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Estimating dredge source terms – a review of contemporary practice in the context of Environmental Impact Assessment in Western Australia

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WAMSI Dredging Science Node

Report

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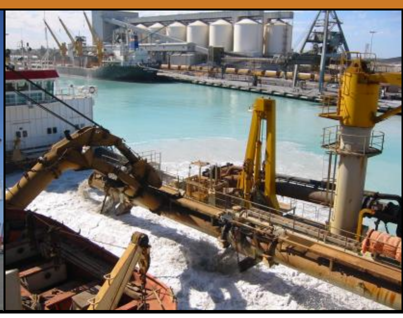
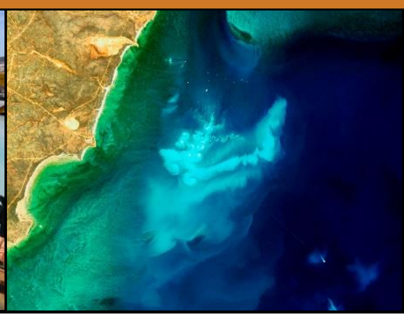
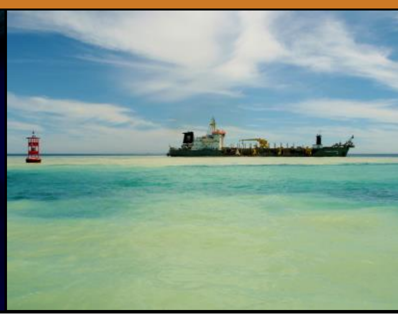

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Department of **Water and Environmental Regulation**

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.

Ownership of Intellectual property rights

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

Image 2: Dredged material from the Cutter Suction Dredge *Leonardo da Vinci* entering the hopper of the Trailing Suction Hopper Dredge *Nina* at the Port of Geraldton. Overflow plume containing high concentrations of 'fines' is visible on the port side of the *Nina*. (Source: OEPA)

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: The Trailing Suction Hopper Dredge *Gateway* at disposal grounds off the Port of Fremantle. Plumes containing 'fines' are clearly visible in the foreground and adjacent to the vessel. (Source: OEPA)

Contents

1 Introduction

Since 2000, there has been an unprecedented level of dredging in Western Australia with 27 dredging projects assessed and approved with a combined total volume of over 250 million cubic metres (Mm^3)(EPA 2013). Furthermore, the size of some recent projects is very large by world standards. The Wheatstone LNG project near Onslow is by far the largest single dredging project in Western Australia to date with a total approved[1] volume of 50 Mm^3 to be dredged and disposed of at sea (the Pluto LNG project was the previous largest at 14 Mm^3).

These projects have been mainly located in the Pilbara region in the northwest of the State, and involve dredging a range of substrate types ranging from very soft and fine deltaic sediments through to very hard crystalline limestone and metamorphic rock. The marine biological communities in these areas include mangrove forests, coral reefs, seagrass meadows and filter feeder communities. The likely spatial extent, intensity and duration of dredging-related suspended sediment plumes are notoriously difficult to predict, and forecasting the ecological effect of these plumes is even more problematic (Masini et al. 2011). These uncertainties, coupled with the application of conservative biological effect and mortality thresholds, were generating predictions of impact over a wide range of scales with the worse-case scenarios significantly over-estimating the spatial extent and severity of impacts (Hanley 2011). The resulting uncertainty about what the actual impact was likely to be often resulted in approvals that included the requirement for complex monitoring programs, over large areas, to provide confidence that impacts were being managed and contained within approved limits (LeProvost 2015).

The first step in predicting impacts related to dredge-plumes involves estimating the rates and characteristics of sediments generated at, and immediately around, the dredge source and, more specifically, estimating the dredge plume source terms. In this review, 'source terms' include the horizontal mass flux, settling characteristics (i.e. particle size distributions (PSD) and assigned settling velocities) and vertical distribution of sediments (re-suspended by dredging activity) as they feed into the far-field plume.

The aim of this project was to review the contemporary practice of estimating the primary source term contributions (in the context of Environmental Impact Assessment) for the two types of hydraulic dredgers that are most commonly employed in major dredging projects in Australia, i.e. trailing suction hopper dredgers (TSHD) and cutter suction dredgers (CSD). The estimation of source terms associated with ocean disposal of dredged material (at 'dredge material placement sites') was out of scope.

1.1 Dredge Plume Development

Dredge plumes occur when fractions of the sediments released into the water column by dredging activities are transported downstream by ambient currents.

The particle size characteristics of the sediments released into the water column will depend on the *in situ* material in the area to be dredged and the size and characteristics of particles generated when that material is subject to dredging processes. All other factors being equal, a higher fines fraction in the sediments released will result in a dredge plume of greater extent.

Sediment plumes can be classified as dynamic, passive or transitional.

Dynamic dredge plumes originate from discharges of high concentration sediment-water mixtures that are significantly denser than the surrounding sea water. For example, trailing suction hopper dredger (TSHD) hopper overflow discharges generally give rise to dynamic plumes. The predominantly fine sediment particles and water in these dynamic plumes tend to move together as a dense, bulk fluid, and with a vertical velocity component that is typically much greater than the settling velocity of the individual particles. The descending dynamic plume entrains surrounding sea water, resulting in a progressive reduction of its excess density and rate of descent as the distance from the discharge point increases. At some distance, the plume is mixed into the surrounding sea water by ambient currents, waves and/or dredge-induced turbulence, marking its transition to a passive plume.

[1] 31.4 Mm^3 actual volume dredged

This transition may occur in the water column and/or after the dynamic plume has impacted the seabed and formed a spreading bed plume. In the latter case a significant amount of sediment from the plume may be deposited locally on the sea bed that would otherwise have been transported further away from the dredging area.

Passive plumes consist of low suspended sediment concentration mixtures that have minimal density or momentum differences relative to the surrounding sea water. Bed erosion induced by propeller jets and material resuspension about cutterheads are two examples of dredge-induced mixing effects that resuspend bed or newly-dredged material sediments and give rise almost immediately to passive plumes. Sediment transport in passive plumes is governed by the ambient hydrodynamics, the vertical settling velocity of the suspended particles and by particle deposition or resuspension at the sea bed. The dredge plume becomes fully passive in its behaviour only at a distance that is beyond any localised turbulent flow generated by the dredging equipment and beyond the extent of any dynamic plume.

HR Wallingford and Dredging Research Ltd (2003) defined the near-field as 'the stage of plume development in which the coarser fraction of suspended sediment settles to the bed while being advected by the ambient currents; the initial stages may be dynamic but the plume becomes more passive with time'.

The horizontal mass flux, PSD and settling characteristics of suspended sediment in near-field plumes will change significantly with distance from the source (or time since release) as some of the released material deposits on the bed.

Once differential particle settling has occurred the suspended sediment plume reaches a stage at which 'only the fines fraction remains in suspension and is capable of being advected over long distances by the ambient current as long as the velocity of that current remains above a critical threshold' (HR Wallingford and Dredging Research Ltd 2003). This stage of plume development is referred to as the far-field. The far-field plume is always considered to behave as a passive plume.

1.2 Far-field (Passive) Plume Prediction

Passive suspended sediment transport models are used to simulate dredge plumes in the far-field. The sediment transport processes represented in these models include advection and turbulent diffusion due to the ambient hydrodynamics, vertical settling of the sediment particles as well as sediment deposition/resuspension at the bed. The model calculations may be performed for several sediment size classes (each with an assigned settling velocity value) to better represent the transport and fate of plume sediments. Passive dredge plume models are not capable of simulating dynamic plume behaviour in the near-field because they do not include critical dynamic plume processes.

Dynamic plume processes and differential settling of sediment particles (including some relatively fine particles) occurring in the near-field need to be taken into consideration when estimating or predicting source terms for far-field dredge plume simulations.

Predictions of environmental impact beyond the immediate dredging area rely on an understanding of the extent and intensity of dredge plumes that are transported away from the dredge work area by ambient currents. Passive suspended sediment transport models are used to simulate the far-field development of these dredge plumes and suspended sediment source term estimates are needed for input to these models.

The purpose of the work reported here is to review the contemporary practice of estimating source terms used for dredge plume predictions as applied in environmental impact assessment of dredging proposals in Western Australia.

