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Generation and release of sediments by hydraulic dredging: a review

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WAMSI Dredging Science Node

Report

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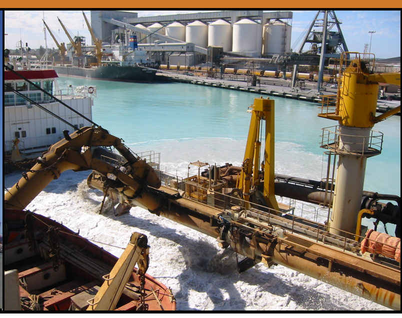
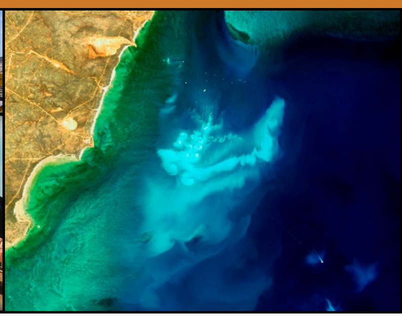


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WAMSI Dredging Science Node

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: Cutter Suction Dredge *Leonardo da Vinci* loading into the hopper of the Trailer Suction Hopper Dredger *Nina* during the Geraldton Port Enhancement Project. (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: Hopper of the Trailer Suction Hopper Dredge *Nina* showing overflow through the stand-pipe during the Geraldton Port Enhancement Project. (Source: OEPA)

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Executive summary

This report presents a literature review on particle generation when soil or rock material is subjected to dredging processes, the introduction of the particles into the water column (dredge-induced resuspension) and the early stages of dredge plume development. Knowledge in these areas is required to specify suspended sediment source terms for input to dredge plume prediction models that are used in environmental impact assessment of dredging proposals. The report focuses on the two types of hydraulic dredgers that are most commonly employed in major dredging projects in Australia, namely the trailing suction hopper dredger (TSHD) and the cutter suction dredger (CSD). The report responds to Task 2.1 of the WAMSI Dredging Science Node Science Plan (Masini et al. 2011).

Dredge-induced sediment generation

Disintegration of soil or rock material may occur during the excavation, mixture formation and hydraulic transport stages of dredging operations, leading to an increase in the mass fraction of small particles in the dredged material.

From an environmental perspective, an increase in the mass fraction of fines (small particles with low settling velocities) in sediment released from dredging activities to the marine environment will generally lead to an increased sediment resuspension rate and to dredge plumes of greater extent and intensity.

Barber et al. (2012) reviewed available knowledge on the disintegration of material dredged by cutter heads and its attrition during hydraulic transport through pipelines and pumps. They found that information on the processes of material breakdown during dredging is limited and the ability to predict the particle size distribution (PSD) of material released into the water column by dredging activities is not well developed, particularly for some cohesive soils and rock materials.

There is currently very little published field data that documents PSD development in dredged material at various points along the full-scale dredging production line (Ngan-Tillard et al. 2009). Field data sets are needed to validate the scaling of results of material attrition tests conducted in the laboratory and to optimise the laboratory test parameters for a range of dredging applications.

Sedimentation in hoppers and overflow

Typically, the predominant source of fine sediment released by TSHD operations (or by other dredging operations with hydraulic loading to a hopper) is from the hopper overflow discharge. It is important therefore to develop an understanding of the processes that operate within the hopper and the way they govern sedimentation and overflow.

Hopper processes have been investigated by conducting laboratory experiments and by taking measurements aboard TSHDs during hopper loading (Van Rhee 2002b, Ouwerkerk et al. 2007). These investigations have revealed the influence of density effects on flow within the hopper. The high sediment concentration mixture pumped into the hopper, because of its excess density, descends vertically, impacts the sediment bed, forms a scour hole, and spreads rapidly across the hopper bed as a density-driven current. Sediment is deposited from this spreading density current, causing the bed level to rise. Finer fractions that do not settle out move into suspension in the overlying water column and develop a vertical profile of suspended sediment concentration. As water overflows the hopper weir it carries with it a load of predominately fine sediment particles.

Van Rhee (2002b) developed a two-dimensional (width-averaged) numerical hopper process model to simulate the sediment flux in the overflow. The 2DV model was validated using both laboratory-scale test results and hopper measurements during full-scale dredging of sandy material.

These laboratory, field and numerical modelling investigations have shown that sediment concentration and PSD in the overflow depends primarily on the volume rate, sediment concentration and sediment size characteristics of the inputs to the hopper, the dimensions of the hopper, and the configuration and control of the loading and overflow systems (Van Rhee 2002b, Ouwerkerk et al. 2007, Lloyd Jones et al. 2010).

There is generally sufficient understanding of hopper processes and an adequate ability to predict losses via the overflow when dredging non-cohesive sediments. However there is greater uncertainty in overflow predictions when dredging cohesive soil or cut rock material. Factors which contribute to this uncertainty include: the limited capacity to measure or predict the breakdown of material during dredging and hydraulic lifting to the hopper (HR Wallingford 2013b), and to account for changes in turbulence levels and density effects when the material entering the hopper consists of a mixture of particles ranging from fines up to large pieces.

Sediment release by TSHDs

Field measurements, laboratory experiments and numerical modelling have been used to investigate individual sources of sediment resuspension from TSHD dredging activities and the behaviours of the dredge plumes that are generated by these sources.

Rates of sediment release in hopper overflow discharge are generally the largest source rates of sediment resuspension from TSHD dredging activities. Propeller-induced erosion of bed material may also constitute an important resuspension source when the TSHD is operating with limited under-keel clearance (e.g. Spearman et al. 2007, HR Wallingford 2013b). By comparison, sediment release rates from drag head disturbance of bed material are generally reported to be insignificant (e.g. Burt & Hayes 2005, HR Wallingford 2013a).

The rate of propeller-induced bed erosion depends on the bed shear stress exerted by the propeller jet and on the nature of the bed material (e.g. HR Wallingford 2010b). The bed shear stress depends on the effective water velocity close to the bed and on a friction factor which varies with bed roughness. The effective water velocity close to the bed is determined by a range of parameters, including: propeller diameter; applied power; distance from the propeller shaft to the seabed; speed of the vessel; and ambient current velocity. Sediment resuspended as a result of bed erosion is generally considered to behave as a passive plume.

The discharge from the TSHD hopper overflow pipe contains a significant concentration of predominantly fine-grained sediment and its bulk density exceeds that of seawater. The overflow discharge generates a negatively-buoyant, dynamic plume which descends rapidly through the water column while being advected by the ambient current flow (e.g. Spearman et al. 2011). The dynamic plume entrains surrounding seawater as it descends and this reduces the sediment concentration, excess density and rate of descent of the plume.

If the cross-flow (i.e. the ambient current relative to the moving TSHD) is strong and the water depth large enough, then the dynamic plume mixes with the surrounding water and transitions to a passive plume before it reaches the sea bed.

However, if the cross-flow is weak and the water sufficiently shallow, then the dynamic plume descends to the sea bed and forms a bed plume (i.e. a density current on the seabed) which spreads while being swept downstream by the ambient current. Sediment progressively settles out of the bed plume, reducing its excess density and its spreading rate. Eventually, the remnants of the decaying bed plume are mixed into the overlying ambient water and a passive sediment plume is formed near the sea bed. This mixing may be driven either by ambient currents and waves, or by other influences, such as the propeller jets (e.g Aarninkhof et al. 2010).

Observations and measurements (e.g. Nichols et al. 1990, Whiteside et al. 1995, John et al. 2000) have demonstrated that, close to the TSHD, some of the sediment from the descending overflow plume can be mixed into near-surface waters. Fine particles in the resultant passive surface plume can remain suspended for hours as they are transported far from the source location by ambient currents.

Recent advances in the ability to accurately simulate the early stages of TSHD dredge plume development (e.g. De Wit 2010, 2015) have led to a systematic investigation of the factors that govern surface plume formation. Several of these factors are specifically related to the operations of TSHDs. They include: dredging speed; water depth; location of the overflow discharge pipe; propeller action; pulsing of the overflow discharge and the entrainment of air bubbles into the overflow (De Wit et al. 2014a, De Wit et al. 2014b, De Wit 2015).

Field measurement protocols have been developed to quantify individual sources of sediment release from TSHDs and to estimate the settling characteristics and mass flux of suspended sediment feeding into the far-field dredge plume (e.g. HR Wallingford & Dredging Research Ltd 2003, Aarninkhof 2008, Breugem et al. 2009).

This has led to the collection of high quality data sets with which to test process-based numerical models of dredge-induced sediment resuspension, near-field plume behaviour and suspended sediment source terms for input to far-field dredge plume models (e.g. HR Wallingford 2013a).

However the number (and particularly the range) of fit-for-purpose data sets that are available to test and validate these models is still limited, considering the wide range of variables (parent material, site conditions, work methods and dredger operating characteristics) that are commonly encountered in dredging projects.

Sediment release from CSDs

CSDs use a rotating cutter head equipped with blades and teeth to break and excavate *in situ* soil or rock material. The blades guide the material into the cutter head where it is mixed with sea water and hydraulically removed through a suction line and centrifugal pumps. For typical CSD operations (with pumping to settlement ponds) most of the sediment resuspension and turbidity around a CSD comes from the action of the cutter head.

Measurements during full-scale CSD dredging operations and laboratory-scale cutter head experiments have been used to study fine sediment resuspension around cutter heads and its dependence on *in situ* material characteristics, site conditions (including currents and waves), dredging equipment and operational parameters. Henriksen (2010) reviewed the published studies and summarised the major findings. Yet, despite the knowledge acquired, major gaps in understanding still persist.

Most published field measurement campaigns have been for maintenance (navigational) dredging of sediments ranging from sandy silts to clays with high water content. Field investigations of sediment resuspension from cutter heads have rarely been reported in the published literature over the past ten to fifteen years, despite the advent of improved measurement protocols and technologies.

Most published laboratory-scale cutter head resuspension experiments have used fine to medium sands. They have been conducted in closed tanks (with no water through-flow) and so they have been unable to investigate the influence of ambient currents on resuspension and plume development.

For soils, the soil type, grain size distribution and *in situ* solids concentration are important parameters that influence fines resuspension around the cutter head (Hayes et al. 2000). For hard material that needs to be cut, the proportion of fines generated as a result of the cutting and mixture formation processes is important. Settling characteristics of released sediments are critical determinants of effective resuspension rates and dredge plume development from CSD operations.

Hayes and Wu (2001) proposed a semi-empirical model to predict the mass rate of suspended sediment that feeds the far-field dredge plume from cutter operations. Specified inputs required by the model are the ‘resuspension factor’, the fraction of fines in dredged material introduced to the water column and the mass rate of *in situ* material removed by dredging. The ‘resuspension factor’ is defined as the mass rate of sediment suspended into the water column relative to the mass rate of sediment removed via dredging. Hayes and Wu (2001) and Hayes et al. (2000) calculated resuspension factors for cutter head dredging operations in mainly silt/clay sediments at five different sites. The numerical range in the resuspension factors derived for each site was very large. However, based on these data sets, Hayes and Wu (2001) concluded that a conservative characteristic resuspension factor for small cutter heads dredging weakly consolidated, fine-grained sediments is about 0.5 per cent. Empirically-derived resuspension factor values for large cutter heads used on CSD capital dredging operations have not been found in the published literature.

Henriksen (2010) reported the development of a numerical simulation model of sediment release and near-field mixing about the cutter head. Operating parameters incorporated into the model included: cutter rotational velocity; suction flow rate; cut type (overcutting, undercutting); thickness of cut; ladder angle; and swing speed. The model simulations were broadly comparable to results from laboratory-scale testing and selected field trial data. Further work is required to improve process representation in the model. For example, little is understood about the turbulent zone around the cutter head and its interaction with ambient currents.

More generally, there is a need for sediment resuspension and plume development data sets across a broader range of CSD dredgers, work methods, soil and rock types and site conditions. The data sets will be used to: better document the influence of these factors on sediment resuspension from CSD operations; improve understanding of resuspension processes; and develop, calibrate and validate improved models of sediment resuspension and dredge plume development from CSDs.

Suspended sediment loss from dredge material placement operations

Dredged material loaded to a TSHD or hopper barge is typically transported and placed at a designated offshore site. The vessel is unloaded by opening doors or valves in the base of the hopper. The unloaded vessel then returns to the dredging site to reload. This cycle is repeated many times during the course of the dredging campaign, giving rise to a series of dredged material disposal events at the placement site which typically occur at intervals of several hours.

For each disposal event, a portion of the dredged material released from the hopper is entrained (resuspended) into the surrounding water column, while the remainder deposits rapidly on the sea bed. The resuspended material consists mainly of lighter particles which form a passive plume whose behaviour is governed by the ambient hydrodynamics and by particle settling.

Sediment resuspension generated by dredged material disposal events is generally less than 10 per cent of the disposed material load according to a range of available estimates from the literature.

Laboratory experiments, full-scale field measurement trials and numerical modelling simulations have been used to investigate sediment resuspension from dredged material disposal events. Important factors affecting sediment resuspension (expressed as a percentage of the dredged material load) have been found to include: soil type; hopper load characteristics (volume, bulk density and PSD); hopper load discharge rate; the steadiness or unsteadiness of the discharge; vessel speed during disposal; the speed and vertical shear of ambient currents; clearance between the vessel hull and the seabed; and the formation and decay of a bed plume following impact with the sea bed.

Several field data sets, collected soon after fine-grained sediment disposal events, initially showed the presence of a vertical column of resuspended sediment which subsequently moved with the current, dispersed and settled to form of a slowly dissipating turbidity cloud close to the sea bed, while turbidity in the mid and upper water column dissipated more rapidly.

