device results and difficulty in transporting undisturbed *in situ* sediment, estimating a stress-resuspension rate relationship from field observation remains an important option. In general, it is not an easy task to estimate resuspension rate because it requires disentangling advection, turbulent mixing, resuspension, settling, and deposition. Fortunately, in a system where sediment transport is approximately one dimensional in the vertical (resuspension balanced by deposition), it is sometimes possible to estimate resuspension model parameters by correlating bottom shear stress and resuspension rate (e.g. Lavelle et al. 1984; Sanford and Halka 1993). Compared to the past, estimating a stress-resuspension rate relationship from field observation became easier thanks to recent technological advances of commercially available instruments. For example, LISST measures particle size distribution and settling velocity (e.g. Agrawal and Pottsmith 2000), and ADV can provide turbulent shear stress, change of bottom elevation (e.g. Andersen et al. 2007), and if particle composition does not change, turbulent flux of suspended particles (Fugate and Friedlichs

2003; Maa and Kwon 2007), which provides a proxy of resuspension rate when measured near the bottom (Shimizu et al. 2005). Compared to *in situ* devices or laboratory experiments with natural sediments, field observation has an advantage that both stress and resuspension rate are measured, but it has a disadvantage that it provides resuspension parameters only for the measured range of shear stress (i.e. only for surficial sediment under ambient conditions).

Resuspension of cohesive sediments is mostly studied under unidirectional or slowly varying (e.g. tidal) currents, but surface wave forcing (or combined wave-current forcing) is essential in shallow waters (e.g. Sanford 1994; Lambrechts et al. 2010). It is understood that physical process of resuspension under wave forcing is different from unidirectional currents because pore pressure fluctuation due to waves can weaken and fluidize the sediment bed (Maa and Mehta 1986; Mehta 1996). This means that the use of (17) with bottom shear stress under combined waves and currents (e.g. Grant and Madsen 1979; Soulsby and Clarke 2005) considers only some parts of the problem, and it does not explain some field data (e.g. Wolanski and Spagnol 2003; Lambrechts et al. 2010). It appears that there is no general way to parameterize the effects of waves. For fluid mud, resuspension can be modelled using a general-purpose mixing scheme for stratified shear flows considering sediment particles as a stratifying agent (Winterwerp 2001; Winterwerp and van Kasteren 2004), but this requires high vertical resolution near the bottom to resolve fluid mud. For practical purposes, (17a,b) is often used under wave forcing (Maa and Mehta 1986; Mimura 1993); a difficulty of this approach is the parameters depend not only on sediment characteristics but also on wave conditions. Another approach is to relate wave height and resuspension rate (e.g. Rodriguez and Mehta 2000; Wolanski and Spagnol 2003; Lambrechts et al. 2010); this approach appears successful in explaining some observations, but the formulation appears rather *ad hoc* because such a relationship was obtained for very limited conditions in laboratory experiments (e.g. Yamanishi et al. 1998).

There is limited information available on cohesive sediment resuspension from tropical Australia. Wolanski and Spagnol (2003) and Lambrechts et al. (2010) suggested critical shear stress of about 0.5 and 0.3 (Pa) for King Sound and Cleveland Bay, respectively; however, both studies did not specify other resuspension parameters and emphasized the importance of wave-induced resuspension. Resuspension parameters are rarely reported in EIA documentation. Due to complexity of the process and difficulty in measurements, there is large uncertainty in predicting the resuspension rate of cohesive sediments. Considering current understanding, we would propose the following for sediment transport modelling.

- In general, erodibility of *in situ* sediments needs to be determined using undisturbed *in situ* sediments. This is because it is impossible to predict erodibility of *in situ* cohesive sediment as a function of bulk sediment properties, such as particle size distribution, bulk density, organic matter content, and biological activity (Roberts et al. 1998; Sanford 2006; Grabowski et al. 2011). However, in some cases, bulk density (or water content or porosity) explains the large part of the variability of erodibility (Sanford and Maa 2001; Amos et al. 2004; see also Dickhudt et al. 2011 for sand-mud mixture), and EPS concentration appears to be an important biological factor (Grabowski et al. 2011).
- Laboratory experiments do not provide the erodibility of *in situ* sediments (Black et al. 2002; Grabowski et al. 2011) unless undisturbed *in situ* sediments are used (e.g. Widdows et al. 2000). Possible exception is a laboratory experiment with deposited beds made from dredged material, which may provide erodibility of freshly deposited dredged materials in the field because the processes involved are primarily physical. However, such an experiment would be problematic if *in situ* deposition occurs as flocs, and would have limited applicability after dredged materials are mixed with natural sediments and/or affected by biological activities.
- The ranges of resuspension parameters from current studies vary by at least an order of magnitude, both due to real variability of sediment erodibility as well as artificial variability associated with instrument design, experimental procedures, and data analysis methods (Tolhurst et al. 2000a; Sanford 2006; Widdows et al. 2007). This means that, in practice, the parameters need to be chosen so that the model reproduces observation, typically suspended sediment concentration. However, it is now possible to

measure settling velocity and turbulent flux (if particle composition does not change) of *in situ* particles, and where possible, such measurements are preferably used to constrain ranges of the model parameters.

- Predicting resuspension under cyclone events requires resuspension parameters of *in situ* sediment as a function of depth. Unless detailed field data under cyclone events are available, the only method to get the vertical profiles is to use an *in situ* device or a portable flume with *in situ* sediment, considering the limited facilities in the Pilbara and Kimberley regions. If the parameters depend mostly on bulk density (or other physical bulk parameters), it may be feasible to predict erodibility using a consolidation model, which is often a part of sediment transport model (e.g. Sanford 2008; Le Hir et al. 2011).

3.3 Forcing (Input) data for hydrodynamic, wave, and sediment transport models

The quality of data used to force the models and as input to the models is vitally important for accuracy of model predictions. Large uncertainties exist for sediment transport model input, but the hydrodynamic model could also suffer from lack of adequate spatial and temporal data to resolve important processes. Here we provide an overview and assessment of current status of forcing data for hydrodynamic, wave, and sediment transport models.

3.3.1 Forcing data for hydrodynamic and wave models

Hydrodynamic and wave models are usually driven by local forcing (wind, pressure, and heat and fresh water fluxes if applicable) or large-scale atmospheric forcing from regional or global models. Land-sea breeze is important in dredge plume dispersion in near-shore region, but large-scale atmospheric model output usually does not represent land-sea breeze. This can cause a potential problem in including the effects of both spatially variable forcing and land-sea breeze. Possible solutions used by practitioners are 1) merging the locally observed winds with large-scale winds, or 2) running the model using the two different forcing datasets to assess the sensitivity. Both options are reasonable approaches.

Large-scale ocean currents due to large-scale atmospheric forcing can also be important for sediment transport as they are capable of carrying the sediment plume much further away from its generation site than when the model is forced only with the local wind and waves. Examples of such ocean currents are the East Australian Current which could be important for sediment transport in the Great Barrier Reef region, and the Leeuwin Current which may affect sediment transport on the North West Shelf. Ideally, the effect of such currents should be addressed with high-resolution small-scale models nested inside lower-resolution large-scale ocean circulation models or using open-boundary conditions that are provided by ocean circulation models or ocean reanalysis products that are forced by large-scale ocean-atmosphere momentum and heat fluxes. The approach of simply superimposing output from coarse-resolution large-scale ocean models with that of high-resolution local hydrodynamic models to address large-scale current effects could introduce dynamic inconsistency and increase uncertainty in model predictions.

Another potential problem for stand-alone coastal domain for hydrodynamic and wave modelling is the neglect of the spatial variation along the model boundaries. This is particularly problematic in a region of complex topography because the boundary conditions are typically taken from existing large-scale model output, and the resolution may be insufficient. For example, global wave model output may provide only one point along the boundaries where significant spatial variations are expected. In this case, care must be taken when using such data. It may be better to make the domain larger (by nesting or using grids with varying size) so that the boundary conditions are better specified.

3.3.2 Forcing data for sediment transport models

We consider only far-field modelling here because dredge plume modelling for EIA purposes is usually done for the far-field. Far-field of a dredge plume is where suspended sediment concentration is so low that the dredge plume behaves passively to the current field. In contrast, the near-field is where suspended sediments from dredge spill or dumping at least partly drive the flow, accompanied with rapid mixing with the ambient water.

Far-field sediment transport modelling requires mass spill rates, settling velocity of the spilled mass, initial vertical distribution of the spill mass, and if ambient sediments are included, their concentration at model boundaries.

Table 3. Summary of selected studies on erodibility of *in situ* cohesive sediments. Symbols are defined as follows; E: Resuspension rate, τ_b: bottom shear stress , τ_c: critical shear stress, M and n: model parameters in resuspension formula $E = M(\tau_b - \tau_c)^n$,ε_f, α and β: model parameters in resuspension formula $E = \varepsilon_f \exp\{\alpha(\tau_b - \tau_c)^\beta\}$, ρ_b: bulk density, φ: porosity, W: water content, POC: organic matter content (often approximated by loss on ignition). The parameterization given in the form $E = E_0(\tau_b/\tau_c - 1)^n$ is converted to the form $E = M(\tau_b - \tau_c)^n$. Definitions of clay and silt fractions are those used in the cited study. Abbreviations are defined as follows; ABS: acoustic backscatter, AF: Annular flume, EDR: exclusive deposition and resuspension; MAF: Mini-annular flume, CSM: Cohesive Strength Meter, ISEF: *In situ* Erosion Flume, NOC: National Oceanography Centre Southampton, PML: Plymouth Marine Laboratory, SDR: simultaneous deposition and resuspension; and SSC: suspended solid concentration. Fit 1 and 2 refer to different model fits to the same data. (Note that E is the final output, and τ_b is the input, therefore these two items do not show up in this table.)