2 Source term attributes

The primary attributes of the suspended sediment source terms that are input to passive dredge plume models are:

- the horizontal mass flux (in kg/s), also referred to as the 'source rate';
- the 'source particle size distribution' (PSD), i.e. the distribution of particle size classes (defined in the model) each with an assigned settling velocity. Note that this information can alternatively be expressed as a 'source settling velocity distribution', i.e. the distribution of the source mass flux across the sediment size classes; and
- the vertical distribution of the source mass flux in the water column. This is required for three-dimensional dredge plume models and is referred to as the 'source vertical distribution' (SVD).

These source term attributes strongly influence the spatial extent and intensity of the dredge plume (Swanson et al. 2004).

In most cases the horizontal mass flux and settling velocity distribution of suspended sediment feeding into the far-field plume differ significantly from those of the dredged material as it is introduced to the water column by the dredging activity. Very coarse material (e.g. gravel and larger) rapidly deposits within the immediate dredging zone, despite its high level of turbulence, while less coarse sediment particles (e.g. sands, silt and clay) leave the dredging zone in suspension and enter the near-field where they may settle at different rates while being transported further away from the dredging location. Typically only fine material (e.g. silt and clay) remains suspended as it feeds into the far-field plume, and this material may be carried by the current over large distances as long as the speed of that current remains above a critical threshold. Some of the fine material may settle out on the bed if the current weakens, and may be resuspended if the current strengthens again.

The horizontal and temporal distribution of the suspended sediments will depend on the dredging schedule (i.e. the dredger types and sizes, its movements, operational characteristics and sediment release types) as well as the site conditions and *in situ* material characteristics encountered during the dredging campaign. The source vertical distribution is particularly linked to the type of sediment release. For example, assuming sediment release in barge overflow occurs at vessel draft depth, then, after near-field processes, the source for the far-field plume may be expected to be distributed vertically between the release point and the sea bed. For the case of a cutterhead, sediment release will occur directly around the rotating cutter and the source for the far-field plume will typically be distributed vertically within a few metres of the sea bed.

There are other source term attributes which are important to dynamic plume behaviour in the near-field such as the initial vertical momentum and buoyancy fluxes of the overflow stream at discharge (see Mills and Kemps 2016) but these are not the focus of this review.

3 Estimating source terms

The estimation of source terms for input into dredge plume models requires knowledge of the material to be dredged, local meteorological and oceanographic conditions, bathymetry and a range of project-specific information including dredging equipment, dredging strategy and activity schedules.

It is generally accepted that a carefully designed program of field data collection during preliminary dredging trials has the greatest potential to achieve realistic source term estimates for dredge plume modelling in advance of a major dredging campaign. The preliminary dredging trials should, ideally, use the same dredging equipment to that chosen for the dredging campaign, working with the *in situ* material, site and hydrodynamic conditions that are considered critical to predicting the extent and intensity of the dredge plume envelope across the dredging campaign. However field trials are costly and logistically complex, requiring access to dredgers and the dredging location before all environmental approvals are in place, and as such are rarely conducted. Hence, the information available during the environmental impact assessment (EIA) phase is typically incomplete, resulting in the adoption of a set of assumptions regarding the interaction of the most likely dredging equipment with a small number of 'typical' material types under plausible local conditions in order to estimate the likely source term values.

The three commonly used approaches for estimating source term values are outlined below.

3.1 Percentage loss rates

A method that is sometimes used for estimating the source terms for input to passive dredge plume models for EIA, assumes that the source rate is a constant percentage of the rate of production (or excavation) of dredged material. In this case the source rate is typically assumed to be a function of a 'loss rate' or 'spill rate'.

Percentage loss rate values are generally derived from either:

- field measurement data (from specific dredging operations) which are used to establish a best fit linear relationship between suspended sediment spill rate and dredging production rate; or
- generalised knowledge of dredging processes, based on broader data sets and experience, and typically sourced from the scientific literature.

Percentage loss rate values based on specific field measurements are sometimes referred to in the scientific literature as re-suspension factors, denoted as R, and defined as the mass of sediment suspended into the water column expressed as a percentage of the mass of sediment removed via dredging (e.g. Hayes and Wu (2001) for cutterhead-related re-suspension factors). However, loss rates are influenced by a number of different factors, particularly those related to some other dredge sources e.g. propeller wash (prop-wash), and hence can be considered to be quasi-independent of excavation/production rate.

The re-suspension factor values cited by Hayes & Wu (2001) were derived from re-suspension data collected during dredging trials prior to the development of modern field measurement techniques and protocols. In most cases the dredging operations were for the maintenance of existing navigation areas and the materials being dredged were mainly unconsolidated or fine cohesive soils. Hayes et al. (2007) commented that the available data do not cover a sufficient range of soil and rock, site and operational conditions to serve as a predictive base for estimating levels of re-suspension from different dredging operations.

In the case of projects that involve dredging fully or partially consolidated material there is the additional complication of allowing for material attrition through the handling processes associated with transferring material from the seabed through pumps and pipes to the seabed (e.g. during sidecasting operations) or the hopper (see Barber et al. 2012). Far-field plume predictions may therefore require an estimate of the 'post-handling particle size distribution', i.e. the particle size distribution of the material introduced to the water column after taking into account material disintegration due to the excavation process and attrition processes within the dredger. This is particularly important in determining source terms for cutter suction dredgers (CSDs) operating in consolidated material and is further complicated when sidecasting and double-handling techniques are employed. Material attrition may also be an issue in the draghead, suction pipe and pumps of TSHDs, which may influence the far-field source rate contribution from the overflow. In situations where attrition is considered likely, material samples collected *in situ* are sometimes subjected to one or more disaggregation tests in a laboratory environment and post-handling PSDs determined from the test results, despite the fact that these tests are known to have serious limitations (see Mills and Kemps 2016).

It should also be noted that suspended sediment measurements were sometimes made very close to the dredge source (e.g. for cutterhead trials) where both coarser and finer sediment size fractions would be in suspension, and sometimes at a greater distance downstream (e.g. for mechanical dredger trials) where only finer material would remain in suspension. These near and far-field measurement strategies effectively create different definitions of the re-suspension factor, one (R*) which expresses the initial release rate of all size class fractions combined, as a percentage of the total production rate, and the other (R) which expresses the release rate of fine, suspended sediment fractions to the 'far-field' as a percentage of the total production rate.

Clearly, the R* and R values are numerically different for any given dredging operation and therefore, it is essential that re-suspension factor values be applied in a manner consistent with the method of their determination. To allow meaningful comparisons to be made, all relevant details should be well-documented, including the dredging equipment, operations and site conditions, as well as the data collection strategies and methods used to derive re-suspension factor values.

3.2 Spill database

In some areas where dredging activities are frequent and largely ongoing (e.g. Singapore), measurements across transects through dredge plumes are regularly conducted to validate mass flux and settling velocity estimates to inform near real-time modelling, and form a critical part of a proactive environmental monitoring and management system (Doorn-Groen and Foster 2007). Over time this has resulted in the compilation of a large dredge spill data base covering a range of dredging equipment types, sizes, activities, dredged material types, source types, site and hydrodynamic conditions. Provided an appropriate degree of similarity of operational conditions exists, the numerical spill rates measured during a prior dredging program may inform, or be directly transferable to, a future dredging proposal, resulting in greater confidence and more realistic simulations without the need for costly dredging trials upfront.

Historically, the situation in Western Australia has not been as conducive to the building of a spill database, with the majority of the relevant monitoring data remaining proprietary and confidential. The concern about restricted availability of environmental data (including dredge source terms) and the link to uncertainty levels in impact prediction is also recognised nationally (Commonwealth of Australia 2014). More recently, some significant changes have occurred in the way large dredging projects are assessed and permitted in Western Australia. There is a greater focus on monitoring to inform management rather than just compliance (EPA 2016) and approvals generally require all relevant data collected as part of the preparation of the environmental impact documentation, or through implementation of the proposal, to be made publically available[2]. If spill data are collected and made available, this will help build a better understanding of the various aspects of suspended sediment generation during dredging in the WA context and provide an evidence base to improve predictive confidence over time.