From a broader perspective, there are additional phenomena, processes and timescales that need to be considered when assessing the pressures imposed on marine biological communities as a result of sediment resuspension at a dredged material placement site (e.g. Ferry 2003). These include:

- the cumulative sediment resuspension and plume generation from an extended sequence of disposal events;
- the accumulation of fines in bed sediments at the placement site from multiple disposal events;
- erosion and resuspension of the accumulated fines and their transport beyond the boundaries of the placement area;
- winnowing of fines from the sea bed surface by typical moderate to low energy wave and current conditions, leaving an upper layer of coarse material that protects underlying accumulated fines from being resuspended;
- mobilisation of an upper layer of coarse surface sediments by less frequent high energy wave and current conditions, exposing underlying accumulated fines to resuspension;

- other bed processes (e.g. consolidation of dredged material after placement and wave-induced fluidization) which may make the sea bed more or less resistant to erosion; and
- the time scales of these phenomena and processes can range from minutes to years and can extend beyond the duration of the dredged material disposal operations.

Considerations for predicting and managing the impacts of dredging

Direct impacts of dredging occur predominantly within and immediately adjacent to infrastructure footprints where dredges excavate the seabed and where rock armour and spoil is dumped.

Dredge plumes comprising the finer fractions of sediments introduced to the water column by dredging activities may be transported by ambient currents well beyond the zone of direct impact. Indirect impacts arise when benthic communities are sufficiently exposed to dredge plumes and are subjected to levels of suspended sediment or sediment deposition (and to consequential pressures, for example reduced light availability) that exceed natural tolerances of the benthic organisms. These plume-related environmental pressures and impacts occur at greater distances from the dredging activities than do the direct impacts.

The goal for the environmental management of dredging projects is to limit marine ecological impacts as much as practicable and to ensure that approved environmental protection outcomes are achieved.

Environmental management requires knowledge of the bathymetry, oceanography and meteorology of the region and an understanding of the geology, sedimentology, benthic community distributions and key environmental baseline conditions within the area of potential influence of the dredge plumes. Environmental management is strongly linked with project planning and design through decisions on the quantities, distribution and characteristics of the material to be dredged as well as the selection of the dredging equipment and operational work methods.

Environmental impact assessment (EIA) is used to support decisions on whether the project may proceed. EIA is based on predictions of environmental impacts and judgements about the degree to which monitoring and management strategies during project execution are likely to be effective at controlling impacts.

Impact prediction requires:

- modelling which provides far-field dredge plume simulations to assess the relevant spatial and temporal scales of suspended and deposited sediment that could occur as a result of the proposed dredging activities; and
- a knowledge of impact thresholds for suspended and deposited sediments that trigger adverse marine ecological responses.

Environmental monitoring to quantify dredging-induced environmental pressures and ecological impacts should be conducted during the dredging project and continued for some period after its completion. The monitoring data should be designed to:

- calibrate and validate the dredge plume model so that it can be applied with confidence at the project site as an environmental management tool which enhances the value of the field measurement data;
- provide feedback to management so that contingency measures may be implemented in a timely fashion if dredge-induced pressures or impacts are detected to be in excess of agreed or approved levels;
- characterise environmental pressures and cumulative ecological impacts resulting from the dredging at key stages of the project, as well as impact recovery times following project completion; and
- determine whether the cumulative ecological impacts comply with approved environmental protection outcomes and how they compare with best practice aspirational management targets defined during the environmental impact assessment and project approvals processes.

Furthermore, the monitoring should be designed to furnish datasets that enable ongoing learning about the cause-effect relationships and underlying processes linking dredging activities, dredging-induced environmental pressures and ecological impacts. Corporate commitment to sharing with the dredging research community the monitoring datasets from individual dredging projects will lead to accelerated learning, improvements in impact prediction methodology, greater certainty in decision-making and a streamlining of monitoring requirements.

Management and prediction of dredge plumes at source

A key priority for the environmental management of dredging projects is to reduce as far as practicable environmental pressures from dredge plumes on benthic marine communities. One way of doing this is to reduce the spatial distribution and intensity of dredge plumes by reducing the dredge-induced source rates of fine, suspended sediment particles that can be advected over long distances by ambient currents.

The source rate of suspended sediment for the far-field dredge plume depends on:

- the *in situ* material PSD and its development as the material is processed by the dredging equipment;
- the mass rates, settling velocity distributions and locations of sediment introduced ("resuspended") to the water column by dredging activities; and
- near-field dredge plume processes that determine the fraction of the dredge-induced resuspended sediment that remains in suspension and feeds into the far-field dredge plume.

Passive suspended sediment transport models are used to simulate far-field dredge plume dispersion for environmental impact assessment and environmental management of dredging projects. Key inputs to these models are the sediment source terms, which do not refer to the sediment release rates directly at the dredger, but rather to the suspended sediment flux that remains available for passive transport at the end of the dynamic phase of plume development. These source terms are specified by: (a) the horizontal mass flux of suspended sediment; (b) its vertical distribution through the water column; and (c) a representative settling velocity for each sediment fraction represented in the model. The source term for a far-field dredge plume simulation varies with location and time in accordance with an actual log or simulated schedule of dredger locations, operations, sediment characteristics and site conditions encountered.

Source terms for far-field dredge plume simulations may be estimated empirically on the basis of field measurements of sediment flux through cross-sections of the plume, or from numerical source models. The source models represent the physical processes which govern (a) the introduction of sediments into suspension by dredging and (b) near-field dredge plume behaviours. These are the processes that ultimately determine the flux of suspended sediment that feeds into the far-field dredge plume. Source models require the input of basic information on the dredging equipment, dredge operating parameters, material characteristics and other site conditions.

Field data acquisition protocols and measurement techniques (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) have been developed to improve the quality, consistency and completeness of the datasets used for empirical source estimation and for the calibration and validation of process-based source models. Both individual sources of sediment resuspension around dredgers (e.g. hopper overflow, propeller-induced bed erosion) as well as the combined source to the far-field plume are addressed.

Available information indicates that source rates may vary significantly both within and between dredging projects because of the large number of possible combinations of *in situ* material, dredging equipment, work methods, dredge operating parameters, bathymetry, current and wave conditions. Source estimates or predictions made at one location, time or dredging situation may not necessarily be applicable or transferable to another (Bridges et al. 2008).

Several field measurement programs for dredge plume source estimation have been described in the published literature (e.g. Whiteside et al. 1995, Jansen 1999, Aarninkhof 2008, Henriksen 2010, Spearman et al. 2011). The actual datasets are not always publically available, however, and the number of combinations of material, site, equipment and operating characteristics and the source types they encompass is still limited. Uncertainties and gaps in the data collected have in some cases reduced the value of the field measurement programs. Further full-scale dredging trials and high quality data sets are needed for empirical source estimation and source model validation purposes, particularly for material, site and dredge operating combinations that have not yet been addressed.

In the context of EIA, the source term estimates must be made prior to the commencement of the dredging project. For proposed dredging sites where there are no previous field datasets for dredge-induced sediment resuspension, therefore, the source term estimates must, out of necessity, be guided by empirical estimates derived from other sites or by using process-based source models which have been calibrated and validated at other sites. To have confidence in the source term estimates for the proposed project they should be guided by data derived from sites that have similar characteristics to the proposed dredging site, and where similar dredging equipment and methods have been used.

Becker et al. (2015) describe and provide worked examples of a general desktop method of estimating source rates for far-field dredge plume simulations, as used in the dredging industry. Broadly speaking, this method is comprised of four stages:

- analysis of the dredging work method for plume sources;
- assessment of the total amount of available fines;
- distribution of the available fines across the work method elements and derivation of far field model source terms; and
- appropriate application of source terms on the computational grid of the far-field dredge plume model.

Predictive estimates of dredge plume source terms are often based on a range of assumptions and may therefore involve a considerable degree of uncertainty. For example, assumptions may be required in respect of: the fines fraction in cut material when dredging hard rock; and the percentage of the available fines in the cut material that are resuspended and contribute to the far-field plume. The adequacy of source term predictions made at the stage of EIA can only be conclusively tested by comparing them to estimates based on field measurement once the dredging project has commenced.

It is therefore sound practice to conduct mobile sediment flux monitoring of the dredge plume combined with on-vessel measurements once the proposed dredging project has commenced (Becker et al. 2015), as this provides a unique opportunity to test the source term predictions and to assess the source term estimation method under a new set of dredging conditions.

The sharing of these datasets with the wider dredging research community will permit more rapid development and more extensive testing of dredge plume source models so that, in the future, they may be more confidently applied over a wider range of dredging conditions to make realistic and verifiable predictions. That in turn should lead to an improvement in dredge plume prediction and a rationalisation of the plume monitoring effort required.

Geological and geotechnical surveys and site assessments

For any dredging project, the understanding of the material to be dredged, its volume, distribution, variability, geotechnical properties and an expert assessment of how it behaves when dredged, transported, placed or resuspended into the water column is vital to determining preferred dredging equipment and work methods, estimating production rates and deciding how best to mitigate dredge plume pressures and environmental impacts.

Various considerations relating to geological and geotechnical surveys and site assessments for dredging projects can be found in Bailey et al. (2009), Bakeer et al. (2010), Kinlan and Roukema (2010), PIANC (2000), Spigolon

(1993b) and Stone (1992). Costaras et al. (2011) discusses site and geotechnical investigation requirements for assessing the environmental effects of dredging.

Generation of fine particles by material attrition during hydraulic dredging

The degradation of material into finer particles due to the action of mechanical and hydraulic forces during dredging has been discussed in section 3. This phenomenon, referred to as dredge-induced material attrition, increases the fines fraction of the dredged material, increases the mass rate of fines released to the marine environment by dredging activities and results in dredge plumes that extend further from the source. By contrast, large lumps may be cut and clayballs formed by particle aggregation when highly plastic, cohesive clayey soils are dredged, and this may reduce the potential load of fines that would otherwise be released into the water column.

Dredge-induced material attrition may occur during excavation, mixture formation and hydraulic lifting and transport. The development of the dredged material PSD depends primarily on the dredging equipment and work methods employed, operational parameters and the geotechnical properties of the material. However information on the degree of material attrition at various stages along the full-scale dredging production line is limited for a range of soil and rock materials and, in many cases, the ability to predict the PSD of dredged material introduced to the water column is not well developed (Costaras et al. 2011, Barber et al. 2012).

Instances of significant material attrition and fines generation due to dredging processes have been reported for the following material types:

- Weak to moderately cohesive, mixed-grain soils; the degree of attrition depends on the primary grain size distribution, the clay content, its plasticity and liquid index (e.g. Spigolon 1993a, Smith 2010).
- Angular, biogenic carbonate sands; significant attrition occurs during hydraulic transport from the dredging site to the material placement site (e.g. Ngan-Tillard et al. 2009).
- Low to moderate strength friable rock (e.g. mudstone) dredged by a CSD; significant attrition occurs during mixture formation within the cutter head, hydraulic lifting and transport (e.g. HR Wallingford 2010a).
- Coralline limestone and coral materials; very fine particles in the 10 micron range can be generated when these materials are dredged and/or hydraulically transported (Sciortino 2010).
- *In situ* limestone, when dredged by cutter head, may produce particles ranging from very fine silts to small rock pieces (Fitzpatrick et al. 2009). When harder limestone is encountered, the proportion of fines generated and released may increase (Lorenz 1999). This does not necessarily mean that the mass rate of fines released increases, however, since the overall production rate is reduced (Palermo et al. 2008). The fines in dredge plume samples taken close to an operating cutter head dredging hard limestone off the Western Australian coast were reported to be dominated by particles of less than 40 µm diameter (Mulligan 2009).

There is presently no well-established or recognised method of reproducing dredge-induced material attrition at a laboratory scale (Costaras et al. 2011, Barber et al. 2012). Standard tumbling tests do not adequately represent the solids concentrations, PSDs, particle trajectories or the forces experienced by particles while subject to dredging processes.

There is currently very little published data on the PSD development in actual dredged material at various points along the full-scale dredging production line (Ngan-Tillard et al. 2009). Such data are required to validate the interpretation of laboratory tests and to fine tune test parameters. In relation to dredge-induced material attrition the results of existing laboratory methods should be interpreted with considerable caution (Ngan-Tillard et al. 2009, Costaras et al. 2011, Barber et al. 2012).

Hopper processes and overflow

It is generally recognised that hopper overflow from TSHDs or hopper barges constitutes a major source of the fine sediments released from these vessels. Section 4 summarises published information on sedimentation in hoppers and sediment release via hopper overflow.

A reliable method for measuring hopper overflow source characteristics has been developed. This involves analysis of overflow samples taken from a well-mixed region near the lower end of the overflow pipe along with estimates of the volume rate of overflow (Aarninkhof 2008). This method is not a routine operational procedure, however, and requires trained personnel, customised installation of equipment as well as quality assurance and calibration of data, both from the test equipment and from the vessel's dredging operations monitoring system.

The sediment concentration and PSD in the overflow depend primarily on the dimensions of the hopper, the volume rate, sediment concentration and sediment size characteristics of the inputs to the hopper, and on the configuration and control of the hopper loading and overflow systems (Van Rhee 2002b, Ouwerkerk et al. 2007, Lloyd Jones et al. 2010).

Several numerical hopper process models have been developed to predict rates and characteristics of sediment discharge via the overflow (e.g. Van Rhee 2002b, Miedema & Van Rhee 2007, Spearman et al. 2011, HR Wallingford 2013a). These models require that the dredged material mixture entering the hopper be specified in terms of its volume rate, sediment concentration and PSD. The vessel's dredging operations monitoring system can generally be used to quantify the volume rate and sediment concentration inputs to the hopper, but not the PSD.