Study	location	τ_c (Pa)	$10^5 M$ (kg m-2s-1Pa-1)	n (-)	$10^5 \varepsilon_f$ (kgm-2s-1Pa-1)	α (-)	β (-)	ρ_b (kgm-3)	φ (%)	W (%)	POC (%)	$clay$ (%)	$silt$ (%)	notes
In situ device - Tidal flat														
Amos et al. (1992)	*Bay of Fundy*					1		1820		20-30	2-3	10-20	40-60	assuming EDR
	fit 1	0.11-0.5	49	0.81		1.62								
	fit 2	0.11-0.5			5.1		0.5							
Amos et al. (1997)	Fraser River Delta	0.1-1.0						790-1270		37-79	0.5-5	15-26	38-74	excluding fluff layer E not function of stress
Houwing et al. (1999)	*Wadden Sea*	0.10-0.18						1500-1800		40-120	4-8	4-35		
Tolhurst et al. (2000a)	*Humber Estuary*													intercomparison of *in situ* devices
	Microcosm	0.2												
	ISEF	0.2-0.3												
	SeaErode	0.2-0.5												
	CSM	0.5-1.5												
Widdows et al. (2007)	*Falmouth and Tavy & Tamar Estuaries*							1130-1480		46-81	5.4-11	72-85		inter-comparison of *in situ* devices
	fluff layer													
	PML AF	0.03-0.08												
	PML MAF	0.02-0.10												
	NOC CSM	0.07-1.4												
	consolidated bed													
	PML AF	0.06-0.29												
	PML MAF	0.03-0.33												
	NOC MAF	0.06-0.40												
	NOC CSM	0.27-4.7												
	EROMES	0.29-1.1												

Study	location	τ_c (Pa)	$10^5 M$ (kg m-2s-1Pa-1)	n (-)	$10^5 \varepsilon_f$ (kgm-2s-1Pa-1)	α (-)	β (-)	ρ_b (kgm-3)	φ (%)	W (%)	POC (%)	$clay$ (%)	$silt$ (%)	notes
In situ device – submerged														
Gust and Morris (1989)	*Puget Sound*										0.85-1.2	11-13	38-79	
	fluff layer	0.02-0.08												
	consolidated bed	0.2												
Maa et al. (1998)	*Baltimore Harbour*	0.01-0.8	20-100	10							3.0-4.5	60-70	30-40	reanalysis by Sanford (2001) and assuming EDR
Ravens & Gschwend (1999)	*Boston Harbour*								76-82			11-27	51-64	
	fit 1	0.1	320	1.0										
	fit 2		410	1.7										
Field observation														
Lavelle et al. (1984)	*Puget Sound*	0	1.7	4.0						160-230	3-5			assuming SDR
Sanford & Halka (1993)	*Chesapeake Bay*							1300-1500	71-82			20-36	57-76	assuming SDR
	fit 1	0.25-1.1	30	4.0										
	fit 2	0	0.19-2.1	1.3-4										
Thomsen & Gust (2000)	*European Continental Margin*													
	fluff layer	0.03-0.14												
	consolidated layer	0.08-0.44												
Wolanski & Spagnol (2003)	*King Sound*	≈0.5	?	3										
Shimizu et al. (2005)	*Tone River*									220		80		fluff layer
	fit 1	0.05	13	1.0	36	24	1.0							limited ABS-SSC calibration
	fit 2													assuming SDR
Lambrechts et al. (2010)	*Cleveland Bay*	≈0.3	?											

Table 4. Spill rates from TSHDs used in EIAs in tropical Western Australia

Project	dredge head/propeller wash	overflow	dumping	note	reference
Anketell Point	0.6% of total when not overflowing. Propeller wash 10kg/s when not overflowing	3% of total (concentration 6000 mg/l)	5% of total		APASA (2010)
Browse	1% of fines	50/9/32 % of fines	20% of fines	base/bow/bypical cases	DoSD, WA (2010)
Cape Lambert A	empirical algorithm for propeller wash	not mentioned	not mentioned		GEMS (2007)
Cape Lambert B	empirical algorithm for propeller wash	not mentioned	not mentioned	pick up of material cut by CSD?	GEMS (2008a)
Dampier Port Upgrade	empirical algorithm for propeller wash	not mentioned	not mentioned		GEMS (2004)
Gorgon	Not mentioned for TSHD only operation. Pick up of material cut by CSD 0% (initial) / 30% (revised) of fines cut by CSD.	Not mentioned for TSHD only operation. Pick up of material cut by CSD 0% (initial) / 30% (revised) of fines cut by CSD.	Not mentioned for TSHD only. Pick up of material cut by CSD 0% (initial) / 20% (revised).		GEMS (2005)
Ichthys	1/3 of fines in overflow or 5% of total fines	15% of fines	not mentioned		HR Wallingford (2010)
Pluto	based on Damara (2004) and van Rijn (1989)	3% or 0.3% of total	unclear (100%?)		APASA (2008)
Port Hedland Outer Harbour	0.03 % of total Propeller wash 0.65m3/min	1% of total	unclear (100%?)		APASA (2009b)
Port Hedland RGP5	not mentioned	not mentioned	not mentioned	150 mg/l from reclamation area	GEMS (2008b)
Wheatstone	1/3 of fines in overflow or 5% of total fines 0.5% of fines in bed & Propeller wash 27.5 kg/s (2-4m under keel) and 10.8 kg/s (4-8 under keel)	7% (realistic) / 15 % (worst) of fines	5% (realistic) / 25% (worst) of fines in hopper	based on 8225m3 TSHD in Hong Kong	DHI (2010)

Table 5. Spill rates from cutter suction dredgers (CSDs) used in EIAs in tropical Western Australia

Project	cutting	barge overflow	disposal	note	reference
Anketell Point	0.5% of total	N/A	N/A	spoil placed on bed	APASA (2010)
Browse	not mentioned	50/9/32 % of fines	20% of fines (dumping)	base/low/typical cases	DoSD, WA (2010)
Cape Lambert A	not mentioned	not mentioned	not mentioned		GEMS (2007)
Cape Lambert B	not mentioned	not mentioned	not mentioned		GEMS (2008a)
Dampier Port Upgrade	not mentioned	not mentioned	not mentioned	partially onshore disposal	GEMS (2004)
Dampier Marine Services	0.5 % of total	N/A	170 mg/l from reclamation area	onshore disposal	APASA (2009a)
Gorgon	50% (initial) / 30% (revised) of fines	N/A	50% (initial) / 20% (revised) of fines (dumping)		GEMS (2005)
Ichthys	50% of fines	N/A	5 % upon placement	spoil placed on bed	HR Wallingford (2010)
Port Hedland Outer Harbour	100% of total	N/A	N/A	spoil placed on bed	APASA (2009b)
Port Hedland SW creek	5% of fines	N/A	150 mg/l discharge water	onshore disposal	Cardno (2010)
Wheatstone	7.5 – 15 % of total	7% (realistic) / 15 % (worst) of fines	not mentioned (same as TSHD?)		DHI (2010)

Table 6. Spill rates from Backhoe and Grab Dredge used in EIAs in tropical Western Australia

Project	Excavation	Barge overflow	Disposal	note	Reference
Browse	not mentioned	8-10 %	20% of fines (dumping)	typical fine loss case	DoSD, WA (2010)
Ichthys	3% of fines	N/A	5% (dumping)	no overflow	HR Wallingford (2010)
Port Hedland RGP5	not mentioned	not mentioned	150 mg/l from reclamation area		GMS (2008b)
Port Hedland SW creek	5% of fines	not considered	not considered		Cardno (2010)
Wheatstone	3% of total	not mentioned	5% (realistic) / 10% (worst) of fines (dumping)		DHI (2010)

Mass spill rates are reviewed by Theme 2; here, we would like to point out that the values used in the past EIAs vary considerably (Tables 4-6). Presumably the variation partly reflects different sediment types and dredgers used, but it is a major source of uncertainty in dredge plume modelling. If a sediment transport model is set up in such a way that the model is linear with respect to the spill rate, this uncertainty could be assessed independently from the uncertainty of dredge plume modelling, but this is not usually the case. Even with such a linear sediment transport model, the uncertainty in spill rate is problematic for model calibration and/or validation.

Settling velocity of the spilled mass is usually obtained from particle size distribution of sediment core samples and assumption about the effects of cutting at the dredge head (see the review by Theme 2). This approach is fine if flocculation is negligible. However, Wolanski et al. (1992), Mikkelsen and Perjrup (2000), and Smith and Friedrichs (2011) showed flocculation in the overflow from dredge plumes, suggesting a potential problem with the current practice. To investigate the importance of flocculation in a dredge plume on the tropical Australia, we need *in situ* measurements of particle size distribution and settling velocity.

Vertical distribution of released mass accounts for mixing processes in the near-field, which is not resolved in a far-field model. The importance of the initial vertical distribution depends on mixing in the far-field; it is important if mixing there is weak and the water column is stratified, but not very important if mixing there is strong.

Currently, ambient sediments are not included in dredge plume modelling for EIA purposes in tropical Australia. If they are included, a lack of the concentration data at model boundaries becomes an issue.

3.4 Model calibration, validation, and performance assessment

We use the term 'model calibration' for a process of choosing model parameterizations and tuning the parameter values using observation, and 'model validation' for a process of assessing the accuracy of calibrated models through comparisons against observation.

Data availability is a limiting factor in the calibration and validation of dredge plume modelling. Preferably the data for model calibration and validation cover at least different seasons and are available at several locations to assess seasonal and spatial variability. Continuous measurements (e.g. one year long) are helpful to assess magnitudes and frequency of some extreme events, which are important for sediment transport. If available data are limited, model calibration and/or validation may not be possible. At the EIA stage, sediment transport models are often not calibrated and validated because dredging has not started. This is understandable but leaves large uncertainty in model prediction. Even if some data regarding sediment transport are available, the uncertainty in the amount of dredged material released to the far-field can pose difficulties in model calibration and/or validation. If possible, the use of past data from a similar region could be considered for validation of dredge plume modelling.

Assessing the accuracy of hydrodynamic, wave, and sediment transport models is an essential process in assessing the uncertainty of dredge plume model prediction. The following lists some basic recommendations.

- For model validation, we recommend to set up and force the models as in the final dredge plume modelling, so that the validation reflects models' uncertainty in the final modelling.
- We recommend that model validation accounts for at least seasonal variability (unless dredging is occurring in a particular season).
- Assessment needs to take into account the inherently different accuracy among hydrodynamic, wave, and sediment transport modelling.
- The data used for model calibration (or the data assimilated to the model) and the data used for model validation are preferably separated, although it is difficult to collect separate data sets for validation of sediment transport models

- Comparisons against measurements should cover both temporal and spatial scales of available data to ensure scales of key processes are resolved. If comparisons are too selective, the reader has to wonder whether they are representative of the entire time period and locations. Comparisons at several locations are preferable because, for example, sediment transport is sensitive to water depth. Extensive comparison plots can be put in an appendix.

Assessing the reliability of model results is difficult when model parameterizations and parameter values are not reported. The lack of information may mean that they are not calibrated, but it may mean that the modellers do not wish to disclose such information. Since dredge plume modelling for EIA purposes is done to be assessed by the regulatory authorities and the public, information essential for assessing reliability of the model results need to be reported. For dredge plume modelling, such information include

- horizontal dispersion (constant/Smagorinsky type, parameter value);
- particle classes;
- settling velocity (values; flocculation formulation and parameter values if included); and
- resuspension and deposition (formulation and parameter values).

For plume modelling the reasons the above parameters are chosen need to be specified. Note that if the sediment transport model is not calibrated against observation, the formulations and parameter values are the primary information available to assess the adequateness of sediment transport modelling. In such cases, sensitivity of the results should be tested with a range of plausible parameter values.