3.3 Process-based models

In recent years attention has been given to understanding the physical mechanisms that govern sediment release from dredgers. These mechanisms, together with material, site and dredging parameters, govern the rates and characteristics of each type of sediment release. Knowledge of these processes has been applied as the basis for developing models for predicting sediment release. Models of near-field plume behaviour have also been developed and coupled with sediment release models to better predict the mass flux and characteristics of the suspended sediment material that feeds into the far-field plume. Model parameters include the relevant specifications of dredging equipment (e.g. hopper dimensions, pipe diameters, pumping rates), dredged material characteristics and other site and hydrodynamic conditions.

Mills and Kemps (2016) refer to the Turbidity ASsessment Software (TASS) Model as applied to TSHDs (HR Wallingford 2013) and note areas where better process understanding is needed to improve the model predictions. Two such areas are the degree of fines generation due to material attrition during dredging and the percentage of sediment flux from the hopper overflow that feeds into the far-field plume. There is also a need to validate the models under a wider range of conditions, including conditions typical for capital dredging projects in WA waters (e.g. the dredging of hard material with low under-keel clearance, a situation that often arises in port construction dredging).

Current limitations inhibit the effective use of process-based models for far-field source term predictions in WA, but the momentum in model development suggests that useful application here may not be far into the future.

[2]Wheatstone LNG project MS 873, (Condition 20 (1-2)) http://www.epa.wa.gov.au/sites/default/files/1MINSTAT/00873.pdf)

4 Source types and the practice of their estimation

The overarching objective of Theme 2 of the Dredging Science Node is to improve the ability to quantify and predict the suspended sediment source rates and characteristics for input to passive suspended sediment transport models to simulate the extent, intensity and duration of far-field dredge plumes. These source rates and characteristics are composed of several contributions, each of which is associated with a particular aspect of the dredging activity that releases sediment to the water column. For a TSHD, for example, one of the suspended sediment contributions feeding into the far-field plume is derived from the erosion of bed sediments as a result of propeller wash. The magnitude of that contribution will depend not only on the bed erosion flux, but also on the percentage of that flux that is able to remain in suspension and contribute to the far-field plume.

An important step in this appraisal of source term estimates is to take stock of the approaches and assumptions that have been adopted by project proponents in recent times. To this end, the EIA-related documentation for 15 Australian proposals with dredging campaigns, including 12 WA projects, were reviewed. Attention has been given to source term contributions for cutter suction and trailing suction hopper dredgers (Table 1) as these types of dredgers are generally used singly, or in combination, to remove the majority of material during large scale capital dredging programs in Western Australia and elsewhere in Australia. The numerical superscripts that appear in the text and tables in this report are references to specific proponent documents as set out in Appendix 1.

Table 1. Primary source term contributions for trailing suction hopper dredgers (TSHD) and cutter suction dredgers (CSD) that are typically used to support dredge plume modelling for environmental impact assessment and management in Australia.

Dredging Equipment	Source Term Contribution
Trailing suction hopper dredge (TSHD)	Hopper overflow*
	Propellerwash erosion
	Draghead
Cutter suction dredge (CSD)	Hopper overflow*
	Cutterhead
	Cutterhead sidecast
	Pumped sidecast

* Considerations are similar for both types of dredgers

4.1 Trailing Suction Hopper Dredger (TSHD)

The TSHD-related sediment source term to the far-field dredge plume includes contributions from the hopper overflow, propeller-induced seabed erosion and draghead disturbance of the seabed (Mills and Kemps 2016).

Attrition and changes in PSD when dredging and loading unconsolidated non-cohesive sediments with a TSHD is generally not documented and is apparently considered insignificant in practice. The PSD of the dredged material that enters the hopper is therefore assumed to closely resemble the *in situ* sediment PSD. This PSD, together with the total mass rate of sediment input to the hopper (which can be calculated from standard on-board measurements) tends to be used to estimate the mass rate of fines entering the hopper. Then, allowing for a small rate of fines retention in the hopper, the fines rate in the overflow discharge is estimated. It follows, then, that the *in situ* PSD can be a major factor in estimating the mass rate of fines discharged in the hopper overflow.

When dredging non-cohesive sediments, most of the fines entering the hopper are expected to escape through the overflow, while most of the larger sized sediment fractions are expected to accumulate within the hopper. Hence, the PSD of sediment escaping the hopper through the overflow is strongly biased towards fines (though some particles up to about 300 µm may be present (Van Rhee 2002)). Typically, the sediment-water mixture discharged from the hopper overflow forms a dynamic plume which descends rapidly through the water column and, if it impacts the sea bed and forms a bed plume, a significant portion of its sediment load (mainly fines) may be deposited on the sea bed. In addition, any coarser particles that are diverted (or mixed) out of the dynamic plume will typically settle fairly rapidly to the sea bed. Hence, not all of the predominantly fine sediment that escapes the hopper through the overflow will feed into the far-field plume.

When dredging cohesive sediments a proportion of fine primary particles may be bound up in clumps (aggregates), resulting in a reduction in the quantity of disaggregated fines that remain suspended in the hopper and available to escape through the overflow. There is very little predictive understanding of the fate of these aggregates as a result of processes in the dredging plant. Fines that do overflow from the hopper into the marine waters may form flocs with higher settling velocities compared to un-flocculated fines, in turn reducing the proportion of fines that otherwise may have fed into the far-field plume.

When dredging consolidated *in situ* material (e.g. rock or stiff clay), the assumptions adopted around the post-handling PSD of the material entering the hopper (taking into account material disintegration due to the excavation process and attrition processes within the dredger) will influence estimates of the mass rate of fines subsequently escaping through the overflow.

The relative importance of propeller-induced re-suspension of fines depends on several factors, including the propeller thrust, under-keel clearance, the erodibility and *in situ* PSD of the sea bed material and the availability and quantum of settled fines from recent dredging activities. Although not a focus of this study, it is useful to note that the PSD of dredged material dumped at a spoil ground may differ significantly from that of the *in situ* or post-handling PSD due to the loss of fines through the overflow. Furthermore, only a proportion of fines in the dumped material feeds into the far-field plume associated with the spoil ground due to ‘trapping’ by heavier particles and the density-driven downwards momentum of the dumped load.

4.1.1 Hopper overflow

Source rate

Predictive estimates of the contribution from hopper overflow to the source rate used in far-field dredge plume modelling were provided for nine proposals involving TSHD dredging operations and a further one involving CSD loading of dredged material to a hopper barge. All estimates were expressed as percentage loss rates with most as a percentage of total production rate (%TP) and the remainder as a percentage of fines production rate (%FP) or a percentage of the rate of fines released through the overflow (%FO). For comparison purposes the estimates were converted (where possible) into %FP, which has the effect of normalising for the differences in the fines fraction between projects.

For the majority of the proposals the source strength of overflow fines feeding into the far-field was estimated at between 5 and 15% of the rate of fines entering the hopper (%FP). Much higher source rates were estimated for two proposals (i.e. 23.0 %FP and ‘part of 59.5 %FP’), presumably resulting in highly conservative (i.e. worst case) estimates. For the latter project, the given source rate of 59.5 %FP appeared to include the contributions from the overflow, draghead and propeller wash sources combined. However, the contribution of the overflow to the far-field plume is generally estimated to be considerably higher than that of the other two sources combined, which would suggest that the source rate contribution from hopper overflow was expected to exceed 30 %FP (i.e. about half the combined value of 59.5 %FP).

The rationale provided in support of far-field source rate estimates contributed to the overflow was often incomplete or unclear. In two cases, estimates were based on international measurements from a spill database established by DHI (2010), while others were based on field data collected at previous projects in the same area or based on values from the international literature. For one proposal, which involved the use of a 25,000 m^3 and a 5,000 m^3 TSHD, it was noted that the predicted overflow source rate for the larger dredger was assumed to be half that of the smaller dredger (i.e. 7.5 %TP and 15 %TP respectively).

Table 2. TSHD far-field source rate contribution from the hopper overflow expressed as a percentage of the total production rate (%TP), a percentage of the fines production rate (%FP) or a percentage of the fines lost through the overflow (%FO). Values in italics are derived. Numerical superscripts are document identifier numbers. The key to the project identifier number (Project ID) and document identifier number is in Appendix 1.