Currently there is no established method of directly measuring or analysing the PSD of the dredged material as it enters the hopper (HR Wallingford 2013b). The input PSD must therefore be inferred on the basis of other measurements and observations, and this can introduce uncertainties which may be significant for some rock, biogenic sediment and cohesive soil types for which the extent of breakage and dredged material attrition up to the stage of hopper loading is not well understood.

The numerical hopper process models have been tested against field and laboratory data, but only for a limited number of datasets. Van Rhee (2002b) recommended that similar datasets should be collected for different dredged sediment characteristics, hopper sizes and layouts to test hopper-overflow models over a wider range of conditions. When these models are used for predictive purposes, attention should be given to whether the models have been verified under similar conditions.

Sediment release from TSHDs

As discussed in section 5, TSHDs can give rise to important sources of sediment resuspension via:

- hopper overflow discharge; and
- propeller-induced erosion of material at the seabed when dredging or transiting in shallow water or with low under keel clearance.

<u>Hopper Overflow Source</u>

Some strategies and measures that could be considered to reduce the fine sediment source rate via the hopper overflow discharge are listed below:

- reduce the proportion of fines in the solids pumped into the hopper. This may be achieved by avoiding or reducing the dredging of:
    - *in situ* soils with a high fines fraction;
    - materials which produce a high fines fraction when dredged;
- optimise sedimentation of the material entering the hopper in order to reduce sediment release via hopper overflow. This may be achieved by:

- selecting a TSHD with hopper dimensions and hopper loading and overflow systems designed to provide adequate water residence times and reduced turbulence levels (e.g. Lloyd Jones et al. 2010); and
- reducing the flow rate of mixture pumped into the hopper at the beginning and end of loading, particularly for dredged material that has a significant fines fraction (e.g. Ouwerkerk et al. 2007).

The total amount of fines released at the dredging site could be controlled by avoiding excessive (uneconomical) periods of hopper overflow or by overflowing for periods less than the maximum economical overflow period, although the latter alternative would increase the overall duration of the dredging campaign. Hopper overflow is sometimes not permitted at all when dredging fine silts and clays in the vicinity of susceptible benthic habitats and communities.

Typically, the mixture discharged from the hopper overflow pipe into cross-flow (the velocity of the ambient current relative to the moving vessel) has a negative buoyancy flux and an initial downwards momentum flux. It forms a dynamic plume which initially descends rapidly through the water column. As discussed in section 5.2.1, the overflow discharge parameters and the cross-flow speed determine whether, in a given water depth, the dynamic plume will descend to the seabed or will be mixed into the surrounding water before reaching the seabed. For example, if the excess density of the mixture overflowed from the hopper is decreased, or if the crossflow speed is increased, the fine sediment plume from the overflow will be more likely to be mixed into the surrounding water column, and therefore more likely to remain in suspension and to supply the far-field plume (e.g. Van Eekelen 2007, Decrop et al. 2013).

De Wit (2015) investigated mixing and entrainment of the overflow plume into near-surface waters due to a range of additional factors specifically associated with TSHD operations (see section 5.2.2). The percentage of sediment flux from the overflow that is diverted into a passive surface plume can vary significantly from one dredging case to another (e.g. De Wit et al. 2014b). This percentage has environmental implications because it may influence the rate of suspended sediment supply to the far-field plume.

To limit mixing of the overflow plume into surface waters, and thereby to limit the source strength of the passive surface and far-field plumes, De Wit (2015) suggested:

- reducing the dredger speed (when the dredger is moving in still water or into the ambient current);
- minimising air bubble entrainment in the overflow discharge (e.g. by using a green valve in the overflow discharge pipe);
- limiting discharge pulsing of the overflow (e.g. by using a green valve and by taking other available ship-handling measures to reduce water level oscillations in the hopper);
- locating the overflow discharge toward the front of the dredger (i.e. further away from the ship's wake and propeller jet); and
- avoiding or minimising hopper overflow while dredging in shallow water.

Other measures which, if practicable, could help to limit the strength of the passive surface and far-field plumes during TSHD overflow may include:

- dredging with the current rather than into the current;
- scheduling dredging in areas when wave and swell conditions are relatively low; and
- avoiding or minimising overflow when the vessel has small under keel clearance. In respect to minimisation, relevant operational measures could include: (a) dredging in shallow areas only around high water tide conditions; and (b) designing TSHD dredging runs to start (with an unloaded hopper and low vessel draft) in shallow water so that overflow does not commence until the vessel has reached deeper water.

Finally, hopper overflow could be avoided when the dredger is operating directly upstream of nearby environmentally sensitive areas.

Propeller-induced bed erosion source

Impingement of the TSHD propeller jet on the sea floor gives rise to erosion and resuspension of seabed sediment and this may occur during dredging (both overflow and non-overflow periods) and when the dredger is in transit between the dredging and placement locations. The suspended sediment plumes generated by propeller-induced erosion are generally assumed to behave as passive plumes. As outlined in section 5, the contribution of these plumes to the far-field sediment source term depends on the sediment resuspension rate, the particle settling velocity distribution and the initial vertical distribution of the resuspended sediment. The resuspension rate depends on the effective water velocity close to the sea bed, the bed shear stress generated and the susceptibility of material on the seabed to erosion and resuspension (e.g. HR Wallingford 2010b).

Measures that could be considered in order to limit propeller-induced erosion rates and plume generation may therefore include:

- planning to avoid or minimise dredging or transiting in relatively shallow areas which have sediments with high fines content;
- avoiding as far as practicable small clearances between the propeller and sea bed (e.g. through appropriate selection of transit routes and, if necessary, operating in shallow areas only at high tide and with low vessel draft);
- dredging or transiting with slower vessel speed (i.e. with less propeller thrust);
- dredging or transiting with the current, rather than into the current; and
- dredging across current, so that interaction between the overflow plume and the propeller jet is reduced, thereby reducing mixing and resuspension of sediment from the overflow plume.

Note that most of these suggested measures have the potential to reduce the far-field source contributions from both the hopper overflow discharge and the propeller-induced resuspension.

Some simple ‘rule-of-thumb’ far-field source rate estimates for propeller-induced resuspension are based on order of magnitude scaling of estimates of the potential far-field source rate from hopper overflow with no green valve (HR Wallingford 2010a). These estimates do not fully take into account the bed material characteristics and do not account for the values of relevant operating parameters such as applied propulsion power and the vertical clearance between the propeller shaft and the sea bed. Source models are available for calculating effective near bed velocities, shear stresses and erosion rates (e.g. HR Wallingford 2010b, 2013a). Datasets that can be used to estimate propeller-induced sources and to calibrate and validate these source models should be gathered as part of each major dredging project, and the outcomes of these investigations compared against the initial source predictions. Datasets should be assembled for different soil types, vessel characteristics and site conditions so that the predictive models can be tested under a wide range of conditions.

Sediment release from CSDs

Sediment resuspension from the cutter head during CSD dredging operations has been the subject of numerous studies (Hayes & Wu 2001, Den Burger 2003, Henriksen 2010), as summarised in section 6.

Other sources of sediment resuspension from CSD operations occur when cut material is pumped to (or left on) the seabed, or when tailwater is discharged from a bunded site to which the dredged material has been pumped.

Typically, in the order of 20 to 30 per cent of material cut by the cutter head is not drawn into the suction pipe and this may increase up to around 50 per cent when cutting hard formations (Dekker et al. 2003, Den Burger 2003, Vlasblom 2005b). This is referred to as the percentage spill of material from the cutter head and is significantly influenced by (e.g. Lorenz 1999, Den Burger 2003, Palermo et al. 2008, Henriksen 2010):

- the nature of the *in situ* material;

- the design of the cutter;
- dredger operating parameters (including cutter rotation speed, suction intake speed, depth of cut, swing speed, cut type and ladder angle);
- the presence of impediments, such as debris, cobbles, boulders and obstructions;
- particle size distribution and density of the cut material; and
- other site conditions, including currents and waves.

Of the spilled material, a proportion contributes to the far-field plume, while the remainder (mainly coarser particles) will deposit locally on the seabed (e.g. Hayes & Wu 2001, Bridges et al. 2008). The source term for the far-field dredge plume will depend on (a) the mass rate and settling velocity distribution of material spilled by the cutter head, (b) the mixing of lighter fractions of the spilled material by a local zone of turbulent flow that is generated around, and for some distance downstream of, the operating cutter head, and (c) differential particle settling during passive suspended sediment plume transport, until the plume reaches a stage at which only fine particles remain in suspension that are capable of being advected over long distances as long as the velocity of the ambient current remains above a critical threshold (Lorenz 1999, Henriksen 2010).

From a management perspective, the sediment resuspension and dispersion from the cutter head depends on the material and site characteristics, the dredging equipment selected and the way in which it is operated. For example, excessive ladder swing speed or excessive rotation speed of the cutter head in relation to its suction capacity, or excessive depth of cut, may result in increased sediment spillage and resuspension (Anchor Environmental 2003).

Most published CSD sediment resuspension investigations have been in relation to the cutting of non-cohesive granular or fine, cohesive sediments (Anchor Environmental 2003, Henriksen 2010). Relatively little has been published in relation to fines resuspension for CSDs cutting other material types, including hard rock (Den Burger 2003).

Predictive far-field sediment source term estimates for the cutter head are often empirical in nature, being based either on an assumed percentage of the estimated rate of fines that become available in spilled material (e.g. HR Wallingford 2010a) or on the adaption of values for resuspension factors (Hayes & Wu 2001) derived from other sites. Understanding of the physical processes governing sediment release from the cutter head and near-field sediment transport is not developed to the point where process-based numerical models can be routinely used for far-field source term estimation (Henriksen 2010).

There have been significant recent developments in the technology of measuring suspended sediment plumes in the field (e.g. Land & Bray 2000, Smith 2010, Taylor et al. 2014). HR Wallingford and Dredging Research Ltd (2003) have provided field measurement protocols for estimating the magnitude of suspended sediment release from semi-stationary dredgers, including CSDs. However, cases where these modern technologies and protocols have been used to estimate far-field source terms for cutter heads are difficult to find in the literature.

Suspended sediment loss from dredged material placement

Dredged material loaded to a hopper barge or TSHD may be discharged at a designated offshore placement site. The vessel is unloaded by opening doors or valves in the base of the hopper. The unloaded vessel then returns to the dredging site to reload. This cycle is repeated many times during the course of a dredged material disposal campaign giving rise to a series of discrete discharges at the placement site at intervals of several hours.

Sediment resuspension from TSHDs or hopper barges discharging dredged sediment at sea has been discussed in section 7.

For each disposal event a portion of the dredged material load discharged is entrained (resuspended) into the surrounding water column forming a passive suspended sediment plume whose behaviour is governed by the ambient hydrodynamics and the particle settling velocities. The remainder of the discharged load deposits rapidly on the sea bed.

Published investigations suggest that the following measures and conditions may be conducive to limiting or reducing sediment resuspension from individual dredged material disposal events:

- discharging from a stationary vessel under weak ambient current conditions (e.g. Gensheimer 2010);
- rapid release of the material load from the hopper (Land & Bray 2000);
- high dry density of the material-water mixture in the hopper (Land & Bray 2000);
- coarse material (low fines content) in the hopper load (Land & Bray 2000, Gensheimer 2010);
- large dredged material load (Land & Bray 2000);
- in the case of cohesive material, encouraging clumping of fine particles, prior to release (Gensheimer 2010); and
- avoiding dredging material with high fines content.

Published investigations suggest that sediment resuspension from individual dredged material disposal events is generally less than 10 per cent of the disposed material load (Land & Bray 2000, Gensheimer 2010).

From a wider perspective, there are several timescales that need to be considered when assessing the pressures imposed on marine biological communities as a result of sediment resuspension from a dredged material discharge campaign (Ferry 2003). These include the timescales corresponding to:

- sediment resuspension and plume generation from individual disposal events;
- combined sediment resuspension and plume generation from an extended sequence of disposal events;
- the development of elevated levels of fines in sea bed sediments as a result of multiple disposal events;
- erosion of sea bed sediments with elevated levels of fines and the resuspension and transport of these fines beyond the boundaries of the placement area; and
- metocean variability and other factors which influence seabed erosion (e.g. consolidation of dredged material after placement and wave-induced fluidization).

The time scales of these phenomena and processes can range from minutes to years and in some cases can extend beyond the duration of the dredged material disposal operations.

1. Introduction

Some of the soil and rock material disturbed by dredging activities is released as particles into the water column and transported away from the source by ambient currents, giving rise to suspended sediment plumes. These plumes are characterised by above-background levels of suspended sediment concentration and turbidity, and by enhanced rates of sedimentation. The increased turbidity reduces visibility and light penetration through the water column. Marine biological communities sufficiently exposed to sediment plumes from dredging activity may therefore experience ecological impacts as a consequence of increased suspended sediment, turbidity and depositional pressures.

The potential for adverse impacts on benthic primary producer habitats and their associated marine communities from exposure to turbid plumes is now a world-wide concern. It is important to recognise that there are other factors (e.g. river inputs, cyclones, shipping and trawling activities) in addition to dredging which have the potential to resuspend sediments and increase turbidity.

When proposing and planning a dredging program it is critical to:

- estimate the relevant spatial and temporal scales of dredge-induced sediment resuspension; and
- determine the thresholds for suspended and deposited sediments that trigger adverse marine ecological responses.