3.5 Modelling approach

3.5.1 Scenarios vs continuous modelling

At the EIA stage, the details of the dredging program are usually not determined, such as dredging schedule, dredgers to be used, and spoil handling. Dredge plume modelling at this stage needs to take different options (e.g. dredgers, spoil ground) into account to adequately assess uncertainty in model predictions. It also needs to consider seasonal variability (e.g. summer vs winter) and interannual variability (e.g. El Niño vs La Niña year) of atmospheric forcing, which are important factors determining regional circulation and hence dredge plume dispersion. It is also important to distinguish short-term immediate impact from dredging and long-term cumulative impact from dredging and natural events or inputs.

Depending on the timing of the dredging, the metocean conditions could vary significantly due to large-scale inter-annual or seasonal climate forcing or local forcing, such as El Niño or La Niña events, winter or summer, wet or dry season. A commonly used approach is to choose a season or year that has the strongest metocean forcing for the hydrodynamic and sediment transport models, so as to generate the maximum possible propagation and resuspension of the plume, a 'worst-case' scenario when the plume extent and severity are the largest.

To address uncertainty in the dredging program, two commonly used approaches are: (1) run a continuous simulation according to a likely dredging scenario for the whole period of dredging (i.e. 'continuous' approach); (2) run short simulations for different phases of dredging program (i.e. 'scenario' approach). Both approaches have advantages and disadvantages, and the best choice is likely to be made on a case-by-case basis. Some points to be considered are: the 'scenario' approach neglects any history effects, such as resuspension of dredged material deposited in the prior phases, and potentially under-predicts suspended sediment concentrations. The 'continuous' approach is more desirable and rigorous if the details of the dredge program are relatively well fixed; however, it is more costly computationally (although one would imagine it is not a huge challenge given the improvement in computing power in recent years). If the dredging equipment to be used is unknown, it is also desirable for both approaches to consider modelling different input and characters of fine particles to the far-field plume model due to the use of different types of dredges, and then combine the outputs to produce a comprehensive envelop of likely dispersion. Additionally, the outputs of this type of modelling could be used to inform the selection of the most appropriate types and sizes of dredges to use to minimise impacts in areas of particularly high environmental sensitivity/importance.

In this project, we will investigate the advantages and disadvantages of both 'scenario' and 'continuous' modelling approaches and we will provide relevant recommendations from our findings.

3.5.2 2D vs 3D modelling

As recommended by the GBRMPA in its *Guidelines on the Use of Hydrodynamic Numerical Modelling for Dredging Projects in the Great Barrier Reef Marine Park*, 3-dimensional (3D) hydrodynamic model is required to adequately model the vertical and horizontal fields. Unless the water column is always well-mixed throughout the year, the 3D modelling is preferred. Even when water temperature is uniform throughout the water column, it has been observed that 3D structure of plume is often present, and the sediment concentration could have a strong sub-surface signature. This could happen when settling dominates turbulent mixing in the water column. In order to model the 3D structure realistically, accurate input data such as settling velocity and source terms are needed.

3.5.3 Eulerian vs Lagrangian frame of reference

The Lagrangian method of particle tracking is capable of modelling the movement of passive plumes following ocean currents. However, when sediment resuspension occurs while the plume is being advected by the currents, it is not straightforward to include it in Lagrangian models. Most of the existing studies on sediment resuspension are conducted using the Eulerian frame of reference, and incorporating resuspension in Lagrangian models would be a research question, but it is currently beyond the scope of this study.

3.5.4 Nested models vs local-domain models

It is important to determine if the area where the plume is likely to travel will be under the influence of large-scale currents. If large-scale currents are important, then there is a need to either set up nested models to account for the large-scale currents while resolving high-resolution features, or set up appropriate open boundary condition with a local domain model (note that nested models often need open boundary conditions as well, depending on how large the model domain is).

3.5.5 Ambient (background) sediments vs dredging-induced sediments

The ambient sediments are usually ignored in sediment transport modelling in EIA processes, and the simulated SSC is often reported as 'above the ambient level'. Including ambient sediments in sediment transport modelling would make monitoring results interpretable and ecological impact thresholds more detectable.

The potential advantages of including ambient sediments in the modelling in EIAs are:

- Better understanding of the dynamics of ambient sediments helps us to better assess the impact of dredging, for example on underwater light and biota. It is also desirable to compare variability of SSC due to dredging relative to that in background conditions (for chronic ecological impact) or during a cyclone event (for acute impact). This could be done with field data and does not necessarily require modelling.
- Dredged material will be gradually dispersed and mixed with ambient sediments. The interaction between dredged and ambient sediments needs to be considered because the behaviour of mixed sediments would be different from that of the dredged sediments. Post-cyclonic change of sediment characteristics in the Great Barrier Reef region suggests that such mixing occurs within a few months to a year (e.g. Larcombe and Carter 2004). Therefore, understanding the dynamics of ambient sediments and their interaction with dredged sediments are essential to understand mid- to long-term fate of dredged materials.
- Trigger levels or water quality thresholds based on 'SSC above ambient level' are operationally difficult to use because they are not easy to quantify from monitoring data, especially under flooding or stormy conditions. Trigger levels based on total SSC may be more practical.

The likely disadvantages of including ambient sediments in the modelling are:

- The dynamics of ambient sediments is most likely to be more complex than that of fresh dredged sediments because it could be strongly affected by biological activity, which is usually not modelled explicitly in sediment transport modelling. Therefore it is possible that even the state-of-the-art sediment transport models are not capable of reproducing observation in regions where ambient and dredged sediment concentrations are comparable, and including both ambient and dredged sediments does not necessarily reduce uncertainty of impact assessments.
- Simulating ambient sediment dynamics costs time and resources, not only for modelling but also for collecting field data required for model calibration and validation. Provided the current lack of necessary data for the calibration and validation of dredge plume modelling, priorities need to be given to data collection that leads to cost-effective reduction of uncertainties in sediment transport modelling for EIA purposes.

In summary, both advantages and disadvantages need to be assessed carefully on a cost-benefit basis. On the one hand, meaningful criteria to limit the extent and turbidity of dredging plumes can only be determined based on site-specific information on species assemblage and natural variability of ambient turbidity and sedimentation. On the other hand, including ambient sediments in the modelling in EIA documents introduces more complexity and costs in modelling and data collection. Analysis of available data on ambient sediments in this project would contribute to assessing the ease/difficulty of modelling ambient sediments.

3.5.6 Light availability

To assess the impact of dredging on ecosystems, it is necessary to translate predicted fields of suspended sediments and deposition into predicted distributions of biological stressors. Turbidity and sedimentation affects ecologically important marine organisms, such as corals, seagrasses, algae, and filter feeders (e.g. Erftemeijer 2006, 2012). Suspended sediments could reduce the amount of light in the water column and reaching the seabed, and deposition of sediments may smother or bury the organisms on the seabed. It was commonly believed that reduced light levels have a detrimental effect on the corals (e.g. Erftemeijer 2012), though recent research suggests smothering of coral by sedimentation is the most dominant factor for coral mortality (see the review by Theme 4). Usually SSC is used as the only indicator for predicting the impact on benthic ecosystems, but there have been some attempts in the EIAs to address this issue of light attenuation by suspended sediments due to dredging. Some EIAs have attempted to model the change in the light climate by applying a light attenuation coefficient that was constant throughout the water column. This is a good attempt but a constant light attenuation coefficient could be inadequate in predicting the actual light reaching the seabed. A more realistic approach will be needed and the review 3.1.1 and research project 3.2 address this issue in detail.

3.5.7 Sedimentation rate

Sedimentation rate or total sediment accumulation has a significant impact on benthic communities and corals are particularly sensitive to smothering from sediment. At the Wheatstone project site near Onslow, tolerance limits for sedimentation rates for corals and seagrass within the zones of impact are summarised in Tables 7-10 taken from Chevron (2012). The combined impact of sedimentation and suspended sediment concentration are used to define the zones of impact of dredging operations. However, it is not always clear how sedimentation rates are determined from model output. The physics of deposition and resuspension have been discussed previously in section 3.2.3 and 3.2.4 respectively and can be incorporated into a fully three-dimensional coupled hydrodynamic and sediment transport model. However, many studies use two-dimensional depth-averaged coupled sediment transport and hydrodynamic models and regions of erosion and accretion of sediment are associated with regions of divergence and convergence of sediment transport respectively. In other words if more sediment enters a model grid cell than leaves it then the excess accumulates on the bottom of the cell, reducing the depth accordingly. Conversely if more sediment leaves a cell than enters it the deficit in sediment is removed from the bottom and the depth increases. DHI undertook an extensive and comprehensive modelling study of projected dredge plumes at Wheatstone (Chevron 2013).

Table 7: Definition of impact zones for sedimentation on coral for nearshore waters (<5m) during summer and winter (from Table 5.6, Chevron (2012)).

Zones	Definitions
Zone of High Impact *EPO: total mortality allowed*	Sedimentation more than 34 mg/cm^2/day (more than 11.9 mm/14 days)
Zone of Moderate Impact *EPO: <30% mortality*	Sedimentation 10-34 mg/cm^2/day (3.5-11.9 mm/14 days)
Zone of Influence *EPO: 0% mortality*	Sedimentation 2.5-10 mg/cm^2/day (0.9-3.5 mm/14 days)
No Impact	Sedimentation less than 2.5 mg/cm^2/day (less than 0.9 mm/14 days)

Table 8: Definition of impact zones for sedimentation on coral for offshore waters (>5m) for all seasons and nearshore during transitional periods (from Table 5.7, Chevron (2012)).

Zones	Definitions
Zone of High Impact *EPO: total mortality allowed*	Sedimentation more than 14 mg/cm^2/day (more than 4.9 mm/14 days)
Zone of Moderate Impact *EPO: <30% mortality*	Sedimentation 5-14 mg/cm^2/day (1.7-4.9 mm/14 days)
Zone of Influence *EPO: 0% mortality*	Sedimentation 1-5 mg/cm^2/day (0.3-1.7 mm/14 days)
No Impact	Sedimentation less than 1 mg/cm^2/day (less than 0.3 mm/14 days)

Table 9: Definition of impact zones for sedimentation on seagrass for offshore waters (>5m) for transitional periods (from Table 5.10, Chevron (2012)).

Zones	Definitions
Zone of High Impact *EPO: total mortality allowed*	Sedimentation > 70 mg/cm^2/day (> 17 mm/14day)
Zone of Moderate Impact *EPO: <50% mortality*	Sedimentation 20 – 70 mg/cm^2/day (7 – 17 mm/14day)
Zone of Influence *EPO: 0% mortality*	Sedimentation 3 – 20 mg/cm^2/day (1 – 7 mm/14day)
No Impact	Sedimentation < 3 mg/cm^2/day (< 1 mm/14day)

Table 10: Definition of impact zones for sedimentation on seagrass for nearshore waters (<5m) for summer and winter (From Table 5.11, Chevron (2012)).