ID	%TP	%FP	%FO	PSD (µm)	Overflow type	TSHD size (m^3)	Notes
1	*0.8–9.8*	15.0[1]		≤63	Barge - CSD dredging mainly unconsolidated sediment		Proponent source rate was based on the DHI-developed rate, presumably of 15%FO (as set out in the notes under project 4 below)[1]. For 15%FO to be equal to 15%FP the proponent appears to have adopted the additional assumption that 100% of fines escape the hopper through the overflow. %TP based on fines fraction range of 0.05–0.65[1].
2	1.0[2]	*2.3–20.8*		<100	TSHD dredging unconsolidated material	10 k 15 k	Proponent source rate was based on literature values[2]. %FP based on fines fraction range of 0.048–0.439[3].
2	1.0[2]	*6.9*		<75	TSHD dredging CSD sidecast material	10 k 15 k	Proponent source rate was based on literature values[2]. %FP based on fines fraction of 0.145[2]
3	3.0[4]	*7.1–18.8*		≤75	TSHD dredging material of various strength	5 k 10 k 20 k	Proponent source rate was based on an SSC value of 6000 mg/L for the overflow, which '…represents the higher end of a range of literature SSC values and correlated well with data drawn from other WA projects…'[4]. %FP based on fines fraction range of 0.16–0.42[4].
4	*1.7–2.1*	*5.1–6.1*	7.0[5]	≤63	TSHD dredging sand	10 k	Based on measurements taken near a working sand dredger (8.2 k) in Hong Kong, which suggested 15% of overflowed fines to contribute to far-field plume. It was assumed that the use of the green valve would reduce this proportion to ~7 %FO (calibrated against scaled DHI measurements collected near dredgers in Singapore). %TP and %FP are based on the assumption that 73–87%[a] of incoming fines escape through the overflow and an average fines fraction of 0.34[6].
5	*1.5–7.5*	15.0[7]		silt & clay	TSHD dredging fine cohesive sediments	5 k	Proponent source rate was a result of a calibration of the sediment transport model using data collected during a prior local dredging campaign[7]. %TP based on fines fraction range of 0.1–0.5[7]
5	*0.8–3.8*	7.5[7]		silt & clay	TSHD dredging fine cohesive sediments	25 k	Proponent source rate was based on assumption that a 25 k hopper is twice as efficient as the smaller hopper[7]. %TP based on an average fines fraction of 0.1–0.5[7].
6	*5.6*	*8.0*	10.0[8]	<63	TSHD dredging unconsolidated material		Proponent source rate of '…lowest 10% of fines…' lost through overflow was based on experience from an earlier dredging campaign at the same location[8]. %FP and %TP based on assumption that 80% of all incoming fines escape through the overflow (authors' assumption) and an average fines fraction of 0.7[8].
7	3.0[9]			Mostly <70	TSHD dredging unconsolidated material	8.5 k	No rationale provided. An estimate for the fines fraction also did not appear to be provided.
7	0.3[11]			Mostly <70	TSHD dredging mainly sand	8.5 k	Proponent source rate based on literature[11]. An estimate for the fines fraction was not provided.
7	0.8[11]	*1.3*[b]		Mostly <100	TSHD dredging CSD sidecast material	8.5 k	Proponent source rate based on literature supported by validation of predictions at 400m using data collected during a prior campaign at an adjacent site[11]. %FP based on an average fines fraction of 0.64[b,9].

8	*6.7*	*23.0*		≤63	TSHD dredging unconsolidated sediments	Medium	%FP for the overflow was deduced from information provided (i.e. 32%FP for dredging with overflow – 9%FP for dredging without overflow)[12]. Source rate was presumably revised down in 2014, but specific information could not be found[13]. %TP based on the original fines fraction of 0.29 used in the modelling[13].
9	Part of 25%[c,14]	Part of *59.5*		≤159	TSHD dredging unconsolidated material	10 k	Proponent source rate (including overflow, draghead and potentially also prop-wash contributions) appears to have been based predominantly on data collected during a prior operation at an adjacent site. %FP based on the average fines fraction (including 'fine sand') of 0.425[14].
10	N/A	N/A	N/A		TSHD dredging soft material	12 k	Overflow not permitted[15].
10					TSHD removal of CSD sidecast material		No information provided.
11					TSHD dredging overburden of soft sand		No information provided.
11					TSHD removal of CSD sidecast crushed rock		The spill of fines at the draghead during pickup of CSD-sidecast material and, subsequently, through the overflow, was estimated at 30% of the fines originally produced at the CSD cutterhead[16], but no estimate of CSD-generated fines was provided[d].

a The percentage of incoming fines escaping through the overflow was based on the proponent's assumption that the fines component will be reduced from 30% 'bed fines' (i.e. sum of overflow fines and residual hopper fines) to 4–8% residual hopper fines[5], suggesting that ~73–87% of the fines entering the hopper is lost through the overflow.

b The proponent assumed the grain size distribution of the CSD-cut and sidecast material picked up by the TSHD to be equal to the grain size distribution released by the CSD (via the diffuser pipe), effectively assuming no fines loss during sidecasting and TSHD pickup.

c Note that the combined far-field source rate of 25 %TP (including overflow, draghead and potentially also propeller wash contributions) was arrived at by the proponent by assuming that 100% of the entrained fine sand and silt fractions and 29% of the *in situ* clay fraction (of the average PSD across the entire area) are spilled and feed into the far-field. The adjustment to the clay fraction was applied to take into account clay 'clumps' and was set at such a value as to arrive at a far-field plume clay percentage comparable to that measured during a previous dredging campaign in the region.

d Removal of CSD-sidecast rock by TSHD is only proposed to occur during the dredging of the LNG access channel and turning basin, but the only estimate provided (relating to CSD-generated fines) was for another location. CSD excavation of the bedrock at the location of the proposed MOF was assumed by the proponent to result in fines (<100 µm) equalling 5% of total material cut. If the same assumption was applied for the LNG access channel and turning basin, then the combined far-field source rate for the TSHD draghead + overflow sources would have been estimated at approximately $(0.05 \times 0.3)/0.975 = 1.54$ %TP given the proponent's assumptions that 30% of the CSD-generated fines are released into the water column at the cutterhead, 20% during sidecasting, 30% by the TSHD (at the draghead and through the overflow) and that, once released, all fines feed into the far-field plume (i.e. no fines are trapped by the density-driven plume).

Only a single proponent provided information from which an estimate for the proportion of the produced silt and clay fractions expected to escape the hopper could be calculated, i.e. 73–87 %FP. However, the values adopted for residual hopper fines by the proponent were derived by extrapolating a weak function between 'bed fines' (back-calculated from overflow fines plus residual hopper fines) and residual hopper fines. This function was almost exclusively based on data collected while dredging material with a fines component of up to 85%.

Of the overflowed fines discharge, only 7% was assumed to reach the far-field, an assumption that was based on: (i) international validation data suggesting this proportion to be 15%; and (ii) the assumption that use of a green valve would result in reducing it down to 7% (which would mean that 93%, rather than 85% of the overflowed fines would be deposited in the near-field).

Source particle size distribution (PSD)

The PSDs used to represent the contribution from the overflow to the suspended sediment source term for input to the far-field models were strongly biased toward the fine fractions, reflecting the predominance of fines in the overflow. Three different approaches were used to estimate the source PSD:

- *in situ* PSDs were adjusted by eliminating all but silt-sized and clay-sized material;
- PSDs were derived from overflow samples, presumably taken from TSHDs with similar hopper sizes and operating characteristics, and with similar parent material and site conditions to those expected for the dredging proposal being assessed; and
- 'Best fit' PSDs were adopted from previous plume model calibration exercises in the same area.

Source vertical distribution (SVD)

The vertical distribution of the suspended fines concentration was generally set to be relatively consistent throughout the depth of the water column below the overflow discharge point in the base of the hull, although for some model setups all sediment was released at a specific depth, presumably equal to the bottom of the hull at maximum vessel draft.

4.1.2 Propeller-induced bed shear stress and draghead spill sources

Source rate estimates for the propeller-induced bed shear stress (propeller wash) and draghead-related contributions to the far-field sediment plume were provided (or could be determined) for five out of 10 proposals involving TSHDs dredging unconsolidated sediments (Table 3). No common approach was evident, with models of propeller-induced shear stress and bed erosion, literature values and direct field measurements all having been used to derive estimates. However, the range of estimates showed that the input from propeller wash and draghead sources to the sediment plume was expected to be less than 1% of total production rate and less than 5% of total fines discharge rate in the hopper overflow. These rates were generally in the range of 3% to 33% of estimated source rate contributions from the actual or potential overflow for the same dredgers. Very few proposals specified the individual contributions from propeller wash erosion and the action of the draghead to the far-field plume. Where the relative contributions were presented, the draghead source rate was generally much smaller than the source rate for propeller wash erosion.