Sediment transport models have been used in recent years to predict the trajectory, extent and intensity of dredge plumes and to support ecological impact prediction and proactive management of dredging projects. These dredge plume models require the input of quantitative suspended sediment source terms which specify temporal mass rates, settling velocities and spatial distributions of the sediments (resuspended by dredgers) that feed into the dredge plume.

The estimation or prediction of these source terms in advance of dredging has been challenging and a significant cause of uncertainty in applying these models in the context of environmental impact assessment, particularly for large capital dredging projects at locations with little or no previous dredging history.

This report presents a review of available knowledge on the generation of particle size characteristics when material is subjected to dredging processes, dredge-induced sediment resuspension and the early stages of dredge plume development. Knowledge in these areas is required to improve the ability to estimate and predict suspended sediment source terms for passive dredge plume models used for far-field plume simulations. The report focuses on the two types of hydraulic dredgers that are most commonly employed in major dredging projects in Australia, namely the trailing suction hopper dredger and the cutter suction dredger. The report responds to Task 2.1 of the WAMSI Dredging Science Node Science Plan (Masini et al. 2011).

Fine-sized particles tend to remain suspended for longer in the water column than coarse-sized particles. Particles released near the water surface tend to remain suspended for longer than similar particles released near the bed. Particles that remain longer in suspension can be transported further by ambient currents. An increase in the percentage of fine particles and in the temporal mass rate of sediment introduced into the water column by dredging activities will result in an increase in the extent and intensity of the dredge plume.

Attrition is a term that signifies the degradation or break down of material into finer particle sizes. Disintegration and attrition of dredged material may occur during the excavation, removal and hydraulic transport stages of dredging operations and this will lead to an increase in the fines fraction in sediment released from the dredging operations to the marine environment.

When dredged material is hydraulically loaded to hoppers or settling ponds the coarser sediments settle and deposit rapidly while fine-grained sediments with low particle settling velocities remain in suspension. Overflow from hoppers and discharge from settling ponds is generally directed to the marine environment and carries with it a load of predominantly fine-grained sediments.

Sediments are initially resuspended into the water column by mechanical and mixing actions and discharges from the dredger. The sources and source characteristics of dredge-induced sediment resuspension depend on the:

- dredging equipment (e.g. dredger type, geometry and specifications), work methods, operating parameters (e.g. flow rates, depth of cut), dredge cycles (e.g. loading, sailing and disposal times) and dredger downtimes;
- dredged material characteristics (e.g. settling velocity distribution);
- site conditions (e.g. bathymetry, sea bed geology, obstacles); and
- environmental conditions (e.g. currents, waves and water surface levels).

In the majority of dredging operations the material released is likely to comprise of a mixture of fine-grained cohesive material (containing silts and clays) and coarser non-cohesive material (e.g. sand and gravel). The non-cohesive material has primary grain sizes greater than 62 µm and tends to settle relatively quickly, driven by gravitational and inertial forces. Fine, cohesive sediment has primary grain sizes of less than 62 µm. After release from the dredger, particles in this size range tend to remain in suspension for longer durations than the non-cohesive material and to travel further away from the dredging area. However the transport and behaviour of the fine cohesive particles is also governed by electrochemical forces, biogenic influences, water velocity gradients and shear stresses as a result of which they may stick together to form larger, low density aggregates called flocs, although some of these may subsequently disaggregate (Das 1970, Gibbs 1983, Mehta 1989, Aijaz & Jenkins 1994). Floc formation enhances the settling and deposition rates of material from fine sediment plumes (e.g. Bundgaard et al. 2011, Smith & Friedrichs 2011).

Sediment particles that have settled out of the plume and deposited on the bed may later be resuspended into the water column under strengthened current and wave conditions that cause bed shear stress thresholds for erosion to be exceeded.

Dredge plumes undergo several stages of development and it is important to recognise these stages when interpreting dredge plume data or modelling dredge plume behaviour.

Sediment plumes can be classified as dynamic, passive or transitional (Winterwerp 2002, De Wit 2010, Decrop et al. 2013). Dynamic dredge plumes may arise from high concentration sediment-water discharges that are denser than the surrounding water. The transport and mixing of these plumes is strongly influenced by their initial discharge momentum, negative buoyancy and the ambient cross flow. The sediment particles and water in dynamic plumes tend to move together like a dense, bulk fluid and with a descent velocity that is typically much greater than the settling velocity of individual particles in the plume. Dynamic plumes retain their identity while they have excess density and momentum, but they weaken as a result of entrainment and plume dilution, sedimentation and turbulence dissipation, and ultimately they are mixed into the surrounding water by the ambient flow, marking the completion of their transition to a passive plume. A strong external mixing influence, for example propeller-induced turbulence, may hasten the transition and mixing of the dynamic plume.

Passive plumes consist of low suspended sediment concentration mixtures that have minimal density or momentum differences relative to the surrounding water. Sediment transport in passive plumes is governed by the ambient hydrodynamics and by the vertical settling velocity of the suspended particles. Passive plume behaviour occurs when the plume has moved beyond any localised turbulent flow generated by the dredging equipment and beyond the extent of any dynamic plumes.

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'. Particle flocculation, in some cases, may contribute significantly to the settling of plume material (e.g. Bundgaard et al. 2011) and may even determine the downstream extent of the near-field.

The horizontal flux, particle size distribution (PSD) and settling characteristics of suspended sediment in near-field plumes will change with distance from the source (or time since release) as some of the released material settles to the bed. The horizontal extent of the near-field will depend on the dredger, source characteristics, sediment type, ambient hydrodynamic conditions and water depth.

Once differential settling has occurred the suspended sediment plume reaches a stage at which 'only the fine 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 & 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.

Passive 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 and resuspension at the bed. Sediment transport calculations are made for several size classes (each with an assigned settling velocity value) which together represent the released sediment. Passive dredge plume models are not capable of simulating dynamic plume behaviour in the near-field because they do not include dynamic plume processes.

Not all of the sediment initially resuspended by the dredger necessarily reaches the far-field. Under the influence of dynamic plume and differential settling processes some material (including a proportion of the fine particles) may be deposited on the seabed and retained within the near-field. This needs to be taken into consideration when estimating or predicting source terms for far-field dredge plume simulations.

Source terms may be estimated from dredge plume and on-board data sets collected during dredging (e.g. HR Wallingford & Dredging Research Ltd 2003, Land et al. 2007, Breugem et al. 2009, Provis & Aijaz 2009). Uncertainties in these estimates (and difficulties with intercomparison of estimates from similar dredging operations) may arise due to a range of factors, including:

- the inherent variability of dredge-induced sediment resuspension;
- differences in site and environmental conditions;
- differences in measurement protocols used; and
- the quality and completeness of the data collected.

In the context of environmental impact assessment there is a need to estimate these source terms prior to the commencement of the dredging project. Bekker et al. (2015) describe a general method for estimating source terms for far-field dredge plumes as practiced in the dredging industry.

For proposed capital dredging in regions with little or no dredging history, there is an additional degree of uncertainty owing to the absence of local resuspension data from previous dredging operations. The availability of fit-for-purpose data sets obtained from like dredging operations with similar bed materials and site conditions then becomes critical. It is also sound practice to conduct mobile sediment flux monitoring of the dredge plume combined with on-vessel measurements once the proposed dredging project has commenced (Bekker et al. 2015), as this provides a unique opportunity to test the initial far-field source term predictions and assess the source term estimation method under a broader range of dredging conditions.

Overall, the number of dredge-induced sediment resuspension and source term data sets has increased significantly in recent years. However many of these are proprietary and their availability is restricted. Furthermore, there are some relatively common dredging situations (e.g. TSHDs dredging with low under keel clearance) that are not well represented by the available data sets. This highlights the need to continue to build and disseminate these data resources so that they are able to support the assessment of a broad range of dredging proposals.

In their framework for research to assess dredge-generated plumes, Burt and Hayes (2005) emphasized the importance of understanding physical processes, including those that govern the dredger source terms. The availability of high quality, fit-for-purpose field and laboratory measurement data sets will facilitate the growth in understanding of these processes and the development and calibration of improved dredge source term models (e.g. Spearman et al. 2007, HR Wallingford 2013b).

2. Major dredging equipment and operations

There are two broad categories of dredging equipment: hydraulic and mechanical.

Mechanical dredgers use various types of bucket, grab or clamshell to dislodge and excavate bed material through the direct application of mechanical force. The dredged material is then lifted mechanically to the surface and is typically loaded to a barge at nearly *in situ* densities (Palermo et al. 2008). The Backacter (or Backhoe) is one of the mechanical dredger types more commonly used for capital dredging projects in Australia.

Hydraulic dredgers promote the formation of dredged material and sea water mixtures which are pumped to a dredged material placement site or loaded into the hopper of a vessel which then sails to a placement site.

This review focuses primarily on the generation and release of sediments by hydraulic dredgers, in particular the trailing suction hopper dredger and the cutter suction dredger. These are the two most common types of hydraulic dredgers used for major capital dredging projects in Australia.

2.1 Trailing suction hopper dredger

A trailing suction hopper dredger (TSHD) is a self-propelled vessel equipped with one or two drag arms (each with an attached drag head), powerful pumps and a large compartment (the hopper) to store the dredged material (Figure 1). The drag arms are lowered so the drag heads can be trailed across the seabed where material is to be dredged. Suction induced by the dredge pumps generates a strong flow field about the drag head intakes. This flow field entrains particles of bed material. A solids-water mixture is formed, drawn in through the drag heads, up suction pipes in the drag arms and is pumped into the hopper. The coarser-sized solids deposit more rapidly inside the hopper to form a material bed, while some finer-sized particles remain suspended in water overlying the hopper bed. As dredging continues the surface level of the water in the hopper rises till it reaches the (adjustable) level of a weir. Excess water then leaves the hopper by overflowing the weir and is conveyed through an overflow pipe to a discharge point at the base of the vessel. The overflow discharge carries with it suspended solids (predominantly finer, more slowly settling fractions of the dredged material) that have not been retained in the hopper.

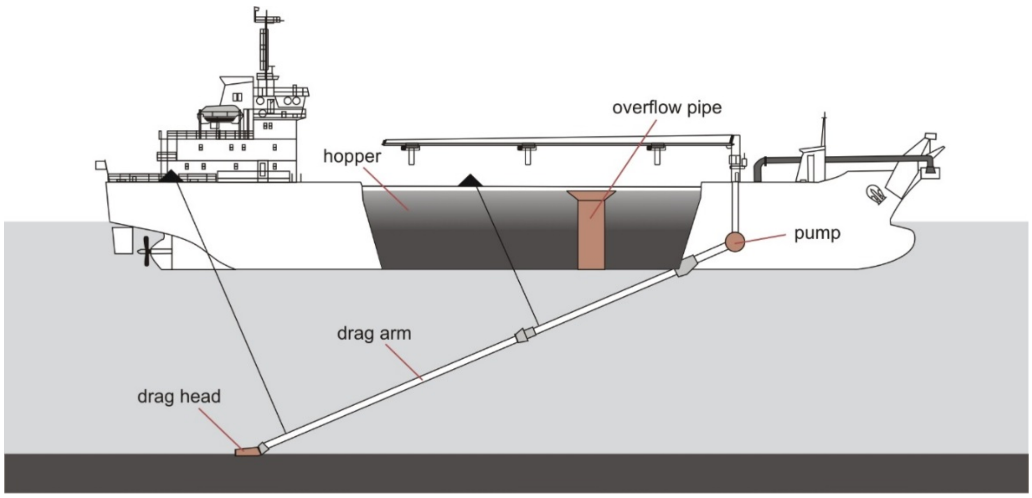

Figure 1. Trailing suction hopper dredger.

The 'environmental' or 'green valve' is a valve in the overflow pipe that can be adjusted to increase hydraulic resistance and smooth the flow of mixture from the hopper into the overflow pipe. This inhibits air entrainment and significantly reduces the air bubble content of the overflowed mixture discharged from the vessel. The sediments in the plume that forms from the overflowed discharge are therefore less susceptible to being mixed upwards into surface waters by rising air bubbles. The plume from the overflow is also denser (when air bubble content is low) and descends more rapidly to the seabed, carrying with it the overflowed sediments. Overall, the extent of the dredge plume and the total amount of sediment that remains suspended can be significantly reduced with appropriate use of the 'environmental valve' (e.g. Van Parys et al. 2001).

Overflow allows dredging and loading of the hopper to be continued for a longer time period. This enables a greater amount of solids to be deposited and stored within the hopper when dredging sand or coarser material. In the case of dredging very fine (and possibly contaminated) sediment, the dredge can be operated without hopper overflow to reduce the risk of adverse environmental effects.

At some point the sediment storage capacity of the hopper is reached or further loading of solid material becomes uneconomical. The suction pipes are then raised and brought back on board. For placement of the dredged material at sea the TSHD sails to the placement site, opens doors in the base of the hopper and releases the material, most of which descend to the seabed. For a land reclamation or beach nourishment programme the hopper bed material is slurried and pumped to its destination either through a pipeline or by projecting it through the air, a technique known as 'rainbowing'.

TSHDs are used for capital and maintenance dredging and also for sand and aggregate mining. They perform dredging while under way and are therefore suited to operating in relatively open areas with adequate water depths. They can function effectively under moderate swell conditions and can adapt to the presence of routine shipping operations. Notwithstanding the above, TSHDs can also work, conditions permitting, with an under-keel clearance as little as 0.5 to 1 m.