Zones	Definitions
Zone of High Impact *EPO: total mortality allowed*	Sedimentation > 100 mg/cm^2/day (> 24.5 mm/14day)
Zone of Moderate Impact *EPO: <50% mortality*	Sedimentation 30 – 100 mg/cm^2/day (10 – 24.5 mm/14day)
Zone of Influence *EPO: 0% mortality*	Sedimentation 4 – 30 mg/cm^2/day (1.5 – 10 mm/14day)
No Impact	Sedimentation < 4 mg/cm^2/day (< 1.5 mm/14day)

One of the modelling studies by DHI undertook repetitive modelling of 14-day periods representative of summer and winter conditions. Net sedimentation after 1, 2 and 16 fourteen-day periods are shown in Figure 1. These results are based on a dredging scenario of 10,000 m^3 TSHD dredging sand along the product loading facility (PLF) approach section 4 with disposal at site C and 10,000 m^3 TSHD dredging weak rock in the middle section of the PLF approach channel.

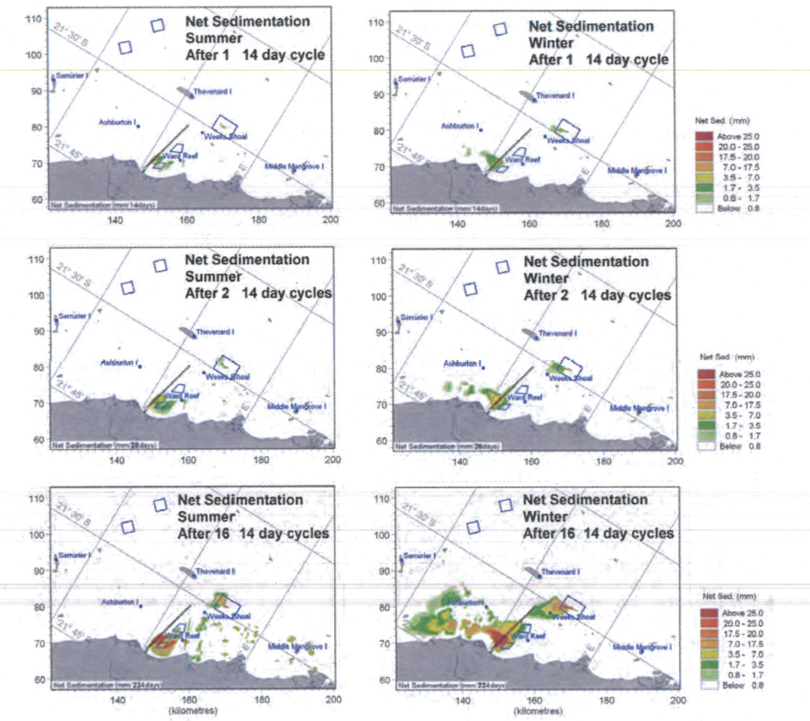

Figure 1: Net sedimentation after 1, 2 and 16 repetitive 14 day simulations for summer (left) and winter (right) (from Figure F.13 Chevron (2010)).

DHI also simulated sedimentation rates associated with mobilisation of the ambient sediments with an assumed D50 of 0.1 mm and 0.2 mm for summer and winter conditions. Profiles of sedimentation rates for D50=0.2 mm along three selected channel segments are shown in Figure 2. Sedimentation of 10 m^3/m/year is equivalent to about 27 mm/m/day, considerably more than the net sedimentation rates shown in Figure 1, though it is noted the two simulations are very different.

As part of a larger study of dredge plume management for the Great Barrier Reef SKM/APASA (2013) report on numerical studies of dredge spoil placement at Gladstone, Rosslyn Bay, Hay Point, Abbot Point, Townsville and Cairns. At Gladstone modelled sedimentation rates greater than 100 mg/cm^2/d were located up to 10 km North West from the placement site as shown in Figure 3. The corresponding sediment thickness is shown in Figure 4. These results are based on relocation of 6,000,000 m^3 of material over 133 days. Following the dredging operations some sediment deposits are reworked and total sedimentation and bottom thicknesses after 12 months are shown in Figure 5. Total sedimentation >0.97 mm was predicted at the eastern extent of Curtis Island, around Rundle Island and within 5 km of the placement sites. At Abbot Point, after 12 months total sedimentation exceeded 0.97 mm at 5 – 10 km from the placement site. At Townsville sedimentation levels greater than 0.97 mm were confined to the placement sites.

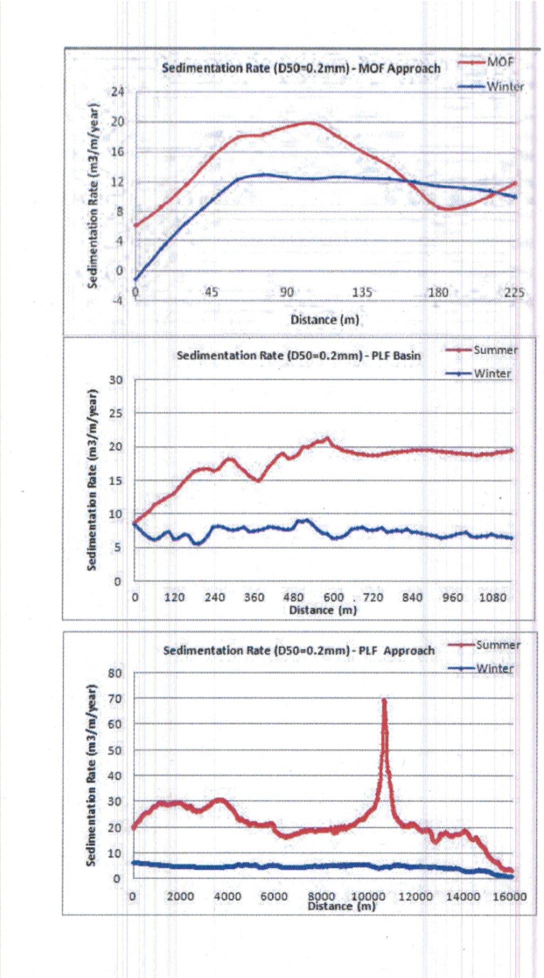

Figure 2: Simulated summer and winter sedimentation rates along MOF approach (top), PLF basin (middle) and PLF approach (bottom) (from Figure 6.37 Chevron (2010)).

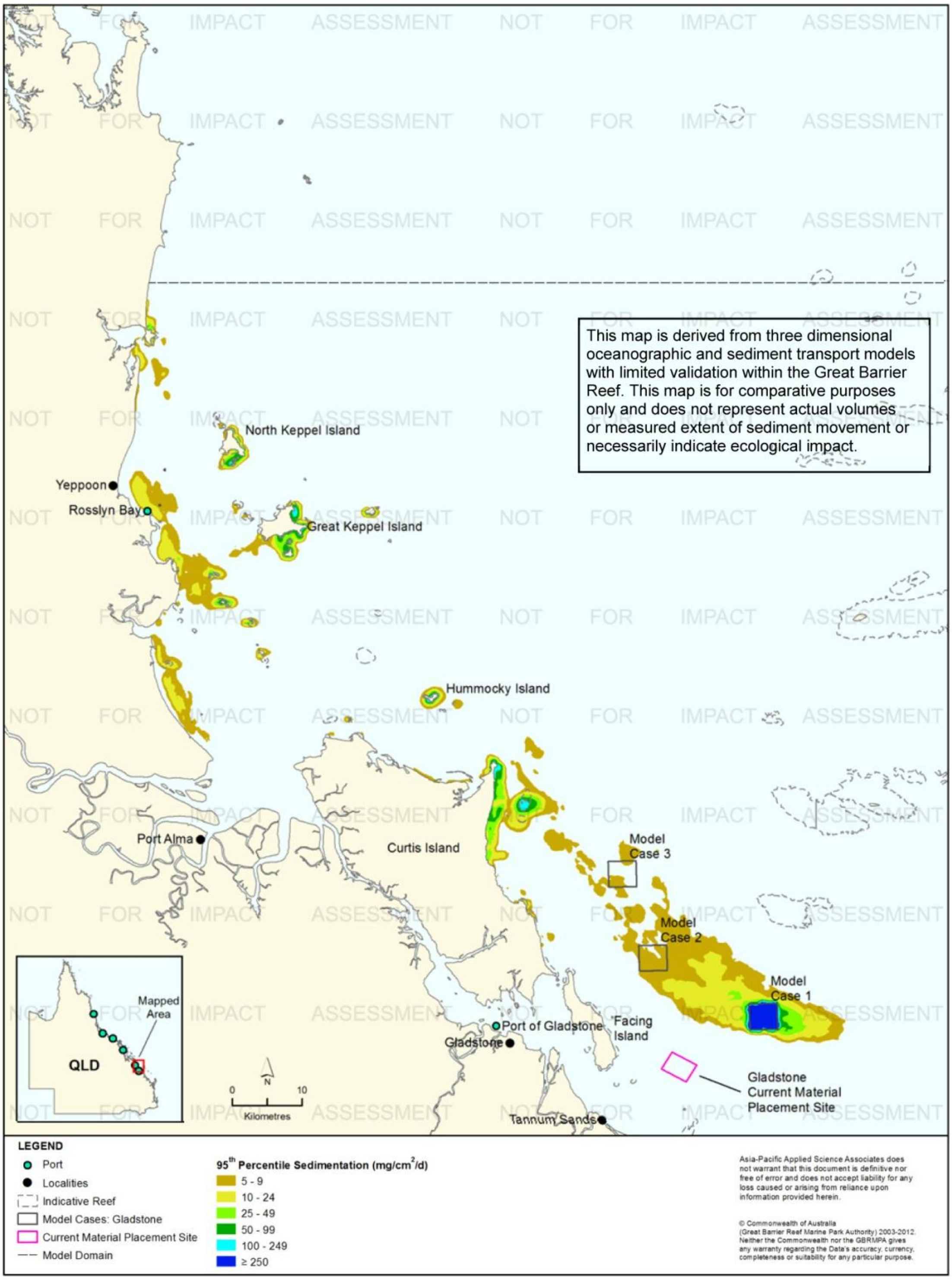

Figure 3: Modelled sedimentation rates off Gladstone associated with dredge spoil placement at the site labelled Model Case 1 (from Figure 40, Appendix E, SKM/APASA (2013)).