Key factors determining the contribution of propeller wash erosion to the far-field plume include the propulsion power, under keel clearance, sediment characteristics and overflow management, with the latter influencing the degree to which easily re-suspended fines have recently settled on the seabed. For most proposals however, the available information was incomplete, which limits transferability and direct comparisons between projects.

Source PSDs, where provided, generally included mostly fines (defined as sediment particles less than 75 µm or 62.5 µm in size, depending on the proposal), with the majority of these fines being distributed in the lower part of the water column within several metres of the seabed.

Table 3. TSHD far-field source rates expressed as a percentage of the total production rate (%TP), a percentage of the fines production rate (%FP) or a percentage of the fines lost through the overflow (%FO) for propwash & draghead sources combined. Numerical superscripts are document identifier numbers. The key to the project identifier number (Project ID) and document identifier number is in Appendix 1.

ID	%TP	%FP	%FO	PSD (µm)	Overflow type	Notes
2	0.03[2]			<100	TSHD dredging mainly unconsolidated sediments and sandstone	Combined source rate for prop wash and draghead (equal to 3% of the overflow source rate estimate: authors' calculation).
3	0.60[4]			≤75	TSHD dredging of unconsolidated sediments and removal of CSD sidecast crushed rock	Based on results of modelling propeller-induced shear stress of the largest TSHD over the range of expected under keel clearances. Estimated at ~20% of overflow source rate[4]. (Draghead source rate was assumed to be negligible at <10% of prop wash source rate[4]).
4			5[5] 5 k m^3 TSHD & 2.33[a] 10 k m^3 TSHD	silt & clay	TSHD dredging sand with a silt/clay component of 10–30%	Given the overflow far-field source rate was estimated at 15%FO, the contribution to the far-field plume by the draghead and prop wash sources was estimated to be equal to 33% of the overflow source rate or ~71% of the overflow source rate with green valve operation for a 5 k m^3 TSHD. For a 10 k m^3 TSHD the contribution appeared to be estimated at 15.5% of the overflow source rate or 33%[a] of the overflow source rate with green valve operation. Source rates derived from DHI data suggest the prop wash contribution of a 10k m^3 TSHD with under keel clearance of 2–4m and 4–8m to be equal to ~26% and ~10% of the overflow contribution respectively[b,5]. The draghead contribution was assumed to be equal to 0.5% of the excavation rate of bed fines[b,5] (equal to ~8% of the overflow source rate estimate: authors' calculation).
5					TSHD dredging fine cohesive sediments	No information provided
6					TSHD dredging unconsolidated sediments	No information provided
7				mostly <70	TSHD dredging unconsolidated sediments	Source rate not provided but was presumably based on results of modelling propeller-induced shear stress and literature values for prop wash-related mass flux.
8		1.00[12]		≤63	TSHD dredging unconsolidated sediments	General value, based on DHI's experience and international spill database (equal to 4.3% of the overflow source rate: authors' calculation).
9					TSHD dredging unconsolidated sediments	No info provided (possibly included as part of the source rate provided for 'overflow plus dredge-head source').
10			2.50[15]		TSHD dredging soft material	Based on the assumption that prop wash (& draghead) contribution to the far-field plume is approximately equal to 5% of the fines released through the overflow (and, given the overflow far-field source rate of 15%FO, equal to 33% of the overflow source rate), but because overflow was not permitted (and, hence, that there would be no additional fines on the seabed available for re-suspension from prop wash erosion) the source rate estimate was reduced by 50%[15] .
11					TSHD dredging overburden of soft sand	No info provided

11					TSHD removal of CSD sidecast crushed rock	The far-field source rate for the combined contributions from resuspension about the draghead (during pickup of CSD-sidecast material) and the overflow, was estimated at 30% of the fines generation rate (i.e. the rate fines are generated at the CSD cutterhead[16]).

a Based on the assumption that the source rate of 87 kg/s is based on 7% of total fines released by the overflow of a 10 k m^3 TSHD as suggested in the material provided[5].

b Based on an overflow source rate of 106 kg/s for a 10 k m^3 TSHD, based on DHI data collected for a 20 k m^3 and 9 k m^3 TSHD dredging 'silty sand' for a Singapore project (presumably dredging with green valve operation) [5].

4.2 Cutter Suction Dredger (CSD)

The main CSD-related spill sources which may contribute to dredge plumes are from hopper overflow, the cutterhead, sidecast from cutterhead when running no suction, and pumped sidecast (Mills and Kemps 2016). This section mainly deals with proponents' estimates for the cutterhead spill source as little information was provided to support spill rate estimates presented for sidecasting operations. For estimates of percentage source rates associated with hopper overflow from barges filled from CSDs see those provided for TSHDs (see Section 4.1.1).

4.2.1 Cutterhead

Source rate

Estimates of cutterhead source rates were provided, or could be determined, for most of the 13 proposals that included CSD operations (Table 4). Far-field source rates were typically expressed as a type of percentage loss rate – which, for clarity, are here reported as a 'percentage of total excavation rate' (%TE) or 'percentage of fines generation rate' (%FG). For one project, a near-field source rate (expressed in turbidity generating units – TGU) was provided from which we calculated a percentage loss rate range (assuming a mean *in situ* dry bulk density range of 1200–2500 kg/m^3) for the purpose of comparison.

For projects predominantly involving dredging of unconsolidated or weakly consolidated sediments, the following was noted: (a) the source rate was typically expressed as a percentage of the rate of fines generated about the cutterhead (%FG) or directly in kg/s and (b) material disintegration due to the excavation process was not considered, such that post-handling PSDs were assumed to be equal to *in situ* PSDs. Estimates ranged from 5–7.5 %FG, which, for comparison purposes, resulted in source rates of 1.0–1.5 %TE (adopting a fines fraction of 0.2: our assumption) and 2–3 %TE (adopting a fines fraction of 0.4: our assumption). For one project the cutterhead source rates were expressed in terms of Turbidity Generating Units (kg/m^3), which converted to 0.6–1.2 %TE and 1.2–2.4 %TE.

For most projects involving the dredging of consolidated material, material disintegration due to the excavation process was taken into account by applying post-handling PSDs based on laboratory abrasion tests, field measurements collected during other dredging programs and/or values from the international literature.

For five projects the provided source rate value more closely resembled a cutterhead 'resuspension' rate (%TE*) – i.e. the rate sediments (including those much coarser than fines) are resuspended about the cutterhead as a function of the total excavation rate – rather than a far-field source rate. These allowed comparisons with published resuspension rates (such as those given by Hayes & Wu 2001). Resuspension rates can be used as input to a passive suspended sediment transport model because the coarser size classes typically settle out in the first few grid cells of the far-field model and, hence, do not contribute to the far-field plume. For these proposals we estimated the 'true' far-field source rate (expressed as a percentage of the total excavation rate – %TE) under the assumption that only fines <75μm would feed into the far-field dredge plume.

Estimates of cutterhead (far-field) source rates related to the dredging of consolidated sediments varied considerably between projects. While estimates provided for four projects (i.e. project ID 3, 7, 13 and 14) ranged from 0.08–0.41 %TE (considerably lower than for projects dredging unconsolidated/weakly consolidated material), much higher estimates were presented for proposals involving the dredging of hard sandstone (12.8 %TE, but this included both cutterhead and sidecast spill sources), medium strength phyllite (3.1 %TE) and hard crystalline limestone and calcarenite (1.5–2.5 %TE, assuming 30–50% of the generated fines at the cutterhead, estimated at 5 %TE, fed into the far-field plume).

Percentage rates for cutterhead losses in the range 0.3–0.5 %TE* represent the upper 5th percentile of the re-suspension factor values reported by Hayes & Wu (2001), but it should be noted that these published values were obtained using small cutterhead diameters working in mainly silt/clay sediments. Considering the difference in dredging equipment and bed types between the projects published in Hayes & Wu (2001), and the projects reported on here, direct comparisons are probably of limited value in determining whether the EIA-related estimates (which are used as input to far-field dredge plume models) for dredging unconsolidated sediments represent likely or conservative outcomes.