TSHDs are mainly used for dredging loose material such as sand, mud or gravel (Vlasblom 2005a, IADC 2014b). Problems may arise when dredging clay, either with congestion in the drag head or controlling the path taken by the drag head. Dredging of rock with a TSHD is normally inefficient and too expensive but can on occasions be justified for rock material that is sufficiently weathered or relatively soft. TSHDs are sometimes used to dredge hard material that has already been pre-treated (broken up and left on the seabed) by cutter suction dredgers. TSHDs are also sometimes used to dredge rock where other means of excavation are not feasible due to, for example, deep water or exposure to large swell and wave conditions. Rock dredging by TSHDs may require the use of specially designed, heavy drag heads fitted with ripping teeth and water jets (e.g. Neelissen et al. 2010).

2.2 Cutter suction dredger

A cutter suction dredger (CSD) is a pontoon or self-propelled vessel that uses a rotating cutter head equipped with blades and teeth to dislodge bed material (Figure 2, Figure 3). The cutter head is attached to an adjustable arm (the 'ladder') mounted at the front of the vessel. The ladder assists the cutting process by distributing additional weight to the cutter head. CSDs have one or more centrifugal pumps that create suction and generate flow toward the rear of the cutter head and into a suction pipe located in the ladder. Cut material and seawater is dragged into the suction pipe, lifted hydraulically to the surface and either loaded to a hopper barge or pumped to a placement site. CSDs normally have two spud poles that can be lowered and pushed into the sea bed to control the position of the vessel while dredging. The main spud is mounted on a spud carriage which enables it to be moved lengthwise along the vessel, while the auxiliary spud pole can only be moved vertically.

While working, the CSD pivots about the main spud which has been pushed into the seabed. A system of steel cables, anchors and winches is used to swing the vessel, ladder and cutter head from port to starboard, or vice versa. The swing of the cutter head moves it along a transverse arc as it cuts a layer of material at the work face. Overcutting (undercutting) occurs when the blade velocity at the top of the rotating cutter has the same (opposite) direction as the swing. The vertical incline of the ladder can be increased to lower the cutter head and cut the next layer down on the work face. The CSD is able to be moved forward up to a few metres at a time by pushing the main spud pole toward the back of the vessel. This manoeuvre, known as 'stepping', enables the cutter head to advance, when required, to stay in contact with uncut material at the work face. After the CSD has made several steps it becomes necessary to lift and return the main spud to the front of the spud carriage and, during this operation, the vessel is immobilised by pushing the auxiliary spud into the seabed.

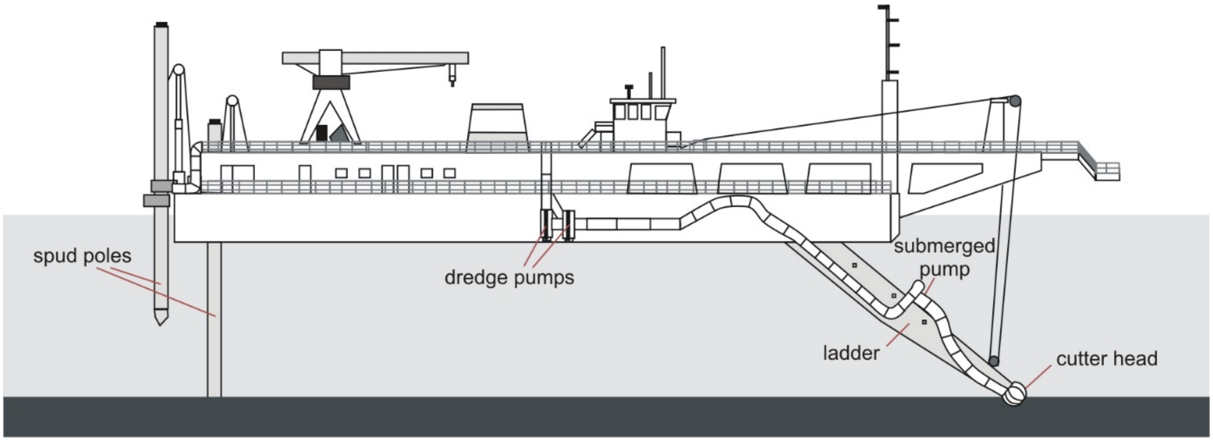

Figure 2. Cutter suction dredger.

CSDs cannot readily adjust their operations to allow shipping movements through the dredging area. The minimum dredging depth for CSDs is about one metre greater than the maximum vessel draft. The vessel draft is generally greater for CSDs with greater installed power.

Self-propelled CSDs generally have the ability to navigate independently, though they are semi-stationary when dredging. Even large CSDs cannot work in wave heights exceeding one metre (Neelissen et al. 2010) and few are capable of dredging in water depths greater than 35 m (IADC 2014a).

CSDs are not equipped with hoppers. The dredged material is therefore either discharged into a hopper barge or TSHD for transport and disposal at sea, pumped to a land-based site or beach renourishment area, or sometimes, in the case of rock, broken up by the CSD and placed on the seafloor for collection at a later time by other dredging equipment.

CSDs are used for dredging of cohesive or hard materials (such as stiff clays and rock) and dense, consolidated bottom sediments (PIANC 2009, IADC 2014a) although they are also capable of dredging soft muds and clays and unconsolidated sands (Vlasblom 2005b). They are often employed in capital dredging projects (e.g. construction of shipping channels or filling for land reclamation) where materials to be dredged require cutting, where the dredging is in shallow water or where the material is to be pumped to a nearby placement site (Bray 2008). The CSD provides an accurate method of dredging as excavation is limited to where the cutter head is deployed.

The main functions of the rotating cutter head are to cut and disintegrate the bed material and place it into the high velocity stream at the suction inlet in sufficient quantities (Turner 1996). Figure 3 illustrates the basic layout and components of a cutter head and shows the cutter head blades fitted with teeth. Cutter head diameters (i.e. at the cutter ring) range from 0.25 to 3.35 m (Hayes & Wu 2001, Den Burger 2003).

The design, geometry and fittings of cutter heads vary depending on the specific soil or rock types for which they are intended (e.g. PIANC 2000, Den Burger 2003, Vlasblom 2005b):

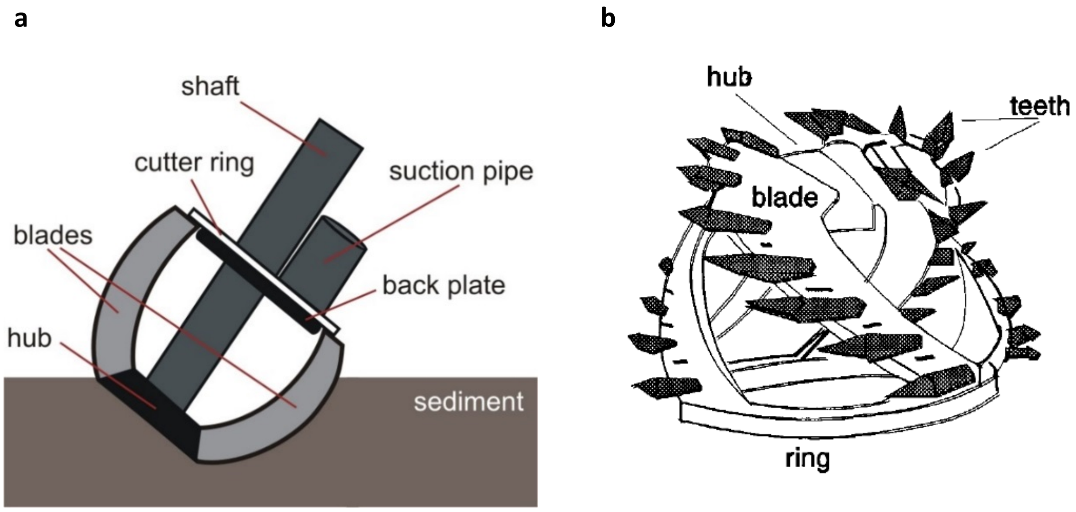

Figure 3. Cutter head: (a) configuration and components (from Henriksen 2009); (b) blades fitted with teeth (from Verhoef 1997).

- For cutting rock and hard material the cutter head must be heavy, robust and able to withstand very large impact forces on one or more teeth. The teeth will usually be in the form of pickpoints and should be readily replaceable. The blades to which these pickpoints are attached should guide the pieces of rock into the cutter head. The size of the fragments should not exceed the minimum passage dimensions of the pump. All components of the cutter head should be designed and constructed to withstand extreme wear.
- For non-cohesive, granular soils the cutter head will have blades and many replaceable teeth. The cutter head, especially the cutting elements, must be able to withstand wear. The cutter head profile should encourage good soil-water mixture formation.
- For cutting cohesive soils such as clays, the cutter head may have either plain or serrated blades. Multiple teeth (often in the form of chisels) may be attached to the blades. The cutter head will generally be round and ample in profile, open near the hub, and there may be fewer blades. This is to reduce the potential for blockage by large resilient soil lumps or clogging by strongly adhesive soil.

Considerable progress appears to have been made recently in the capability of CSDs to dredge hard material. PIANC (2000) stated that only a few CSDs are capable of working efficiently in rock with an unconfined compressive strength (UCS) of about 20 MPa unless the rock is closely fractured. However Wijma (2005) reported successful trials with CSDs working in hard rock materials, some with maximum UCS values greater than 60 MPa. The cutter heads were fitted with modern tooth systems and the CSDs had installed cutting power in the range 3000-6000 kW.

3. Dredge–induced sediment generation

Excavation by dredging may involve the cutting, ripping or disaggregation of bed material by mechanical or hydraulic forces. Further material breakdown may occur during hydraulic dredging as the solid-water mixture moves up the suction pipeline, through the centrifugal pump(s), and then is piped for discharge either to a hopper or directly to a placement site.

In some cases rock is first broken to pieces by cutter suction dredging, or by drilling and blasting, and left on the sea bed for later collection by a TSHD. Follow-up dredging by the TSHD leads to further disintegration of the recently-crushed rock material.

Costaras et al. (2011) summarised the mechanisms whereby material can be broken down by dredging operations as follows:

- mechanical breakage where dredging equipment (e.g. a cutter head) excavates the bed;
- impacts or contacts between fragments or particles (e.g. in pumps and pipelines);
- collisions or contacts of particles with pipe and pump surfaces; and
- erosion or abrasion due to the flow of water around fragments and grains.

Attrition is a term which signifies the degradation or break down of material into finer particle sizes as a result of collision, contact, erosion or abrasion. A measure of attrition is the percentage mass 'loss' of a particular sediment size fraction to smaller-size fractions.

Clearly, the PSD of material may be changed as a result of attrition and this may occur at various stages along the dredging production line. The nature and magnitude of these changes depend primarily on the type of dredging equipment, the work methods employed, operational parameters and the properties of the parent material.

From an environmental perspective it is important to be able to predict the development of the PSD as material is excavated, lifted and transported to its destination. Material released to the marine environment at different points along the dredging production line may have different particle size characteristics. The PSD and, more fundamentally, the settling velocity distribution of the material released strongly influences the spatial extent of the resulting dredge plumes (Swanson et al. 2004). However information on the degree of material disintegration during dredging is limited, particularly for rock material, and the ability to predict these changes is not well developed (Costaras et al. 2011, Barber et al. 2012).

3.1 Sediment generation during excavation

3.1.1 Excavation by trailing suction hopper dredgers

Excavation efficiency of TSHDs is strongly dependent on soil type, the available power and the way in which the drag head is equipped to break up the parent material (Vlasblom 2005a). These factors also influence the development of the dredged material PSD. When excavating with drag heads the *in situ* material can be considered in three broad classes:

- liquid soil types (silt and soft clay);
- non-cohesive soil types (sand and gravel); and
- cohesive soil types (firm clay and rock).

For excavation of fine-grained soils the Atterberg derived limits [plasticity index (PI) and the liquid index (LI)] are important (Vlasblom 2005a). Soils with a high PI have high clay content and those with a low PI are sandy, with low silt and clay content. Soils with intermediate PI tend to be silts. The liquid index determines if the material behaves like a fluid (and thus is easy to dredge by suction) or has a firmness (and thus has to be cut).

Excavation by drag head may occur (Spigolon 1993a) by:

- direct suction;
- erosion and entrainment; or
- cutting, ripping or scraping.

Which of these processes gives optimal production at the drag head depends largely on the soil type, its geotechnical properties, the design and operation of the drag head and the available power.

Direct suction

Direct suction during dredging excavation occurs when the sediment that enters the hydraulic suction pipe is at or very near its *in situ* density. Direct suction is possible with extremely soft cohesive soil or fluid mud with high silt and clay content, high liquidity index, high void ratio, low *in situ* density and very low *in situ* shear strength (Spigolon 1993a). No special drag head features are required.

These highly liquid soft soils and fluid muds are composed predominantly of fine particles that, if released to the water column, may potentially remain in suspension for considerable periods. If flocculation occurs, however, the material will settle more rapidly (Bundgaard et al. 2011, Smith & Friedrichs 2011).

Erosion and entrainment

Unconsolidated granular soils, free of cohesive fines, are readily eroded hydraulically (Spigolon 1993a). For erosion to occur, a flow along the seabed which picks up the particles and transports them under the drag head rim and toward the suction mouth must be present (Verschelde et al. 2013). This flow is created by a pressure difference between the inside and the outside of the drag head which is set up by the centrifugal pump of the TSHD. The pressure difference also generates vertical groundwater flow under the drag head, decreasing the effective stress in the soil and facilitating erosion. The minimum water velocity for traction or resuspension occurs for clean sands in the size range 200 to 400 µm (Spigolon 1993a). Coarser grains, because of their body weight, require more energy to be eroded and suspended. Strongly cohesive clay-rich soils require greater shear forces for their erosion and, to facilitate the removal of these soils, drag heads may also be equipped with water jets and mechanical cutters.