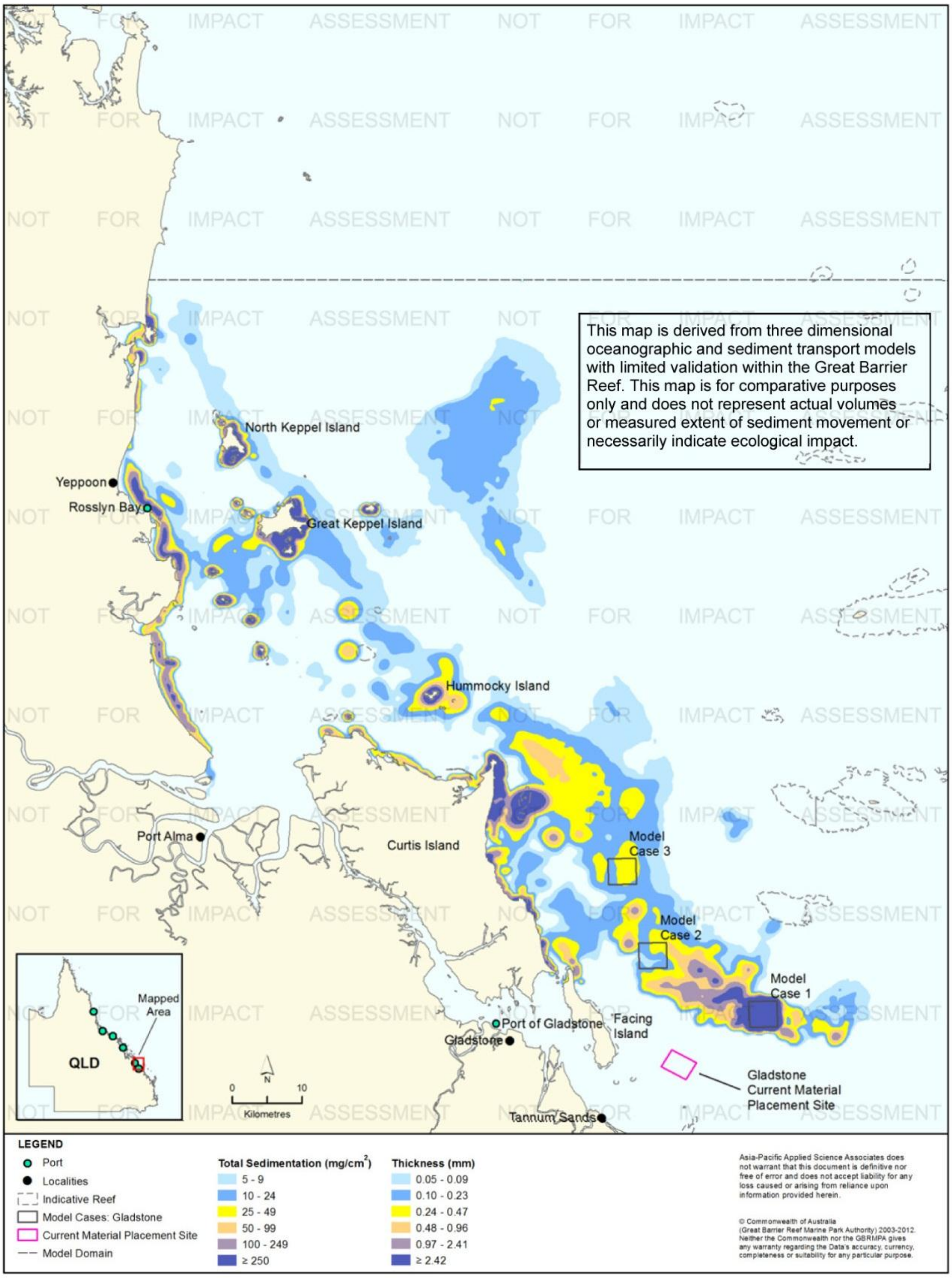

Figure 4: Total sedimentation and bottom thickness associated with dredge spoil placement at site shown as Case 1 (from Figure 45, Appendix E, SKM/APASA (2013)).

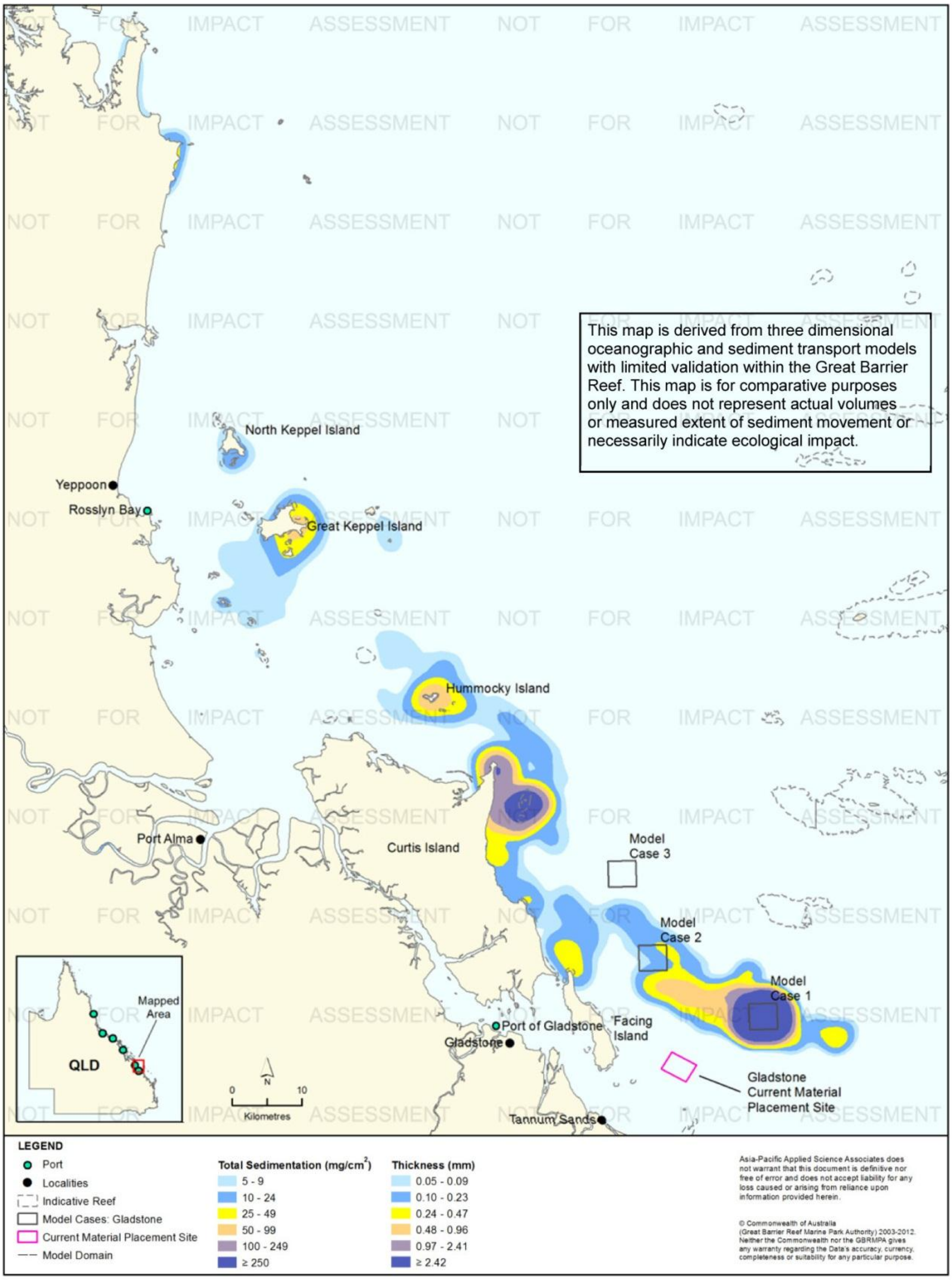

Figure 5: Numerical output for total sedimentation and bottom thickness after 12 months off Gladstone (from Figure 49, Appendix E, SKM/APASA (2013)).

4. Discussion and Conclusions

Quantifying and modelling the transport and fate of sediments released during dredging operations is an essential component of the EIA process in large-scale port and coastal developments. When used with ecological thresholds, sediment transport and fate modelling forms the basis of impact prediction and the spatially based zonation scheme used to assess and manage dredging programs in WA (EPA 2011) and on the GBR (GBRMPA 2012). However, the key physical processes that control the extent, intensity and duration of sediment plumes from both the dredge site and dredge spoil grounds are very complex and difficult to model. The rate of deposition and resuspension by waves and currents will vary across habitats and will lead to further dispersal. The capability of predicting sediment deposition and erosion rates, and bottom light availability is required to predict impact on the benthic ecosystems.

We have reviewed the available scientific literature for state-of-the-art knowledge in modelling key processes in sediment transport for EIAs. We have found a very wide range of approaches and modelling practices for predicting the dynamics and fate of dredge-generated sediment plumes. The processes controlling sediment plumes are highly complex, and likely to be site- and sediment- specific. Consequently, it is a great challenge to achieve fidelity and accuracy in predicting dredge plume dispersal and fate.

The review of key processes in sediment transport modelling reveals that the dynamics of cohesive sediments is complex. Part of the reason is that it depends not only on physicochemical factors but also on biological activity. It is clear that we are presently not able to predict flocculation and resuspension of cohesive sediment from bulk characteristics of sediments, although the dynamics of freshly dredged material would be somewhat simpler than ambient sediments as biological activity has not significantly affected the freshly dredged material. Nevertheless, site-specific *in situ* data are essential for model calibration and validation, as well as obtaining accurate model parameterizations. As such, we recommend that proponents take *in situ* measurements to validate model results after dredging commences, and make the data publically available. This will provide valuable knowledge of model performance and could lead to improved model parameterizations over time.

Dredge plume modelling in EIAs has been reviewed separately for hydrodynamic and wave modelling, and sediment transport modelling. The accuracy of prediction depends on the quality of models and the complexity of the processes involved. Relatively speaking, hydrodynamic and wave modelling have been well established, however, the following points need to be considered:

- Temporal and spatial coverage of the model calibration and validation is often limited due to the lack of suitable data. When such data are available, model-data comparisons should cover both temporal and spatial ranges of available data so that different scales of key processes are resolved.
- Three dimensional models are preferable to two dimensional models so that the vertical and horizontal structures of the plumes can be adequately simulated.
- If the dredge plume is likely to travel to areas that are under the influence of large-scale currents, it is recommended to address such influence by either setting up nested models or appropriate open boundary conditions.
- Most modelling work addresses unavoidable uncertainties, such as problems of near-shore wind forcing, interannual variability, and uncertain dredging schedule. The ways these uncertainties are addressed are varied. It appears that there is no best way and each approach has advantages and disadvantages.