It is also difficult to collectively appraise the source rate estimates relevant to consolidated material, given the large variation in material strength and characteristics; the lack of reference data in the scientific literature; and a general lack of available validation data. Furthermore, the rationale underpinning the choice of these values was often also not clearly presented. Either crucial information required for source rate calculation was not provided (e.g. the *in situ* bulk dry density, the fines fraction and/or the predicted re-suspension factor) or the process by which the post-handling PSDs were estimated was unclear. In other cases the source rate was partially based on 'rules-of-thumb'. For instance, a common assumption was to use 30% of the total cut material as the amount that escapes the suction line and is released about the cutterhead, either as suspended or deposited material (Dekker et al. 2003, Den Burger et al. 2005, Vlasblom 2005). The cutterhead source rate was then calculated from knowledge of the post-handling PSD (particularly the fines fraction) of this material and an estimate for the proportion of the total amount of fines released that will remain suspended (which, in one case, was assumed to be a function of the depth of the cut).

Table 4. CSD cutterhead-related far-field source rates expressed as a percentage of the fines generation rate (%FG), i.e. the rate of fines generated by the excavation process (ideally taking into account material disintegration due to the excavation process); and/or as a percentage of the total excavation rate (%TE), i.e. the rate of cutting material (as opposed to the rate of material entering the suction pipe). Note that for five proposals the far-field source PSD included sediment size classes larger than fines (denoted as PSD*) and was associated with a 'resuspension' rate at the cutterhead (denoted as %TE*). As sediments coarser than fines are expected to settle out within the first few grid cells of the far-field model, it was necessary to calculate an 'effective' source rate (%TE) by multiplying the resuspension rate with the fines fraction (arguably defined as <75µm) in the post-handling PSD. Values in italics are derived. Numerical superscripts are document identifier numbers. The key to the project identifier number (Project ID) and document identifier number is in Appendix 1.

	ID	%FG	%TE*	PSD (µm)*	%TE	PSD (µm)	Consideration of material disintegration due to the excavation process	*In situ* material
Unconsolidated weakly consolidated sediment	1	7.5%[1] (DHI-developed source rate)				Fines <63µm	No	Weakly cemented and cemented marine sediments.
	4	*7.5*[a]			*1.5–3.0*[a]	Silt & clay	No	Loose soil & weak rock
	5	*No information provided*					No	Fine cohesive sediment
	9				*0.6–1.2*[b]	Fines	No	Unconsolidated and weakly consolidated material with a clay component
	9				*1.2–2.4*[c]	Fines	No	TSHD 'dumped' material (for re-handling by CSD into a reclamation area)
	12	*5.0*[g,17]			*0.9*[g]	Fines <64 µm	No	Soil: predominantly clay, silt, sand mixture
Consolidated sediment	2		20[j,3]	Source PSD includes 36% material ≥75 µm[7]	*12.8*[j]	Fines <75 µm	Yes - no rationale provided	Hard sandstone with the potential for relatively high clay content.
	3		0.50[h,4]	includes 58–84% material ≥75 µm[4]	0.08–0.21	Fines <75 µm	Yes - based on lab-generated PSD curves, literature and field data	Hard material of various types/strengths
	7				0.30[9] (no rationale provided)	Fines ≤70 µm	Yes - no rationale provided	Rock
	10	*15.0*[d]			*3.10*[d]	Fines <75 µm	Yes - based on abrasion test results	Phyllite (mudstone) with some conglomerate (10–30 MPa)
	11				2.50[e,16] (no rationale provided)	Fines <100 µm	Yes - no rationale provided	Hard crystalline limestone & calcarenite
	13		0.50[f,18]	includes 18% material ≥75 µm	*0.41*	Fines <75 µm	Yes - based on lab test results, literature and field data	Limestone rock with UCS range of <5–>25 Mpa with ~55% of rock >15 Mpa
	14		0.50[19]	includes 68% material >75 µm	*0.16*	Fines ≤75 µm	Yes – based on literature values	Harder consolidated material
	15		0.30[i,20]	includes material >75 µm			Yes – supported by sensitivity testing conducted during Australian Marine Complex dredging program	Sand and shell overlying Tamala limestone incl. calcarenite and calcareous sandstone of variable strength

a %FE far-field source rate was based on the following proponent assumptions: (1) ~30% of the cut material escapes the suction pipe and is left in the cut as residual (which was based on the results of laboratory tests of CSD scale models described in Vlasblom 2005) and (2): 25% of the fines in this 30% feeds into the far-field (DHI assumption based on the idea that a proportion of fines after a single pass of the cutterhead will not be released into the water column but settle out in the cut and will then enter the suction pipe of the CSD on consecutive passes)[5]. %TE rate was based on the range of 'silt and clay' fractions provided in the general description of the sediments within the dredge area, i.e. 20-40%[6].

b %TE far-field source rate range was based on the following assumptions: (1) cutterhead turbidity generating units (TGU) of 48 kg/m^3 for the near-field (proponent assumption[14] – source of value is unclear); (2) 30% of the material released in the near-field to enter the far-field (proponent assumption[14] – source of value is unclear); and (3) a bulk dry density range for the excavated material of 1,200-2,500 kg/m^3 (our assumption).

c As above but adopting a TGU of 96 kg/m^3 (proponent's assumption[14]– source of value is not clear) based on the expectation that the TSHD side-cast material was less consolidated than the in-situ material.

d %TE far-field source rate was based on the following assumptions[15]: (i) a 'dredging efficiency of 70% (proponent's assumption which we took to mean that 30% of the cut material escapes the suction pipe and is left in the cut); (2) a fines fraction of 0.204 in the cut material (proponent's assumption); and (3) 50% of these fines feeding into the far-field plume (proponent's assumption) – i.e. 30 %TE * 20.4% * 50% = 3.1 %TE and 30 %TE * 50% = 15.0 %FG.

e Proponent source rate was based on the following proponent's assumptions: (1) a fines fraction (<100µm) in the cut material of 5%; and (2) 50% of released fines to feed into the far-field.

f Proponent suspension rate was based on literature values

g Proponent suspension rate resulted in source rate consistent with the upper range of sediment mobilisation rates summarised in Bridges et al. (2008). %TE far-field source rate was based on mean fines content (<64µm) of material within the dredge area. i.e. ~18%[17].

h Proponent suspension rate was based on: (i) literature values; (ii) data drawn from a Cockburn Sound dredging project and (iii) a correction factor of 1.67 considering that hydraulic removal of generated sediments did not apply[4].

i Proponent suspension rate was based on the results of sensitivity testing conducted during the validation study using data drawn from a prior campaign at an adjacent location.

j Proponent suspension rate including both cutterhead and sidecast spill sources. No further rationale was provided.

Source PSD

Source PSDs, as input parameters to passive dredge plume models, were biased towards fines to reflect the predominantly fines composition of the far-field plume. For projects involving dredging of unconsolidated or weakly consolidated sediments and for which material disintegration due to the excavation process was not considered, the most common approach was to normalise the various fine fractions in the representative *in situ* PSD after discarding coarser fractions on the basis they would have rapidly settled out of suspension. The particle size cut-off point for fines depended on the project and was generally either 63 µm or 75 µm. For one proposal, the clay component was reduced to allow for clumping and settling out prior to normalising.

For proposals involving dredging of consolidated material the source PSDs were commonly based on normalising the fines fractions (<63 µm or <75 µm) of the post-handling PSD as determined through either laboratory abrasion tests or field measurements collected during other dredging programs. However, as mentioned in the previous section, for five of the reviewed proposals involving the dredging of consolidated material, the source PSD included particle sizes coarser than fines, such that effectively the passive dredge plume model was used to allow the settling out of coarse material that would in reality settle out in the near-field.

Source vertical distribution (SVD)

Information on the initial vertical distribution of suspended sediments for input into far-field sediment plume models was provided for less than 50% of the reviewed proposals, despite the fact that 3D models were used for most. Where a far-field SVD was provided, most of the released material from cutterheads was located within 3 m of the seabed. We were not able to find any far-field cutterhead source term estimates in the literature, however the initial spatial resuspended sediment concentration field is thought to extend no more than about two cutter diameters above the cut elevation (Hayes 1986) with resuspended sediment concentrations decreasing significantly at a distance of one suction pipe diameter above the top of the cutter ring (Brahme 1983), which provides some degree of confidence the far-field SVDs provided in EIA documentation may be appropriate.