The eroded grains are entrained in a high volume, high velocity flow, forming a slurry which is drawn into the suction pipe (Spigolon 1993a, Vlasblom 2005a). Direct losses to the water column from excavating drag heads are normally very low (e.g. Coastline Surveys Limited 1999, Burt & Hayes 2005, Aarninkhof et al. 2010, HR Wallingford 2013a). Attrition and change in PSD during excavation of unconsolidated granular soils with a drag head is generally not documented and is apparently considered insignificant in practice.

Cutting, ripping and scraping

Cutting is the dominant process for excavation of cohesive material types (soft rock, clay and silty clay). For this purpose blades and teeth are mounted in the drag heads (Vlasblom 2005a). The required cutting force depends on the material type, permeability and depth of cut (Miedema 1987, Braaksma 2009).

Clay-rich soils have plasticity across a wide range of water content. Cutting of highly plastic, cohesive clays can produce resilient lumps and these may be worked by dredging processes into clay balls up to hundreds of millimetres in diameter (Matousek 1997, PIANC 2000). Water jets attached to drag heads can be used to cut/rip stiff clay, break down the size of clay balls, prevent drag head clogging, direct material toward the suction pipe and improve flow efficiency within the pipe (Vandycke 2002).

Less cohesive soils may crumble into small particles or groups of particles when cut or scraped (Spigolon 1993a). In mixed-grain soils such as sandy-clayey gravel or clayey sand, reduced 'stickiness' of the clay fraction increases soil friability. The important geotechnical properties for determining friability are grain size distribution, clay content, clay plasticity, and water content (liquidity index).

Smith (2010) measured the composition of dredge plumes from TSHD overflow when dredging sand-silt-clay mixture soils and noted the abundance of bed aggregate particles which may, he suggested, have overflowed the hopper, having originated from the excavation process.

Some rock formations which would normally be dredged with a CSD can now also be dredged with an adequately equipped TSHD (Neelissen et al. 2010). Larger, heavier drag heads with ripper teeth and water jets have been designed, tested and successfully used for this purpose (e.g. Neelissen et al. 2010). The total installed power of the TSHD, its propulsion power and the dimensions of the suction pipes have been increased along with the size and weight of the drag heads to generate the forces required for ripping, cutting and suctioning of the rock material. Where closely spaced fractures or weaknesses exist in the rock material, the drag head has only to loosen or rip the material along these weaknesses (Barber et al. 2012).

3.1.2 Excavation by cutter suction dredgers

Barber et al. (2012) reviewed fundamental knowledge relating to the break up and attrition of material during cutter suction dredging and pipeline transport. An important part of that review focused on the basic physics of cutting, material failure modes and their influence on the disintegration of material during excavation by the cutter head. Non-cohesive, cohesive and rock material types were considered. Much of the information presented in this section is drawn from Barber et al. (2012).

Cutting non-cohesive granular material

Barber et al. (2012) found that the literature does not provide much information on attrition and PSD development of non-cohesive granular material at the cutter head. They considered that this was because the specific energy (i.e. the energy required per unit volume) to dredge such material is relatively low (150 to 350 kPa) and probably insufficient to cause significant attrition.

Cutting rock material

The physics of rock cutting is complex and only partially understood. Turner (2004) recognised that hard, intact rock cannot be dredged through shear alone and that, as illustrated in Figure 4, it needs to be shattered into fragments or chips through high impact forces (e.g. Verhoef 1997, Prieto 2012).

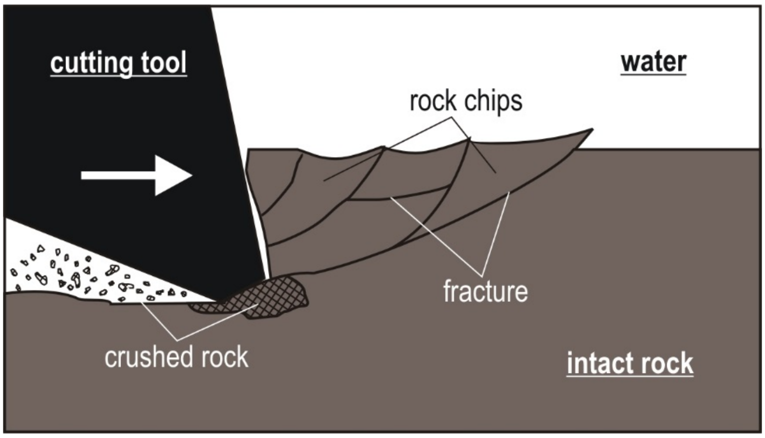

Figure 4. Chip formation and crushed zone when cutting rock under water (from Verhoef 1997).

Verhoef (1997) and Barber et al. (2012) summarised knowledge relevant to the disintegration of intact rock when cut with CSDs. According to Barber et al. (2012) 'a heterogeneous crushing zone occurs at the tooth-rock interface where nearly all of the cutting energy is expended. Material in this zone crushes entirely and then transfers the load to the supporting intact material, causing micro-cracks to spread, leading to failure of the chip. These cracks will naturally exploit in-situ fractures and weaknesses. Each tooth cut produces chips of differing size according to the small-scale variations in the character of the rock and the applied cutting forces. Normally, such chips form the bulk of the cut volume and are accompanied by a smaller volume of fine material from the crush zone'.

Gehring (1987) proposed the ratio of the UCS to the Brazilian Tensile Strength (BTS) as a parameter to assess the likely failure modes (either brittle, transitional or ductile) of intact materials. The range of parameter values proposed for each failure mode are shown in Table 1.

Table 1. Failure modes of intact material by the Unconfined Compressive Strength to Brazilian Tensile Strength ratio (from Gehring 1987)

UCS/BTS	Failure Mode
< 9	Ductile
9 – 15	Transitional
> 15	Brittle

Brittle failure generally produces a relatively large chip which separates from the rock mass as the tooth advances. Ductile failure yields a much smaller chip. The specific energy required to cut material of similar strength is higher for ductile failure than for brittle failure. For a given cutting force this means that the incision depth must typically be smaller for ductile failure. In extreme cases, where the material is very hard and the cutting force is barely adequate, the cutter teeth only leave excavated grooves in the rock (Barber et al. 2012).

For excavating rock with closely-spaced fractures, the cutting force required only has to dislodge the material along these weaknesses. Intact rock strength parameters are therefore of lesser importance in such cases and rock fracture spacing will influence the size distribution of rock fragments produced by excavation (Barber et al. 2012).

Cutting clay material

Barber et al. (2012) drew on the work of Van der Schrieck (2009) and Miedema (2010) to discuss the failure modes that may occur when cutting clay. Five failure modes are illustrated in Figure 5, ranging from highly plastic (or flow behaviour) to chips of very stiff clay. Failure modes 1 to 3 are more typical for clays, while modes 4 and 5 are more representative of rock failure modes and rarely apply to clay.

Material properties (e.g. cohesion, adhesion and tensile strength) and operational parameters (such as cutting velocity and tooth / blade angle) are important determinants of the failure mode of clays (Van der Schrieck 2009, Miedema 2010). As shown in Table 2, Van der Schrieck (2009) related undrained shear strength (c_u) to the failure mode and suggested strength ranges that provide an initial indication of the form of the clay particles as they enter the cutter head.

Table 2. Failure modes of clays by undrained shear strength (c_u), as proposed by Van der Schrieck (2009).

c_u	Failure Mode
< 100 kPa	1 and 2
100 – 150 kPa	3 and 4
> 150 kPa	5

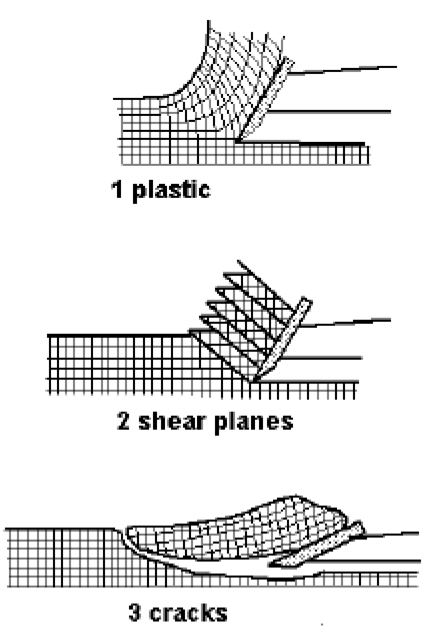

Figure 5. Failure modes when cutting clay (from Van der Schrieck 2009).

Mixture formation within the cutter head

One of the functions of the cutter head is to promote the formation of a water-solids mixture that can be lifted and transported hydraulically. Particles of cut material that are guided into the cutter head are subjected to mechanical forces from the rotating blades and hydraulic forces from a highly turbulent flow field.

The frequency of particle-particle and blade-particle collisions increases as the particle concentration within the cutter head increases (Den Burger et al. 2005), however little attention has been given to the particle attrition that may result from these collisions.

On the basis of laboratory abrasion tests, HR Wallingford (2010a) considered that freshly-cut clasts of weak to medium strength phyllite rock (mudstone) may be partially broken down to fine particles by erosion and disaggregation due to turbulent and abrasive flow within the cutter head.

In general, very little has been published on material attrition at the stage of mixture formation within the cutter head.

Case studies with CSDs

Further information on the generation of sediment characteristics by cutter head excavation is available from specific cases.

The CSD *Castor* dredged variable strength limestone and soft clay till formations in the Oresund, between Denmark and Sweden (Jansen 1999, Lorenz 1999). It was found that the teeth and blades of the cutter head broke the limestone into pieces of up to 30 cm diameter and also that a considerable volume of fine particles was released during the limestone cutting process (Jansen 1999). Lorenz (1999) noted that the percentage of excavated material released as fines was higher when excavation rates were low and, by inference, when CSD *Castor* was dredging high strength limestone material.

Based on observations, geotechnical tests and analyses of dredge plume water samples it was concluded that CSDs dredging hard limestone off the Western Australian coast can produce particle sizes ranging from fine silts and clays up to small rock fragments (Fitzpatrick et al. 2009, Mulligan 2009). PSDs obtained from sampling dredge plumes close to an operating cutter head indicate that the suspended material was dominated by particles of less than 40 µm diameter (Mulligan 2009).

Coralline limestone and coral materials break up readily when dredged and/or transported hydraulically. Colloidal material from freshly broken coral fragments is released into the water, creating milky white 'clouds' (PIANC 2010). For dredging with CSDs in the presence of coralline limestone, the cutter head generates considerable fines in the 10 micron range that remain in suspension for very long periods of time (Sciortino 2010).

HR Wallingford (2010a) made an assessment of the likely breakup and attrition during cutter suction dredging of phyllite, a variable strength mudstone that occurs in Darwin Harbour, Australia. On the basis of fracturing and abrasion tests in the laboratory it was considered that phyllite of moderate strength (UCS values of 9 to 23 MPa) would be broken into clasts by the action of the cutter head teeth, but with very low production of fines. By contrast, attrition of the phyllite clasts by turbulent, abrasive flow within the rotating cutter head was considered to produce up to 35 per cent fines for material with UCS values of up to 10 MPa.

3.2 Sediment generation during hydraulic transport

In the context of this review the term hydraulic transport signifies the use of a system of pipes and pumps to transport solid particulate material as part of a solid-water mixture. During hydraulic dredging a mixture of excavated solids and seawater is formed at the dredge head, drawn up the inclined suction pipe(s), and either loaded to a hopper or pumped through a pipeline to a placement site several kilometres away. In-pipe water velocities need to be maintained at or just above critical values to keep the solids in motion and to deliver them with maximum efficiency (Vlasblom 2005b). For large rock fragments or clay balls these critical velocities may be in the order of 10 m s^{-1} or greater.

A literature survey by Barber et al. (2012) found that there has been only limited research on the subject of material attrition during hydraulic transport of solid and water mixtures through dredge pipes and pumps. They concluded that the understanding of (and ability to predict) solids attrition during hydraulic transport is by no means complete.

3.2.1 Hydraulic transport

Barber et al. (2012) discussed some key aspects of hydraulic transport that influence dredged material attrition, including flow regimes, particle settling and the effects of the solids on the hydraulic gradients required to drive flow. The remainder of this section contains a brief summary of their discussion.

The physics of hydraulic transport varies depending on flow speed and particle size and may be classified in terms of flow regimes, each of which has a characteristic cross-sectional distribution of solid particle concentrations (Barber et al. 2012, Ramsdell & Miedema 2013). Fine particle slurries typically have a homogeneous concentration distribution and demonstrate a fluid-like response to pressure gradients. They act as a dense carrier fluid for larger particles. The carrier fluid travels at a greater velocity than the larger particles supported by it. Medium sand particles (200 to 630 µm) are typically suspended in hydraulic transport, but with increasingly non-uniform concentration distributions as the particle size increases, and this flow regime exhibits non-fluid behaviour. Still larger particles that are unable to remain in suspension will form a bed. Bed transport (rolling, sliding or hopping) or intermittent resuspension processes will occur if there is sufficient shear stress at the bed/fluid interface.

Dredged material mixtures contain a range of particle sizes and exhibit complex behaviours. Wilson et al. (2006) sought to analyse and understand these behaviours as a combination of the simplified flow regimes outlined above.

Settled particles experience the passage at significant relative velocities of both the abrasive carrier fluid as well as larger particles carried in suspension. Settled particles are directly exposed to greater concentrations and sizes of suspended solids that occur near the fluid-bed interface. Furthermore, settled particles reduce the flow area, increase hydraulic roughness, adversely affect the hydraulic gradient and lower the flow efficiency. When settled, therefore, particles are likely to be subject to altered levels of attrition.