Compared to hydrodynamic and wave modelling, sediment transport modelling has many challenges. The problem partly originates from more complex nature of sediment transport processes and lack of data, which is a considerable obstacle for improving model predictions. Here are some major points to consider:

- Modelling non-cohesive sediments (sand) and cohesive sediments (mud) require different approaches. For example, different size classes of non-cohesive sediments often behave independently, but this is not the case for cohesive sediments because flocculation or resuspension causes interaction between different size classes. Since detailed modelling of this interaction is not practical in field conditions yet, including many particle size classes does not necessarily improve model predictions for cohesive sediments. We note that cohesive sediment transport modelling in scientific literature usually uses only a few particle classes.

- Sediment transport models are often not calibrated or validated against field data due to the lack of data. This is understandable because dredging has not started at the EIA stage, but this produces large uncertainty in assessing the models' predictive skill. It would be a great step forward to require dredge and dredge spoil monitoring and management plans to include model-data comparisons as part of the monitoring efforts. Recently, in Condition 14 of the *Approval for Abbot Point Capital Dredging* released on December 10, 2013, the Federal Environment Minister Greg Hunt required the Abbot Point Ecosystem Research and Monitoring Program to include 'Methodology to validate the hydrodynamic modelling provided in the Public Environment Report and the findings of the technical studies undertaken for the Improved Dredge Management for the Great Barrier Reef Region during each dredging campaign at both the dredge and disposal sites.'
- Parameterizations and parameter values used in sediment transport models are often not reported in EIA documents leaving considerable uncertainty in assessing the model performance and inter-comparison with other models. We recommend that project proponents be required to report model parameter values and parameterizations to enhance the ability of regulators to evaluate EIA model performances.
- Current sediment transport modelling in EIAs does not include ambient sediments. Understanding the dynamics of ambient sediments is important in determining overall impact of dredging, and trigger level based on total SSC may be more practical because 'suspended sediment concentration (SSC) above ambient level' is not easy to quantify from monitoring data, especially under flooding or stormy conditions.
- Although there are potential benefits from including ambient sediments, the issue of ambient sediment modelling needs to be carefully assessed in the future because it poses more data requirements and a number of technical challenges. The dynamics of ambient sediments is likely to be more complex than that of fresh dredged sediments because it could be strongly affected by biological activity, which is usually not modelled in sediment transport models. Therefore the issue of ambient sediment modelling needs to be carefully assessed in the future. On the other hand, monitoring of ambient sediments is beneficial even if ambient sediments are not modelled, as natural variability of ambient sediment concentration and the impact of dredging could be assessed.
- To assess the long-term impacts of dredging requires the modelling of extreme events (such as tropical cyclones and floods) and collection of calibration and validation data for such events. In addition, the interaction between dredged and ambient sediments needs to be considered because the behaviour of mixed sediments would be different from that of the dredged sediments once dredged materials are dispersed and mixed with ambient sediments. For long-term impacts, approaches other than modelling, such as the analysis of sediment records and bed morphology, might be beneficial. Currently most EIAs do not address the long-term impact of dredging but it is important for strategic planning.

Reducing the uncertainty of sediment transport modelling requires site-specific data and background research to understand key sediment transport processes, but the cost could be significant. Therefore, we need to set priorities to tackle this problem practically. The details are out of the scope of this review, but some important points are listed below:

- Uncertainty in sediment transport modelling should be compared to uncertainty in released mass of dredge spills (essential input data for sediment transport modelling), and uncertainty in the impacts of dredge plume to receptors. If the uncertainty in dredge spills is large, reduced uncertainty in sediment transport modelling may not affect the overall uncertainty significantly.

- Model results may be sensitive to some specific processes and model parameters while relatively insensitive to other processes and parameters. For example, if dredge spill occurs in deeper water where deposited sediments are unlikely to get resuspended, the priority should be to focus on the mass released from the dredge spill and the settling velocity, rather than details of resuspension process.
- Improving model accuracy should be considered in the context of current science and financial costs. There are processes that we understand better than others. For example, settling velocity is essential for dredge plume modelling in any circumstances, and measuring settling velocity of particles/flocs in dredge plumes can be done using existing technologies. It is also expected that parameterising settling velocity of dredged particles is easier than that of ambient particles, which include organic matter and plankton. On the other hand, cohesive sediment resuspension under surface wave forcing appears to be poorly understood and not well represented in sediment transport models; hence improving this aspect would require long-term research. Therefore, it appears more cost effective to improve settling velocity parameterization than resuspension parameterization under surface wave forcing. Project 3.3 of this theme is addressing some aspects of sediment resuspension.

5. References

Aarninkhof, S.G.J. and Luijendijk, A. P. 2009. Safe disposal of dredged material in a sensitive environment – Operational planning of dredging activities based on innovative plume predictions. Proceedings Dredging Days 2009, Ahoy Rotterdam, the Netherlands.

Agrawal, Y. C., and H. C. Pottsmith. 2000. Instruments for particle size and settling velocity observations in sediment transport. Mar. Geol., 168: 89-114.

Alldredge, A. L., and C. Gotschalk. 1988. *In situ* settling behaviour of marine snow. Limnol. Oceanogr. 33: 339-351.

Amos, C. L., G. R. Daborn , H. A. Christian, A. Atkinson, and A. Robertson. 1992. *In situ* measurements on fine-grained sediments from the Bay of Fundy. Marine Geology, 108: 175-196.

Amos, C. L., A. Bergamasco, G. Umgiesser, S. Cappucci, D. Cloutier, L. DeNat, M. Flindt, M. Bonardi, and S. Cristante. 2004. The stability of tidal flats in Venice Lagoon – the results of *in situ* measurements using two benthic, annular flumes. J. Mar. Sys. 51: 211-241.

Andersen, T. J., J. Fredsoe, and M. Pejrup. 2007. *In situ* estimation and deposition thresholds by acoustic Doppler velocimeter (ADV). Estuarine, Coast. Shelf Sci., 75: 327-336.

APASA. 2009a. Dampier port authority: Marine environmental modelling. APASA project number J00562008. Pluto LNG development – sediment dispersion study: methods for revised dredge modeling with the inclusion of sediment resuspension. APASA project number J0024.

APASA. 2009b. Quantum project: modelling of the dredge and disposal programme.

APASA. 2010. Anketell Point: Marine environmental modelling. APASA project number J0061.

Ariathurai, R. and K. Arulanandan. 1978. Erosion rates of cohesive soils. J. Hydraul. Div. Am. Soc. Civil Eng., 104: 279-283.

Black, K. S., and D. M. Paterson. 1997. Measurement of the erosion potential of cohesive marine sediments: a review of current *in situ* technology. J. Marine Env. Eng., 4 : 43-83.

Black, K. S., T. J. Tolhurst, D. M. Paterson, and S. E. Hagerthey. 2002. Working with natural cohesive sediments. J. Hydraul. Eng., 128: 2-8.

Boudreau, B. P. 1998. Mean mixed depth of sediments: The wherefore and the why. Limnol. Oceanogr., 43: 524-526.

Burd, A. B., and G. A. Jachson. 2009. Particle aggregation. Annu. Rev. Marine Sci. 1: 65-90.

Cardno 2010. Port Headland South-West Creek dredge plume modelling. Report LJ15011/Rep1017p Version 4.

Chevron 2008. CHEVRON Gorgon gas development revised and expanded proposal. EPBC Referral 2008/4178.

Chevron 2010. Appendix Q1, in Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project: Technical Appendix Q1), 923 pp.

Chevron 2012. Wheatstone Project. Dredging and dredge spoil placement, environmental monitoring and management plan, Chevron doc., ws0-000-hes-rpt-cvx-000-00086-000, rev. 2, 223 pp.

Christopher W. Eisma, D., 1993. Suspended Matter in the Aquatic Environment. Springer, Berlin, 315pp.

Dickhudt, P. J., C. T. Friedrichs, and L. P. Sanford. 2011. Mud matrix fraction and bed erodibility in the York River Estuary, USA, and other muddy enrivonement. Cont. Shelf Res., 31: S3-S13.

Department of Environment (formerly Department of Sustainability, Environment, Water, Population and Communities or SEWPAC), Australia. 2009. National Assessment Guidelines for Dredging (NAGD).

Department of State Development, Government of Western Australia. 2010. Appendix C-13, Browse Liquefied Natural Gas Precinct dredging and spoil disposal assessment.

DHI 2010. Wheatstone project dredge spoil modelling. Report My5527-1.

Droppo, I. G. 2004. Structural controls on floc strength and transport. Can. J. Civ. Eng. 31: 569-578.

Dyer, I. N. 1984. Size spectra and aggregation of suspended particles in the deep ocean. Deep Sea Res. 31: 329-352.

Dyer, I. N. 1989. Sediment processes in estuaries: future research requirement. J. Geophys. Res., 94: 14327-14339.

Einstein, H. A., and R. B. Krone. 1962. Experiments to determine modes of cohesive sediment transport in salt water. J. Geophys. Res. 67: 1451-1461.

Eisma, D. 1986. Flocculation and de-flocculation of suspended matter in estuaries. Netherland J. Sea Res., 20: 183-199.

Eisma, D., A. J. Bale, M. P. Dearnaley, M. J. Fennessy, W. van Leussen, M.-A. Maldiney, A. Pfeiffer, and J. T. Wells. 1996. Intercomparison of *in situ* suspended matter (floc) size measurements. J. Sea Res. 36: 3-14.

EPA 2011. Environmental Assessment Guidleline for Marine Dredging Proposals – EAG No. 7. Environmental Protection Authority, Perth, Western Australia.

Erftemeijer P. L. A., Roy R. Robin Lewis III, Environmental impacts of dredging on seagrasses: A review, Marine Pollution Bulletin, Volume 52, Issue 12, December 2006, Pages 1553-1572.

Erftemeijer P. L. A., Bernhard Riegl, Bert W. Hoeksema, Peter A. Todd, Environmental impacts of dredging and other sediment disturbances on corals: A review, Marine Pollution Bulletin, Volume 64, Issue 9, September 2012, Pages 1737-1765.

Fennessy, M.J., Dyer, K.R., Huntley, D.A., 1994. INSSEV: an instrument to measure the size and settling velocity of flocs *in situ*. Mar. Geol. 117, 107±117.

Fugate D. C., and C. T. Friedlichs. 2002. Determining concentration and fall velocity of estuarine particle populations using ADV, OBS, and LISST. Cont. Shelf Res. 22: 1867-1886.

Fugate D. C., and C. T. Friedlichs. 2003. Controls on suspended aggregate size in partially mixed estuaries. Estuarine, Coast., and Shelf Sci., 58: 389-404.

GBRMPA 2012. The use of hydrodynamic numerical modelling for dredging projects in the Great Barrier Reef Marine Park, Great Barrier Reef Marine Park Authority, Townsville. GBRMPA External Guideline. In: GBRMPA (ed), Townsville (Queensland, Australia)

GEMS 2004. Dredge disposal impact modelling Port of Dampier. Report No. 19/04.