4.2.2 Cutterhead sidecast

Only one of the reviewed proposals involved CSD sidecasting without suction. For this project the far-field cutterhead source rate could not be determined. The information provided was unclear and appeared to indicate that a resuspension rate estimate of 0.5 %TE* was used as input to the dredge plume model[4]. A resuspension rate is associated with a source PSD that includes sediment size classes larger than fines, which, when introduced to the dredge plume model, are expected to rapidly deposit to the bed. For comparison purposes, the resuspension rate (%TE*) can be multiplied with the fines fraction in the post-handling PSD to produce a source rate (%TE), but unfortunately insufficient information on the post-handling PSD was available.

The value of the resuspension rate was reportedly arrived at by the proponent after: (a) considering published values in the scientific literature for cutterhead source rates (using suction) and the results of a dredge plume model validation study elsewhere in WA, indicating that 0.3 %TE (or 0.3 %TE* – the information provided was unclear) is a suitable input for a large CSD using suction; and (b) increasing the source rate arbitrarily to allow for the lack of hydraulic removal of fines[4].

The two rock types encountered during the geotechnical investigations were cemented sedimentary carbonates and metamorphosed crystalline basalt. Post-handling PSDs were based on the PSD curves representative of each of these materials '…in a more weathered state…', with no further adjustments made to simulate the generation of additional fine material due to the excavation process[4]. The two reasons that were given in support of this approach were: (i) that there is no established method for reliably estimating post-handling PSDs; and (ii) that the process of obtaining the PSD curves in the laboratory does not adequately take into consideration the potential for colloidal or floc behaviour and, hence, that the adopted source PSDs were already likely to be conservative[4]. The information provided, therefore, suggested that the source PSD was based on the PSDs expected at the cutterhead and, hence, included size classes coarser than fines.

The majority of suspended sediments were distributed over the lower part of the water column within 3 m of the sea bed.

4.2.3 Pumped sidecast

Far-field source rates were provided – or could be estimated from the information provided – for all five reviewed proposals involving CSD operations with pumped sidecasting. There was no clear common approach, although the apparent end result for two of these proposals were far-field source rates equal to the fines sidecast rate, i.e. 100% of the fines in the sidecast material were assumed to feed into the far-field plume[3,11]. For two other proposals far-field source rate estimates were provided of <3%[5] and 5%[15] of the fines sidecast rate. For the fifth proposal we calculated the far-field source rate to be 28.6% of the fines sidecast rate. This calculation was based on the proponent estimates/assumptions[16] that (a) the resuspension rate at the sidecast location is 20% (or 0.2) of the fines generation rate at the cutterhead, and (b) that 70% (or 0.7) of the fines generation rate at the cutterhead is delivered to the sidecast location (i.e. $0.2/0.7 \times 100 = 28.6$).

In general, there was little discussion of the assumptions adopted in the estimation of sidecast far-field source rates, which may be an indication that attrition processes within the plant (as opposed to those related to excavation by the cutterhead) are not usually considered. However, for one proposal, which involved dredging phyllite (mudstone) with some conglomerate (10–30 MPa), attrition within the plant was assumed to double the fines fraction resulting in a source rate estimate of 60% fines (<75 µm) for sidecast material[15]. For the two proposals for which information on the source vertical distribution of suspended sediments was provided, the majority of this material was assumed to be distributed within several metres of the release depth (which was near the seabed and at 5 m ASB respectively).

5 Discussion and implications for management

Our review of recent EIA documentation from Australia revealed that a diversity of approaches have been adopted for estimating far-field source terms. It was also evident that estimates for far-field source rates for each source type differed considerably between proposals. While these differences are in part a reflection of the range of different substrate types between locations/proposals, the relative levels of confidence about the geotechnical (and metocean) conditions likely to be encountered, and the type/size of dredger(s) and associated operating schedules and characteristics, some of the estimates representing the upper end of the range appeared overly conservative. In the early stages of EIA, particularly in green-fields sites where there is often limited knowledge of even the most basic elements of a dredge program – e.g. the characteristics of substrates to be dredged and the types of dredgers and work methods to be used – far-field source terms are estimated using a range of untested assumptions. Many of the EIA documents reviewed fall into this category which helps to explain the variation in estimates between projects, and even within projects as the knowledge base matures (e.g. when geotechnical data become available).

For TSHDs, estimates of source terms for fines entering the far-field from the hopper overflow, excluding contributions from the draghead and propeller wash, ranged from 0.3–9.8% when expressed as a percentage of total production; 1.3–23% when expressed as a percentage of fines production; and between 7–10% of the total fines overflowing from hoppers. These far-field estimates are also considered applicable to overflow events from CSDs loading hopper barges, provided the fines fraction of the material in the hopper barge reflects post-handling PSDs where appropriate.

There were fewer estimates of the far-field source contribution due to TSHD draghead and propeller wash, but they ranged from 0.03–0.6% when expressed as a percentage of total production; one estimate of 1% of fines production; and between 2.3–5% when expressed as a percentage of the total fines overflowing from hoppers.

These findings suggest that for TSHDs, overflow is generally estimated to be significantly larger (by a factor of 3 or greater) as a source of fines entering the far-field than the contributions from draghead and propwash sources combined.

For CSDs cutterhead (far-field) source rates ranged from 0.08–12.8% when expressed as a percentage of total excavation rate and 5–15% when expressed as a percentage of fines generation rate.

Based on the EIA documentation reviewed, and in very general terms, it would appear that source term estimates for cutterhead losses from CSDs when operating in suction mode are typically considered to be at least equivalent to, or greater than, the combined draghead/propeller wash losses for TSHDs when expressed as a percentage of the total excavation rate (which, for TSHDs, is approximated by the total production rate).

We are not able to confidently recommend numerical values for source term parameters based on this review due to the paucity of relevant field data to compare estimates against.

5.1 Improving predictive confidence

There are several approaches that could be used to address the lack of relevant field data.

- Establish and adopt standardised field data acquisition protocols and measurement techniques for estimation of dredge plume source terms, based on work from the dredging literature (e.g. Land & Bray 2000, HR Wallingford & Dredging Research Ltd 2003, Hydronamic 2005, Land et al. 2007, Aarninkhof 2008, Smith 2010, Bundgaard et al. 2011, Taylor et al. 2014). This would facilitate the collection and sharing of comprehensive, reliable data sets and enable development and testing of process-based source models.

- Recognise that field data collected consistently and according to standard protocols during a dredging campaign in a particular area (e.g. a port) can be considered as field trials for subsequent proposals using similar dredges in similar geotechnical settings and can be used to validate dredge plume models for both the near- and the far-fields.

- Becker, et al. (2015) described and provided worked examples of a general desktop method of estimating source rates for far-field dredge plume simulations using collated quality-assured field data – showing the benefits that could accrue in WA if an environment is created that encourages the storing and sharing of field data between individual project proponents and dredging consultants.

- Consistent mobile sediment flux monitoring of the dredge plume, combined with on-vessel measurements once the dredging project has commenced, and comparing estimates based on these data with source term predictions made at the EIA stage would provide an objective basis to test current approaches and help improve accuracy of predictions (Becker et al. 2015).

These opportunities can only be realised in Western Australia if the current 'data poor' situation is systematically addressed. It will depend on commitment to develop and populate a local dredge source term 'data library' that covers the different types of dredgers used and the various substrate types typically encountered in Western Australia. The data library could be used to improve understanding of primary source term contributions and the factors that determine sediment generation and re-suspension, for given substrate/dredger combinations and environmental settings.

Importantly, these locally-relevant data collected under local conditions would provide an objective basis to estimate 'realistic' far-field source term contributions from the primary sources (e.g. overflow, propeller wash, cutterhead etc.) in the first instance, and later to calibrate, validate and fine-tune the models to the local operating environment.