For particles to remain suspended, settling needs to be balanced by vertical turbulent diffusion. Particles with greater settling velocity therefore require greater turbulence levels generated by a greater mean flow velocity, and this requires a greater rate of energy expenditure. Based on experimentation, Gillies et al. (1982) suggested that attrition is proportional to energy expenditure.

Dredged material is hydraulically lifted from the sea bed to the surface. Flow in inclined pipes requires a greater velocity (and therefore greater rates of energy expenditure) to keep all the solids moving, because there is a component of the particle weight that has to be overcome (e.g. Wilson & Tse 1984). By inference, greater rates of attrition would be expected per unit length in an inclined pipe compared to a horizontal pipe for hydraulic transport of the same mixture.

3.2.2 Characteristics of attrition during hydraulic transport

It is generally considered that material attrition versus duration of pipe flow takes the form of a decay curve for a wide range of particle sizes. Higher initial rates of attrition are consistent with fracturing and the wearing of angular clasts and rough edges present in dredged material shortly after excavation (e.g. Gillies et al. 1982).

Impacts between particles and collisions of particles with interior pipe surfaces occur during hydraulic transport and these can result in particle fracturing. Abrasion of weak to medium strength material by high velocity, turbulent flow of the carrier fluid may also contribute to the attrition of material during its passage through the pipe (e.g. Costaras et al. 2011).

Particles may be subject to particularly damaging forces during the short period that they travel through the centrifugal pump. Coarser particles in particular gain considerable momentum and their trajectories differ from mean flow trajectories, resulting in severe impacts with pump surfaces. The resulting attrition rate is high, however the material transit time through the pump is small (Barber et al. 2012).

Attrition depends greatly on the dredged material type and its geotechnical characteristics. For clays, the plasticity and stiffness are important; compressive/tensile strength are important parameters for rock (Barber et al. 2012).

Highly plastic clays tend to be cut as lumps (PIANC 2000); clay balls in the order of 100 mm diameter may form a rolling bed during hydraulic transport. The attrition of these clay balls depends on material plasticity, density (stiffness) and flow velocity (Leshchinsky et al. 1994).

Barber et al. (2012) describe the results of material attrition tumbling tests conducted on phyllite rock samples ranging in strength from 0.9 to 23.4 MPa. The moderate strength (about 10 MPa) rock samples showed the greatest initial break up and, with further tumbling, produced the highest proportion of fines (< 63 µm). All of the weak to moderate strength rock samples were eventually completely broken down to fine particles, however the stronger rock samples showed very little attrition.

Barber et al. (2012) suggest that, for materials with a high susceptibility to pipeline attrition, the overall amount of attrition undergone is greater in long pipelines than in pumps, while, for high strength materials such as siliceous gravels, the overall amount of attrition undergone is greater in the pumps than in pipelines due to the destructive forces in the pumps being greater.

3.2.3 Laboratory-scale assessments of dredged material attrition

Barber et al. (2012) discuss several laboratory test procedures that have been used to assess particle attrition of dredged material during hydraulic transport. These include:

- standardised drum (material tumbling) tests; and
- closed-loop pipe tests and single pass pump tests.

They noted that standard tumbling tests (developed for purposes such as road construction engineering) may not adequately represent either the PSDs or the hydraulic flow regimes and impact dynamics that are found in dredging applications. Furthermore, little information is available regarding the calibration of laboratory test parameters or the scaling of test results to actual dredging situations. The results of these tests may thus be considered largely qualitative (or at best semi-quantitative) in their relation to dredging.

Previous material tumbling test investigations have demonstrated that failure to properly represent the physics of the material breakdown due to dredging operations can lead to anomalous results (Costaras et al. 2011). Using Micro-Deval tumbling tests, Ngan-Tillard et al. (2009) found that quartzitic sand suffered unexpectedly high degradation as compared with shelly carbonate sand. This was attributed to the angular shape of the carbonate sand fragments, leading to them having fewer contacts with the steel balls at the bottom of the tumbling cylinder where the highest impact forces are experienced. Ngan-Tillard et al. (2009) sought to address this perceived anomaly by changing the drum rotation speed and the total weight and diameter of the steel balls used in the test.

It is possible to calibrate pipe loop system experiments to generate particular levels and cross-sectional distributions of suspended sediment concentration. However the literature contains very little in relation to the scaling laws that would support experimental design and enable material attrition results to be interpreted in terms of full-scale dredging. A problem with closed-loop pipe tests is that the material must pass through the pump multiple times.

Matousek (1997) included an adjustable section into his pipe loop apparatus to simulate the incline of a dredger suction pipe. He tested materials in the size range 0.2 mm to 5 mm diameter and observed the attrition that took place in the system over a range of concentrations and inclines.

In summary, Barber et al. (2012) concluded that there is presently no well-established or recognised method of reproducing dredge-induced particle attrition at a laboratory scale. More representative, specifically designed, tests are required to adequately replicate the physical processes that lead to attrition of materials during dredging. In the absence of such tests, existing laboratory methods should be used with careful consideration, thorough procedures and the results should be interpreted with caution (Costaras et al. 2011).

3.3 Knowledge gaps

A detailed, predictive understanding of dredged material attrition and PSD development induced by dredging processes is required to realistically estimate suspended sediment source characteristics for input to dredge plume simulation models.

Current theoretical knowledge of cutting processes leading to material disintegration is based on simplified models (Barber et al. 2012). These models have aided a generalised understanding of the break up that is likely to occur for different materials and failure modes (Barber et al. 2012). However, detailed estimates of material break up and PSDs that result from the cutting action of dredge heads still appear to be based on empirical data and professional judgements.

Barber et al. (2012) found that there has been only limited research on the subject of attrition due to hydraulic transport of dredged material through pipes and pumps. They concluded that the understanding of (and ability to predict) solids attrition during hydraulic dredging is by no means complete.

There are currently very few published data on the level of attrition and PSD development in dredged material at various points along the full-scale dredging production line. Consideration should be given to trialling alternative methods as a prelude to developing standard protocols and quality assurance procedures for the collection and reporting of these data.

Various laboratory test procedures have been applied to soil and rock samples in an attempt to represent the breakup and attrition that could occur during dredging. These include:

- small-scale impact, abrasion and attrition tests; and
- closed-loop pipe tests and single pass pump tests.

Barber et al. (2012) concluded, however, that there is currently no widely-accepted, laboratory-based method of reproducing particle attrition processes experienced during full-scale dredging and that more work is required to develop such tests. Further work could be undertaken to fine tune attrition test parameters (e.g. drum rotation rate, steel ball charge, duration of testing) for particular material types, dredging equipment and work methods. The successful development and validation of representative laboratory-scale tests would depend on the availability of reference data on material attrition from a range of full-scale dredging operations.

4. Sedimentation in hoppers and overflow: processes and predictive models

TSHDs and hopper barges are designed to capture and store dredged material by sedimentation from the solid-water mixture that is pumped into the hopper.

Coarse-sized solids settle fairly rapidly inside the hopper to form a material bed, while fine-sized particles tend to remain suspended in water overlying the bed. As dredging continues the hopper fills to a level at which the overlying water and suspended particles overflow an adjustable weir and are discharged to sea, typically via a pipe opening through the hull of the vessel.

By allowing overflow, the loading of dredged material can be continued over a longer period and the amount of solid material that is deposited within the hopper can be increased. Dredging with overflow is practiced when the dredged material contains significant fractions of sand-sized or coarser particles that can readily settle and be deposited in the hopper. Finer fractions of the material predominantly leave the vessel as a component of the overflow although a small proportion may be captured in the hopper as part of the sedimentation process. Loading of the hopper is typically continued until the dredger reaches its maximum load (or permitted vessel draft), until it becomes uneconomical to continue loading, or until the concentration of sediment discharged in the overflow exceeds an agreed limit.

When dredging mud, the mass of solids stored in the hopper is not appreciably increased by continuing to dredge while overflowing, because large quantities of fine sediment are discharged via the overflow to the marine environment. In some instances overflow is not permitted when dredging mud in the vicinity of sensitive marine environments.

4.1 Hopper processes

This section reviews laboratory-scale and full-scale investigations of hopper processes and the development of hopper process models to predict sedimentation and overflow from the hopper. These investigations demonstrate that the efficiency of hopper sedimentation depends on the dimensions of the hopper, the inflow rate, solids concentration and bulk density of the incoming mixture, the settling velocity characteristics of the dredged material, turbulence levels in the hopper and the design and operation of the hopper loading and overflow systems (Van Rhee 2002b, Braaksma et al. 2007, Ouwerkerk et al. 2007, Lloyd Jones et al. 2010).

4.1.1 Laboratory-scale hopper process experiments

Van Rhee (2002b) conducted large-scale laboratory experiments loading sand slurry into a test hopper (dimensions 12 m x 3.1 m x 2.5 m) to better understand the processes at work within the hopper. In addition to logging hopper inflow and overflow parameters, detailed measurements of velocity, suspended sediment concentration and bed levels were taken within the test hopper. These measurements led to the development of a conceptual model of the flow field in the hopper (Figure 6) and revealed the importance of density effects. The dense, inflowing mixture, introduced at one end of the hopper, was observed to descend vertically, impact the sediment bed, form a scour hole and then to spread horizontally across the hopper bed as a density-driven current. Sediments were deposited from this spreading density current, causing the bed level to rise (and helping to maintain mixture density gradients). The largest horizontal velocity was measured within the density current (just above the bed), while velocities above the density current (and away from the inlet zone) were smaller and upwardly directed throughout most of the hopper volume. Finer fractions of the incoming sediment that did not settle were observed to move into suspension. At the water surface the sediment concentration was low and the mixture was observed to be flowing horizontally toward the overflow.

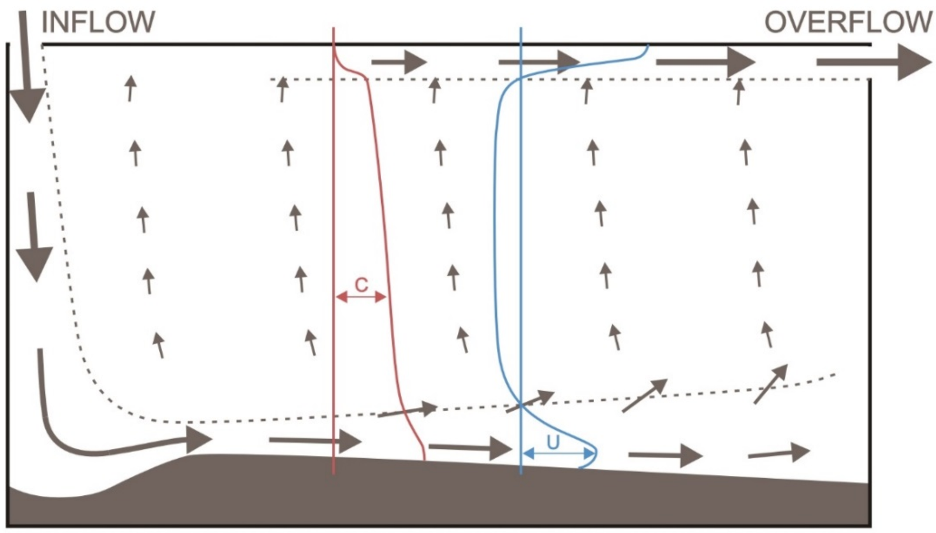

Figure 6. Conceptual model of the flow field in a hopper (from Van Rhee 2002b). c is suspended sediment concentration; u is horizontal component of velocity.

Van Rhee (2002b) also conducted closed flume tests with sand to investigate the role of bed shear stress in reducing net sedimentation rate. These tests showed that reduction of the net sedimentation rate was small for near bed velocities of less than 0.5 m s^{-1}. Near-bed velocities in the test hopper were generally below this level. Hence it was concluded that settlement was virtually unhindered and erosion not important at the scale of the test hopper. However this may not be the case at the scale of hoppers installed in TSHDs.

It was therefore recognised that the test hopper experimental results, although yielding valuable insights into hopper dynamic processes, were not readily scalable to match the performance of prototype hoppers of a size commonly found in the dredging industry.

4.1.2 Full-scale hopper process studies

To address this issue, Van Rhee (2002b) conducted a measurement program aboard the TSHD *Cornelia* during dredging operations in fine to medium sands off the Dutch coast. The measurement program was designed both to improve understanding of hopper processes at full scale and to provide data sets for the validation of hopper-overflow process models. The hopper volume of TSHD *Cornelia* was 5000 m^3 with dimensions of 52 m x 11.5 m x 8.4 m. The following variables were recorded from the ship's measurement system: discharge and bulk density of the incoming mixture; water level in the hopper; height of the overflow weir; and the draft of the vessel (used to calculate loaded tonnage). Instruments were mounted within the hopper for the purposes of this research to measure the level of the settled sediment bed and the vertical profiles of horizontal velocity and suspended solids concentration. The *in situ* sediment and the overflow mixture were sampled and analysed for PSD.

Analysis of the data showed that processes within the full-scale hopper operate in a manner generally similar to those in the laboratory-scale hopper tests of Van Rhee (2002b). The maximum measured horizontal velocity in the hopper occurred within a thin, dense layer of high suspended sediment concentration (several hundred kg m^{-3}) that spread across the bed. Measured bed level increased over time as sediment deposited from the dense spreading layer. Near the water surface, a low concentration layer was observed to be flowing toward the overflow.