GEMS 2005. Gorgon development dredging program simulation studies. Report 21/05.

GEMS 2007. Cape Lambert port development oceanographic studies and dredging program simulations. Report 462/06.

GEMS 2008a. Cape Lambert Port B oceanographic studies and dredging program simulation.

GEMS 2008b. RGP5 port facilities dredging program simulation studies at Harriet Point.

GHD 2012. Abbot Point Cumulative Impact Assessment – 3D Dredge Plume Modelling.

Gibbs, R. J. 1981. Floc breakage by pumps. J. Sedimentary Res. 51: 670-672.

Gibbs, R. J. 1982a. Effect of pipetting on mineral flocs. Environ. Sci. Technol. 16:119-121.

Gibbs, R. J. 1982b. Floc stability during Coulter counter size analysis. J. Sedimentary Res. 52: 657-660.

Gibbs, R.J., 1985. Estuarine flocs: their size, settling velocity and density. J. Geophys. Res. 90, 3249±3251.

Gibbs, R. J., and L. N. Konwar. 1983. Sampling of mineral flocs using Niskin bottles. Environ. Sci. Technol. 17: 374-375.

Grabowski, R. C., I. G. Droppo, and G. Wharton. 2011. Erodibility of cohesive sediment: the importance of sediment properties. Earth-Science Rev., 105: 101-120.

Grant, W. D., and O. S. Madsen. 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res. 84: 1797-1808.

Great Barrier Reef Marine Park Authority, 2012. Guidelines on the Use of Hydrodynamic Numerical Modelling for Dredging Projects in the Great Barrier Reef Marine Park.

Grant. J., U. V. Bathmann, and E. L. Mills. 1986. The interaction between benthic diatom films and sediment transport. Estuarine, Coast. and Shelf Res., 23: 225-238.

Gularte, R. C., W. E. Kelly, and V. A. Nacci. 1980. Erosion of cohesive sediments as a rate process. Ocean Engng., 7:539-551.

Ha, H.K and J.P.-Y. Maa. 2009. Evaluation of two conflicting paradigms for cohesive sediment deposition. Mar. Geol., 265: 120-129.

HR Wallingford. 2010. Ichthys gas field development project dredging and spoil disposal modelling. Report Ex 6219.

Jiang Q., and B. E. Logan. 1991. Fractal dimensions of aggregates determined from steady-state size distributions. Environ. Sci. Technol. 25: 2031-2038.

Kajihara, M. 1971. Settling velocity and porosity of large suspended particle. J. Oceanogr. Soc. Jpn., 27: 158-162.

Kawanisi, K. and S. Yokosi. 1997. Characteristics of suspended sediment and turbulence in a tidal boundary layer. Cont. Shelf Res. 17: 859-875,

Kranck, K. 1975. Sediment deposition from flocculated suspensions. Sedimentology 22, 111-123.

Kranck, K. 1981. Particulate matter grain-size characteristics and occulation in a partially mixed estuary. Sedimentology 28, 107-114.

Kranenburg, C. 1994. The fractal structure of cohesive sediment aggregates. Estuarine, Coast. Shelf Res. 39: 451-460.

Kranenburg, C. 1999. Effects of floc strength on viscosity and deposition of cohesive sediment suspensions. Cont. Shelf Res. 19: 1665-1680.

Kranenburg, C., and J. C. Winterwerp. 1997. Erosion of fluid mud layers. I: Entrainment model. J. Hydraulic Eng., 123: 504-511.

Krone, R. B. 1963. Study of rheological properties of estuarial sediments. Hydr. Engr. Lab. And Sanitary Eng. Res. Lab., U. of Calif., Berkeley.

Krone, R. B. 1993. Sedimentation revisited. Coastal and Estuarine studies. 42: 108-125.

Krone, R. B. 1999. Effects of bed structure on erosion of cohesive sediments. J. Hydraul. Eng., 125: 1297-1301.

Kusuda, T., T. Umita, K. Koga, T. Futawatari, and Y. Awaya. 1984. Erosional process of cohesive sediments. Wat. Sci. Tech., 17: 891-901.

Kusuda, T., T. Umita, K. Koga, H. Yorozu, and Y. Awaya. 1982. Depositional process of fine sediments. Wat. Sci. Tech., 14: 175-1854.

Lambrechts, J., C. Humphrey, L. McKinna, O. Gourge, K. E. Fabricius, A. J. Mehta, S. Lewis, and E. Wolanski. 2010. Importance of wave-induced bed liquefaction in the fine sediment budget of Cleveland Bay, Great Barrier Reef. Estuarine, Coast. and Shelf Sci. 89: 154-162.

Larbombe, P., and R. M. Carter. 2004. Cyclone pumping, sediment partitioning and the development of the Great Barrier Reef shelf system: a review. Quat. Sci. Rev., 23: 107-135.

Lavelle, J. W., H. O. Mofjeld. 1987. Do critical stresses for incipent motion and erosion really exist? J. Hydraulic Eng., 113: 370-393.

Lavelle, J. W., H. O. Mofjeld, and E. T. Baker. 1984. An *in situ* erosion rate for a fine-grained marine sediment. J. Geophys. Res., 89: 6543-6552.

Lau, Y. L., and B. G. Krishnappan. 1992. Does reentrainment occur during cohesive sediment settling? J. Hydraul. Eng., 120: 236-244.

Law, B. A., P. S. Hill, T. G. Milligan, K. J. Curran, P. L. Wiberg, and R. A. Wheatcroft. 2008. Size sorting of fine-grained sediments during erosion: results from the western Gulf of Lions. Cont. Shelf Res. 28: 1935-1946.Le Hir, P., P. Cann, B. Waeles, H. Jestin, and P. Bassoullet. 2008. Erodibility of natural sediments: experiments on sand/mud mixtures from laboratory and field erosion tests. P.137-153, In T. Kusuda, H. Yamanishi, J. Spearman, and J. Z. Gailani (eds.), Sediment and ecohydraulics: INTERCOH 2005, Elsevier.

Le Hir, P., F. Cayocca, and Benoit Waeles. 2011. Dynamics of sand and mud mixtures: A mutiprocess-based modelling strategy. Cont. Shelf Res., 31: S135-S149.

Lick, W. 1982. Entrainment, depositin and transport of fine-grained sediments in lakes. Hydrobiologia, 91: 31-40.

Lick. W., H. Huang, and R. Jepsen. 1993. Flocculation of fine-grained sediments due to differential settling. J. Geophys. Res. 98: 10279-10288.

Maa, J. P.-Y., and A. J. Mehta. 1987. Mud erosion by waves: a laboratory study. Cont. Shelf Res. 7: 1269-1284.

Maerz, J., R. Verney, K. Wirtz, and U. Feudel. 2011. Modeling flocculation processes: Intercomparison of a size class-based model and a distribution-based model. Cont. Shelf Res. 31: S84-S93.

Manning, A.J. and Dyer, K.R. (2007). Mass settling flux of fine sediments in Northern European estuaries: measurements and predictions. Marine Geology, 245, 107-122, doi:10.1016/j.margeo.2007.07.005.

Manning, A. J., J. V. Baugh, J. R. Spearman, and R. J. S. Whitehouse. 2010. Flocculation settling characteristics of mud:sand mixture. Ocean Dyn. 60: 237-253.

Mantovanelli, A., and P, V. Ridd. 2006. Devices to measure settling velocities of cohesive sediment aggregates: A review of the *in situ* technology. J. Sea Res. 56: 199-226.

Matsuo, T. and H. Unno. 1981. Forces acting on floc and strength of floc. J. Env. Eng. Div., ASCE. 107: 527-545.

Mehta, A. J. 1988. Laboratory studies on cohesive sediment deposition and erosion. pp. 427-445, In J. Dronkers and W. van Leussen (eds.), Physical processes in Estuaries, Springer, Berlin.

Mehta, A. J. 1996. Interaction between fluid mud and water waves. pp. 153-187, In V. P. Singh and W. H. Hager (eds.), Environmental Hydraulics, Kulwer Academic.

Mehta, A. J., and W. H. McAnally. 2008. Fine-grained sediment transport. pp.253-306, In ASCE Manual No. 110, Sedimentation Engineering.

Mehta, A. J., and E. Partheniades. 1975. An investigation of the depositional properties of flocculated fine sediments. J. Hydraul. Res. 13: 361-381.

McAnally, W. H., and A. J. Mehta. 2000. Aggregation rate of fine sediment. J. Hydraul. Res. 126: 883-892.

McAnally, W. H., and A. J. Mehta. 2002. Significance of aggregation of fine sediment particles in their deposition. Estuarine, Coast. and Shelf Sci., 54: 643-653.

McCave, I. N., and S. A. Swift. 1976. A physical model for the rate of deposition of fine-grained sediments in the deep sea. Geol. Soc. Am. Bull., 87: 541-546.

McCave, I. N. 1984. Size spectra and aggregation of suspended particles in the deep ocean. Deep Sea Res. 31: 329-352.

Mikkelsen, O., Pejrup, M., 1998. Comparison of flocculated and dispersed suspended sediment in the Dollard estuary. Sedimentary Processes in the Intertidal Zone, Black, K.S., Paterson, D.M., Cramp, A. (Eds.). Geol. Soc. Lond. Spec. Publ. 139, 199-209.

Mikkelsen, O.A., Pejrup, M., 2000. *In situ* particle size spectra and density of particle aggregates in a dredging plume. Mar. Geol. 170, 443–459.

Mikkelsen, O.A., Pejrup, M., 2001. The use of a LISST-100 laser particle sizer for *in situ* estimates of floc size, density and settling velocity. Geo-Marine Lett., 20: 187-195.

Mikkelsen, O.A., Paul S. Hill, Timothy G. Milligan, Robert J. Chant, 2005. *In situ* particle size distributions and volume concentrations from a LISST-100 laser particle sizer and a digital floc camera. Continental Shelf Research 25 (2005) 1959–1978.

Milligan, T.G., Hill, P.S., 1998. A laboratory assessment of the relative importance of turbulence, particle composition, and concentration in limiting maximal floc size and settling behavior. J. Sea Res. 39, 227–241.

Mimura, N. 1993. Rates of erosion and deposition of cohesive sediments under wave action. Coast. Estuarine Studies, 42: 247-264.

Mitchener, H. and H. Torfs. 1996. Erosion of mud/sand mixture. Coastal Eng., 29: 1-25.

Odd, N. V. M., and A. J. Cooper. 1989. A two-dimensional model of the movement of fluid mud in a high energy turbid estuary. J. Coastal Res., Special issue 5, 185-193.

Oseen, C., 1927. Hydrodynamik. Akademische Verlagsgesellschaft, Leipzig (chapter 10).