In order to maximise the utility of such a database, a number of basic protocols should be established to ensure all the relevant data are systematically captured and quality-assured, and those data are reported consistently. We recommend a focus on the following:

- the geotechnical characteristics of the substrates being dredged, as a crucial component of the validation dataset;

- the PSDs and physical properties (e.g. settling velocities) of the suspended sediments, depth of collection relative to the seabed/water surface and the locations of the data collection sites relative to the dredger;

- where material disintegration and attrition by dredging processes are significant, attention should be given to estimating and recording the post-handling PSDs;

- the specifications of the dredger, its log of activities and operating characteristics up to and including the period of data collection;

- the meteorological and oceanographic conditions preceding and during the data collection period to help interpretation and extrapolation; and

- the units by which source rates are presented should be clearly defined, for example when expressing as a percentage of fines production the size class for 'fines' should be defined.

Dredge spill data bases have been developed for some other locations (e.g. Singapore) where dredging and reclamation are virtually ongoing, although data are generally confidential and proprietary and hence of limited availability. In order to improve predictive capacity in Western Australia, it will be critically important to ensure that data collected locally as part of the implementation of projects are made generally available.

Over time, as predictive capacity increases, the degree of confidence in far-field sediment modelling and environmental impact predictions will improve, subsequently reducing the time, effort and resources required to technically assess dredging proposals and implement environmental monitoring and management programs.

6 Recommendations

Recommendation 1

Establish and promote standard approaches for (i) defining geotechnical characteristics of dredged substrates; (ii) defining sediment size classes (e.g. for 'fines'); (iii) determining post-handling PSDs where material disintegration and attrition by dredging processes are significant; and (iv) reporting the key aspects of the dredgers operations (e.g. cutter rpm, pump flow rates), in order to maximise utility and facilitate the sharing of information and to ensure information collected can facilitate model calibration and verification.

Recommendation 2

Establish and adopt standardised field data acquisition protocols and measurement techniques for estimation of dredge plume source terms, based on work from the dredging literature (e.g. Land & Bray 2000, HR Wallingford & Dredging Research Ltd 2003, Hydronamic 2005, Land et al. 2007, Aarninkhof 2008, Smith 2010, Bundgaard et al. 2011, Taylor et al. 2014). This would facilitate the collection and sharing of comprehensive, reliable data sets and enable development and testing of process-based source models.

Recommendation 3

Proponents of development proposals with a dredging component should collect relevant source term data and make these data publicly available via a data library.

Recommendation 4

Develop, populate and maintain a local dredge source term data library to comprehensively cover the different types of dredgers used (including their modes of operation) and the various substrate/geotechnical conditions encountered in dredging practice in Western Australia.

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8 Appendix

Appendix 1. List of dredging projects and documents reviewed as part of this study. The project identifier number (ID) and document identifier number are used in the tables within the body of the report.

Project identifier number (ID)	Project name(company, project name, location, state)	Document identifier number (ID)	Document reference
1	Lanco, berth 14 expansion, Bunbury, WA	1	Wave Solutions (2012). Bunbury Port Berth 14 Expansion and Coal Storage and Loading Facility - Technical Report 4: Hydrodynamic and Sediment Transport Modelling. Prepared for Lanco Resources Australia Pty Ltd.
2	BHP, Outer Harbour project, Port Hedland, WA	2	APASA (2009). Quantum Project: Modelling of the Dredge and Disposal Programme. Prepared for Sinclair Knight Merz.
2	BHP, Outer Harbour project, Port Hedland, WA	3	SKM (2011). Port Hedland Outer Harbour Development: Sampling and Analysis Plan Implementation Report. Revision 3.
3	API, Anketell Port, Anketell Point, WA	4	APASA (2010). Anketell Point: Marine Environmental Modelling. Prepared for: API Management Pty Ltd.
4	Chevron, Wheatstone project, Onslow, WA	5	DHI (2010). Wheatstone Project Dredge Spill Modelling. Appendix B: LWI and DHI Spill Rate Assessments. In: Chevron Australia Pty Ltd (2010) Technical Appendix Q1: Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project.
4	Chevron, Wheatstone project, Onslow, WA	6	URS (2010). Sediment Quality Assessment - Wheatstone Dredging Program. Appendix Q5 in: Chevron Australia Pty Ltd (2010) Technical Appendices Q2 to Q5 - Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project. July 2010.
5	NQBPC, Abbot Point Port, Abbot Point, QLD	7	GHD (2009). North Queensland Bulk Ports Corporation Ltd - Report on Proposed Abbot Point Multi Cargo Facility: Hydrodynamic and Sediment Transport Modelling. December 2009.
6	Pilbara Iron, Port of Dampier, Dampier, WA	8	GEMS (2005). Dredge Plume Modelling - Port of Dampier Dredging Phase B. GEMS Report No 2005/391. Prepared for Pilbara Iron.
7	Woodside Energy Ltd., Pluto LNG development, Dampier, WA	9	APASA (2007). Pluto LNG Development - Sediment Dispersion Study: Methods for Revised Dredge Modelling with the Inclusion of Sediment Re-suspension. Draft Report. Appendix D in: Woodside (2007) Addendum to Public Environment Report/Public Environmental Review Supplement and Response to Submissions.
7	Woodside Energy Ltd., Pluto LNG development, Dampier, WA	10	MScience (2007). Pluto LNG Development - Marine Baseline Studies: Final Report. Report MSA61R14. Prepared for: Woodside Burrup Pty Ltd.
7	Woodside Energy Ltd., Pluto LNG development, Dampier, WA	11	APASA (2006). Pluto LNG Development - Sediment Dispersion Study: Dredging Operations Associated with Construction of a Navigation Channel, Installation of a Subsea Gas Export Trunkline and Disposal of Spoil. In: Woodside (2006) Pluto LNG Development - Technical Report.
8	Department of State Development, Browse LNG precinct, James Price Point, WA	12	Department of State Development (2010). BLNG Precinct Dredging and Spoil Disposal Assessment. Appendix C-13 in: Department of State Development (2010) Browse Liquefied Natural Gas Precinct Strategic Assessment Report. . (Department of State Development, Government of Western Australia., 2010).
8	Department of State Development, Browse LNG precinct, James Price Point, WA	13	Department of State Development (2012). BLNG Precinct - Section 43A Application - Change in Dredging Volumes., (2012).
9	Gladstone Ports Corporation, Gladstone Western Basin development, Gladstone, QLD	14	Witt, C. Teakle, I and Jorissen, J., (2009) Gladstone Western Basin EIS – Numerical Modelling Studies. Gladstone Western Basin Dredging and Reclamation EIS. BMT-WBM Oceanics Australia Report R.B17382.002.02 to Gladstone Port Authority, September 2009.
10	INPEX,	15	Wallingford, H (2010). Ichthys Gas Field Development Project - Dredging and Spoil Disposal Modelling. Report EX 6219. INPEX Document Number C036-AH-REP-0067, Release 5.0.

			Appendix 13 in: INPEX Browse Ltd (2010) Draft Environmental Impact Statement.
11	Chevron, Gorgon Development, Barrow Island, WA	16	GEMS (2008). Chevron Australia Gorgon Development - Dredging Simulation Studies to Support the PER for the Revised Proposal. Appendix E: Dredge Plume Modelling Report for the Revised Marine Infrastructure. In: Chevron (2008) Gorgon Gas Development Revised and Expanded Proposal - Public Environmental Review: Appendices.
12	Port Hedand Port Authority, SW Creek, Port Hedland, WA	17	Cardno (2010) Port Hedland South-West Creek Dredge Plume Modelling. LJ15011/Rep1017p Version 4. Prepared for Port Hedland Port Authority. 4 November 2010.
13	Oakajee Port and Rail, Oakajee Port development, Oakajee, WA	18	APASA (2011) Oakajee Port and Rail: Sediment Plume Modelling. Final Report Rev. 1 - 10/03/2011 prepared for Oceanica Consulting Pty Ltd. and OP&R.
14	Dampier Port Authority, Dampier Port Upgrade, Dampier, WA	19	APASA (2009) Dampier Port Authority: Marine Environmental Modelling. Final Report prepared for Dampier Port Authority. 17 December 2009.
15	Fremantle Port Authority, Fremantle Outer harbour project, Cockburn Sound, WA	20	Fitzpatrick, N., Burling, M. and Bailey, M. (2009) Modelling the marine environmental impacts of dredge operations in Cockburn Sound, WA. Report prepared for Fremantle Ports and Oceanica Consulting Pty Ltd.