Otsubo, K. and K. Muraoka.1988, Critical shear stress of cohesive bottom sediments. J. Hydraulic Eng., 114: 1241-1256.

Panagiotopoulos, I., G. Voulgaris, M. B. Collins. 1997. The influence of clay on the threshold of movement of fine sandy beds. Coastal Eng. 32: 19-43.

Pandya, J. D., and L. A. Spielman. 1982. Floc breakage in agitated suspensions: theory and data processing strategy. J.Colloid and Interface Sci. 90: 517-531.

Parchure, T. M. and A. J. Mehta. 1985. Erosion of soft cohesive sediment deposits, J. Hydraulic Eng., 111: 1308-1326.

Parker, D. S., W. J. Kaufman, and D. Jenkins. 1972. Floc breakup in turbulent flocculation processes. J. Sanitary Eng. Div. ASCE., 98: 79-99.

Partheniades, E. 1965. Erosion and deposition of cohesive soils. J. Hydraul. Eng., 91: 103-139

Partheniades, E., R. H. Cross III., and A. Ayora. 1968. Further results on the deposition of cohesive sediments. Coastal Engineering Proceedings, 1: 723-742.

Parchure, T. M., and A. J. Mehta. 1985. Erosion of soft cohesive deposits. J. Hydraul. Eng., 111: 1308-1326.

Passow, U. 2002. Transparent exopolymer particles (TEP) in aquatic environments. Prog. Oceanogr. 55: 287-333.

Pejrup, M., 1988. Flocculated suspended sediment in a micro-tidal environment. Sediment. Geol. 57, 249±256.

Raudkivi, A.J., 1998. Loose Boundary Hydraulics, fourth ed. Taylor & Francis, London.

RMC/Sprott, 2014. Dredging and Australian Ports: subtropical and tropical ports. Prepared for Ports Australia.

Roberts J., R. Jepsen, D. Gotthard, and W. Lick. 1998. Effects of particle size and bulk density on erosion of quartz particles. J. Hydraulic Eng., 124: 1261-1267.

Roberts, J. D., R. A. Jepsen, and S. C. James. 2003. Measurements of sediment erosion and transport with the adjustable shear stress erosion and transport flume. J. Hylraul. Eng. 129: 862-871.

Rodriguez, H. N., and A. J. Megta. 2000. Longshore transport of fine-grained sediment. Cont. Shelf Res., 20: 1419-1432.

Sanford, L. P. 1994. Wave-forced resuspension of upper Chesapeake Bay muds. Estuaries, 17: 148-165.

Sanford, L. P. 2006. Uncertainties in sediment erodibility estimates due to a lack of standards for experimental protocols and data interpretation. Integrated environmental assessment and management, 2: 29-34.

Sanford, L. P. 2008. Modeling a dynamically varying mixed sediment bed with erosion, deposition, bioturbation, consolidation, and armouring. Computers and Geosciences, 24: 1263-1283.

Sanford L. P., and J. P. Halka. 1993. Assessing the paradigm of mutually exclusive erosion and deposition of mud, with examples from upper Chesapeake Bay, Marine Geol., 114: 37-57.

Sanford, L. P., and J. P. Y. Maa, 2001. A unified erosion formulation for fine sediments, Marine Geol., 179: 9-23,

Saffman, P. G., and J. S. Turner. 1956. On the collision of drops in turbulent clouds. J. Fluid Mech. 1: 16-30.

Schiller,L.,Naumann,A.,1933.Uber die grundlegenden Berechnungen bei der Schwerkraftaufbereitung, Z.VDI,vol.77.

Shimizu, K., T. Ishikawa, and M. Irie. 2005. A field study of near-bottom turbulence and resuspension of fine sediment in Tone River Estuary, p. 2137-2143. In Lee & Lam [eds.], Environmental Hydraulics and Sutainable Water Management. Taylor & Francis Group.

SKM 2010. Port Hedland Port Authority South West Creek Dredging – Geotechnical Interpretive Report.

SKM/APASA. 2013. Improved Dredge Material Management for the Great Barrier Reef Region.

Smith, S. J., and C. T. Friedrichs, 2011. Size and settling velocities of cohesive flocs and suspended sediment aggregates in a trailing suction hopper dredge plume. Cont. Shelf Res. 31, S50-S63.

Son, M., and T.-J. Hsu. 2011. The effects of flocculation and bed erodibility on modeling cohesive sediment resuspension. J. Geophys. Res., 116, C03021, doi:10.1029/2010JC006352.

Soulsby, R. 1997. Dynamics of marine sands: a manual for practical applications. Thomas Telford Publ., London.

Soulsby, R. L. and S. Clark. 2005. Bed shear-stresses under combined waves and currents on smooth and rough beds. HR Wallingford Report TR 137.

Soulsby, R. L., A. J. Manning, J. Spearman, R. J. S. Whitehouse. 2013. Settling velocity and mass settling flux of flocculated estuarine sediment. Mar. Geol. 339: 1:12.

Spearman, J., de Heer, A.F.M., Aarninkhof, S.G.J. and van Koningsveld, M., 2011. Validation of the TASS system for predicting the environmental effects of trailer suction hopper dredgers. Terra et Aqua, No. 125.

Spencer, P. T., and S. E. Pratsinis. 1996. Coagulation and fragmentation: universal steady-state particle-size distribution. AIChE Journal. 42: 1612-1620.

Stolzenbach, K. D., and M. Elimelech. 1994. The effect of particle density on collisions between sinking particles: implications for particle aggregation in the ocean. Deep Sea Res. 41: 469-483.

Suzuki, N. and K. Kato. 1953. Studies of suspended materials marine snow in the sea. Part I. Sources of marine snow. Bull. of Faculty of Fisheries, Hokkaido Univ. 4: 132-137.

Ten Brinke, W.B.M., 1994. *In situ* aggregate size and settling velocity in the Oosterschelde tidal basin (the Netherlands). Neth. J. Sea Res. 32, 23±35.

Thomsen, L., and G. Gust. 2000. Sediment erosion thresholds and characteristics of resuspended aggregates on the western European continental margin. Deep-Sea Res. 47: 1881-1897.

Tolhurst, T. J., K. S. Black , D. M. Paterson, H. J. Mitchener, G. R. Termaat, S. A. Shayler. 2000a. A comparison and measurement standardisation of four *in situ* devices for deterimining the erosion shear stress of intertidal sediments, Cont. Shelf Res., 20: 1397-1418.

Tolhurst, T. J., R. Rithmueller, and D. M. Paterson. 2000b. *In situ* versus laboratory analysis of sediment stability from intertidal mudflats. Cont. Shelf Res., 20: 1317-1334.

Tambo, N. and Y. Watanabe. 1979. Physical aspect of flocculation process – I: fundamental treatise. Water Res. 13: 429-439.

Van Kessel, T., H. Winterwerp, B. Van Prooijen, M. Van Ledden, and W. Borst. 2011. Modelling the seasonal dynamics of SPM with a simple algorithm for the buffering of fines in a sandy seabed. Cont. Shelf Res. 31: S124-134.

Van Leussen, W. 1997. The Kolmogorov microscale as a limiting value for the floc sizes of suspended fine-grained sediments in estuaries. Pp.45-62, In N. Burt, R. Parker, and J. Watts (eds.), Cohesive Sediments, John Wiley and Sons.

Van Prooijen, B. C., and J. C. Winterwerp. 2010. A stochastic formulaion for erosion of cohesive sediments. J. Geophys. Res. 115: C01005, doi:10.1029/2008JC005189.

Verney, R., R. Lafite, J. C. Brun-Cottan, P. Le Hir. 2011. Behaviour of a floc population during a tidal cycle: laboratory experiments and numerical modelling. Cont. Shelf Res. 31: S64-S83.

Verbeek, H., C. Kuijper, J. M. Cornelisse, and J. C. Winterwerp. 1993. Deposition of graded natural muds in the Netherland. Coast. Estuarine Studies. 42: 185-204.

Wallingford, 2003. Protocol for the Field Measurement of Sediment Release from Dredgers. A practical guide to measuring sediment release from dredging plant for calibration and verification of numerical models. Produced for VBKO TASS Project by HR Wallingford Ltd & Dredging Research Ltd.Wiberg, P. L., D. E. Drake, and D. A. Cacchione. 1994. Sediment resuspension and bed armoring during high bottom stress events on the northern California inner continental shelf: measurements and predictions. Cont. Shelf Res., 14: 1191-1219.

Widdows, J., M. D. Brinsley, P. N. Salkeld, C. H. Lucas. 2000. Influence of biota on sptial and temporal variation in sediment erodibility and material flux on a tidal flat (Westerschelde, the Netherlands). Mar. Ecol. Prog. Ser. 194: 23-37.

Widdows, J., P. L. Friend, A. J. Bale, M. D. Brinsley, N. D. Pope, and C. E. L. Thompson. 2007. Inter-comparison between five devices for determining erodability of intertidal sediments. Cont. Shelf Res., 27: 1174-1189.

Williamson, H. J., and M. C. Ockenden. 1993. Laboratory and field investigations of mud and sand mixtures. p. 622-629 in S.S. Y. Wand [ed.], Advances in Hydro-Science and Engineering, vol. 1.

Winterwerp, J.C., 1998. A simple model for turbulence induced flocculation of cohesive sediment. IAHR J. Hydraul. Res. 36 (3), 309–326.

Winterwerp, J.C., 2002. On the flocculation and settling velocity of estuarine mud. Cont. Shelf Res. 22, 1339–1360.

Winterwerp, J.C., van Kesteren, W.G.M., 2004. Introduction to the Physics of Cohesive Sediment in the Marine Environment, Developments in Sedimentology series, 56. Elsevier, Amsterdam.

Winterwerp, J. C., A. J. Manning, C. Martens, T. de Mulder, and J. Vanlede. 2006. A heuristic formula for turbulent-induced flocculation of cohesive sediment. Estuarine, Coast. Shelf Res. 68: 195:207.

Wolanski, E., R. Gibbs, P. Ridd, and A. Mehta. 1992. Settling of ocean-dumped dredged material, Townsville, Australia. Estuarine, Coast. and Shelf Sci. 35: 473-489.

Wolanski, E., and S. Spagnol. 2003. Dynamics of the turbidity maximum in King Sound, tropical Western Australia. Estuarine, Coast. Shelf Res. 56: 877-890.

Worley Parsons, 2009. The Heng Shan Project – South West Creek Berths 1 and 2 (SWC1 and SWC2) Geotechnical Investigation. Prepared for FORTESCUE METALS GROUP LIMITED. Ref. 00093-P-12044-RP-GE-0003.

Yamanishi, H., O. Higashi, T. Kusuda, and R. Watanabe. 1998. Scouring of sloping cohesive sediment bed under waves. J. Japan Society of Civil Engineers, 607/II-45: 55-67 (in Japanese with English abstract).