It should be noted, however, that maximum horizontal velocities in excess of 1 m s^{-1} occurred in the full-scale hopper just above the sediment bed, whereas they did not exceed 0.5 m s^{-1} for the test hopper. Based on his laboratory investigations of the influence of bed shear stress on net sedimentation rate, Van Rhee (2002b) concluded that significant bed erosion would occur and that settlement would be hindered under the conditions experienced within the full-scale hopper. As a result, the sedimentation velocity (or rate of rise in the level of the bed) would be reduced and, over time, both the suspended sediment concentration in the hopper and the flux of sediment in the overflow would be increased. For the test hopper experiments hindered settlement was not considered significant.

Van Rhee (2002b) recommended that similar datasets should be collected for different dredged sediment characteristics, hopper sizes and geometries to test hopper-overflow models over a wider range of conditions.

IHC and Dredging International (DEME) also undertook hopper loading research using a 1:4 scale test hopper at the MTI Holland Laboratory and conducted prototype measurements on board TSHD *Antigoon* (e.g. Ouwerkerk et al. 2007). The findings of this research were broadly consistent with those of Van Rhee (2002b) and were used to develop improved hopper overflow prediction models, redesign hopper loading devices and implement controlled loading procedures, including an adjustable flow rate into the hopper for dredging fines, with slower flow rate both initially and toward the end of the loading process (Ouwerkerk et al. 2007).

4.1.3 Hopper process and overflow models

Development and comparison of hopper process models

Following his laboratory and field investigations Van Rhee (2002a, 2002b) formulated a one-dimensional (horizontally-averaged) hopper process model with multiple layers in the vertical, including a sand layer overlain by mixture layers, the lowest of which accepts mixture inflow and the highest of which allows mixture discharge ('overflow'). The model is based on the advection-diffusion equation for sediment transport in the vertical and includes the influence of the hopper plan dimensions, the water throughflow and the PSD. The model accounts for the effects of the vertical water velocity, turbulent diffusion and particle settling, including the mutual interactions of different sediment size fractions. The model was validated against one-dimensional sedimentation experiments and model simulations were found to compare reasonably well to the laboratory-scale hopper sedimentation test results of Van Rhee (2002b). However, because of its one-dimensional formulation, the model was unable to represent horizontal flow across the hopper bed and was therefore unable to represent the bed shear stress and account for a potential reduction in bed sedimentation rate.

Van Rhee (2002b) therefore developed a two-dimensional hopper process model to better represent the hopper configuration and to allow for the development of density-driven flows including horizontal flow across the hopper bed. The 2DV model is width-averaged with variability in the longitudinal and vertical directions. It is based on strong dynamic coupling of the hydrodynamic (Reynolds-averaged Navier Stokes), turbulence (k-epsilon) and suspended sediment transport equations together with an equation of state (linking suspended sediment concentration to mixture density). It takes into account interactions between multiple sediment fractions which together represent the PSD. The model includes an adjustable overflow level, a moving water surface level and a rising bed level.

The 2DV model was validated using the laboratory-scale hopper sedimentation test results and data from hopper measurements during full-scale dredging of sandy material. An example from a full-scale hopper simulation is illustrated in Figure 7. Comparisons of model simulation results with data from measurements conducted aboard the TSHD *Cornelia* showed that the 2DV model is capable of predicting the measured overflow loss and the measured d_{50} of solids in the overflow (Van Rhee 2002b). The 2DV model simulations also confirmed the importance of accounting for the bed shear stress and the corresponding reduction of net sedimentation at full scale.

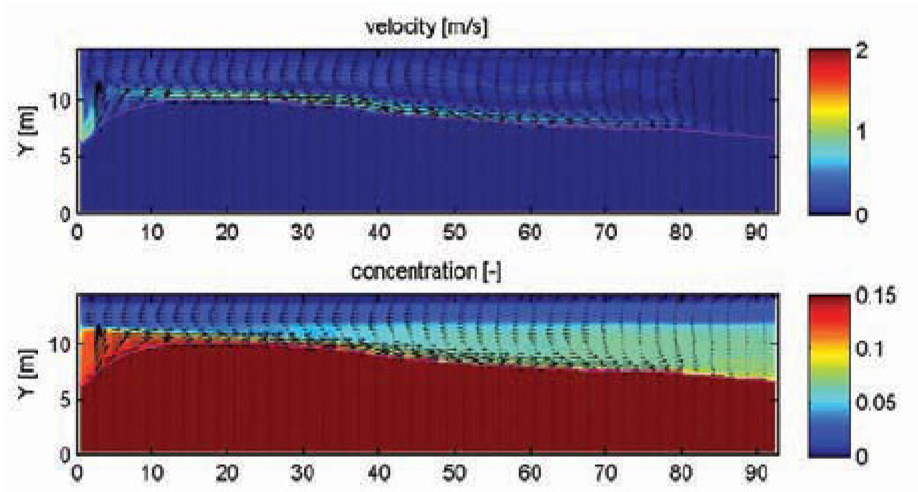

Figure 7. Mixture velocity and concentration distribution and bed level in a hopper during loading – 2DV model simulation (from Lloyd Jones et al. 2010, Crown Copyright, courtesy of UK Marine Aggregate Levy Sustainability Fund (MALSF)).

Because van Rhee's 2DV model better represents the hopper geometry, the zones of inflow and overflow and the dynamic processes within the hopper, and because it has shown an ability to realistically simulate observed density-driven flow, sediment settling efficiency and sediment flux in overflow from the hopper, it is currently considered as a reference model (Miedema & Van Rhee 2007), albeit that the model is computationally intensive. Van Rhee (2002b) provided a set of recommendations for further improvements to (and more extensive validation of) the model.

Most earlier hopper overflow models were based on a simple model developed by Camp for the field of sewage water treatment (e.g. Camp 1946). These models all have idealised or simplified inflow and outflow configurations and a prescribed distribution of horizontal velocity in the hopper. At the input section the suspended sediment is assumed to be distributed uniformly over the hopper depth. The sediment particles settle as they are advected horizontally through the length of the hopper. Particles that reach the bed before exiting the hopper are considered to have been retained. The percentage retention or overflow of the various sediment size fractions introduced to the hopper depends primarily in these models on the relative magnitudes of two ratios: the particle settling velocity to horizontal advection velocity ratio; and the depth to length ratio of the hopper. The hopper load parameter is defined as the settling velocity when these two ratios are equal.

Miedema and Van Rhee (2007) briefly reviewed attempts to build on the Camp model by including representations of the effects of turbulence, hindered settling, bed erosion, a rising sediment bed, adjustable overflow, time varying inputs and hopper response times. The implementation of all these effects into a Camp-like model was documented in Miedema (2008), a modification from Miedema and Vlasblom (1996).

Miedema and Van Rhee (2007) compared results for the Miedema and Vlasblom (1996) model, modified along the lines of Miedema (2008), with results from the 2DV model of Van Rhee (2002b). The model comparisons were conducted for three cases of loading sand (d_{50} = 400 µm) to hoppers with different dimensions. Despite the quite different schematisation and basis of these models, they gave similar magnitudes for the total overflow losses for each of the three hopper cases, although the development with time of those losses was different. Miedema (2008) concluded that the parameter dominating these simulations in both models is the so-called hopper load parameter (volume discharge divided by plan area of the hopper), since this is the upward flow velocity in the van Rhee model and it is also the settling velocity of a particle entering the hopper at the top and just reaching the sediment bed at the other end of the hopper in the Miedema and Vlasblom (1996) model. Further simulations using different hopper specifications and sediment characteristics would be required to more thoroughly assess the relative performance of these two models. However, it is clear that models which accurately represent the physical processes within the hopper would be required for more detailed investigations of the influence of hopper geometry, loading and overflow system configuration and operational strategies (Lloyd Jones et al. 2010).

TASS hopper process model

HR Wallingford (2013a) described another hopper process model that has been developed as one of several components of the Turbidity Assessment Software (TASS) system for TSHDs. This model is designed to enable the user to predict sediment release rates and PSDs in the hopper overflow discharge. The overall structure of TASS and its performance against field trial data will be described in section 5 of this review.

The hopper process module implemented in TASS version 4.0 (HR Wallingford 2013a) is also described in Aarninkhof et al. (2010) and Spearman et al. (2011). The hopper is schematised in terms of three zones:

- an input jet zone (which gives rise to a layer of high concentration mixture moving rapidly across the sediment bed);
- a central zone, including most of the hopper, where the direct influence of the input jet has largely diminished; and
- an outflow zone where an orifice flow field is assumed to convey fluid to the overflow.

The model is set up to represent the central zone of the hopper. It is one-dimensional in the vertical (i.e. horizontally averaged) and has a fixed number of stacked horizontal layers of water-sediment mixture. The orifice flow (not modelled) in the outflow zone is assumed to extend throughout the depth of the hopper. Horizontal discharge from the model layers is therefore possible if it is assumed to be accommodated by the orifice flow of the outflow zone. The (horizontally-averaged) velocity of the layers can therefore have lengthwise as well as vertical components.

Flow in the model is based on a 1DV horizontal momentum balance and continuity of mass. Vertical distribution of suspended sediment is governed by an advection-diffusion equation. Settling velocities for each sediment size fraction are adjusted to include the effects of hindered settling, return current from the settling of coarser particles and vertical throughflow in the hopper. Sediment deposition to the bed is used to update the hopper bed level. The turbulence model is a mixing layer equation which calculates eddy viscosity, with additional viscosity contributions due to grain-grain interactions and turbulence damping by vertical density gradients taken into account. Coupling of flow, sediment transport and turbulence equations occurs through the eddy viscosity and eddy diffusivity. The governing equations and numerical solution scheme are provided in HR Wallingford (2013a).

The hopper process module accounts for the size of the hopper and requires data on the flow rate of mixture pumped to the hopper as well as the concentration and settling characteristics of solids in that mixture.

The development of the vertical distribution of suspended sediment concentration in the model improves the accuracy of the computed settling flux onto the bed of the hopper and better reproduces the slow increase in concentration that is commonly observed as the overflow stage progresses (Spearman et al. 2011).

4.2 Knowledge gaps

Most process-based investigations of hopper dynamics, sedimentation and overflow have been carried out in relation to the dredging of relatively loose, unconsolidated *in situ* sediments (Van Rhee 2002b, Ouwerkerk et al. 2007, Miedema 2008). However it is not uncommon for TSHDs and hopper barges to be used in operations connected with the dredging of either rock or fine cohesive bed material. The detailed understanding of hopper processes is less well developed when dealing with these latter two material types, as is the ability to predict solids retention and overflow from the hopper.

4.2.1 Hopper processes associated with dredging hard rock material

Rock may be cut and lifted hydraulically by a CSD and pumped into an attendant hopper barge or TSHD. Alternatively the cut / crushed rock may be placed on the seabed by the CSD to await later dredging and collection by a TSHD.

The material produced by CSDs dredging hard rock may have a very wide range of particle sizes. The produced material typically consists of rock fragments (e.g. Fitzpatrick et al. 2009), some of which may be up to 30 cm in diameter (Jansen 1999), ranging down to small silt-size particles (e.g. Lorenz 1999, Mulligan 2009). The significant production of fines by CSDs dredging hard rock and loading to hoppers has been noted by several authors (e.g. Lorenz 1999, Fitzpatrick et al. 2009, Mulligan 2009, Aarninkhof & Luijendijk 2010). When TSHDs dredge previously-crushed material that has been left on the seabed there is potential for further attrition and fines production to occur as angular clasts are suctioned up through the drag arms (HR Wallingford 2013b).

Good quality data on the PSD, total solids concentration and flow rate of the mixture pumped into the hopper are required in order to make predictions of solids retention in the hopper and losses via the overflow.

There are a number of measurement issues, knowledge gaps and uncertainties in relation to understanding hopper processes and predicting sediment losses via the hopper overflow when dealing with crushed rock material. Some of these are discussed below.

There is currently considerable uncertainty and very little predictive capacity concerning the extent to which hard rock material is disintegrated during dredging, hydraulic lifting and pumping to the hopper (HR Wallingford 2013b). This is due in no small measure to the lack of high quality data on the PSD of dredged material as it enters the hopper.

There appears to be no established method of measuring the PSD of solids just prior to entering the hopper. Such a method would need to span the full range of particle sizes but also to resolve size fractions of significance to the accuracy of hopper retention and overflow loss predictions. The frequency of data delivery would need to be sufficient to account for heterogeneity within the delivered mixture and to provide representative PSD data for specific areas of dredging.

Hydraulic lifting of a mixture containing large rock pieces requires increased flow rates through the CSD or TSHD suction lines. These increased flow rates will result in smaller water residence times and increased levels of turbulence within the hopper. Additional turbulent kinetic energy will also be generated by the rapid descent of the rock pieces and coarse particles to the hopper bed.

Very little experimental work appears to have been done to parameterise the increase in turbulence in the hopper due to the rapid descent of the rock pieces to the hopper bed. If this effect is shown to significantly influence sediment flux in the overflow, then it should be implemented into hopper process models and the revised models validated against measured overflow data.

Previous investigations of hopper processes (e.g. Van Rhee 2002b, Ouwerkerk et al. 2007) for sand - water mixtures have identified the importance of density effects on the flow field within the hopper, including the role of density currents in distributing incoming sediment horizontally over the bed and, at the same time, hindering/slowing the net rate of sediment deposition because of the magnitude of the bed shear stresses generated by the density current.

Where large rock pieces and coarse particles are included in the incoming mixture they will fall very rapidly to the bed and come to rest close to the point of impact, while finer particles (e.g. fine sands and silts) may still be able to form a density current at the bed, but with a lower suspended sediment concentration and lower excess density than if all of the incoming solids mass was composed of finer particles. The role of density effects on flow, bed shear stress and sediment transport in the hopper should be re-evaluated for this case.

4.2.2 Hopper processes associated with dredging cohesive bed material

Cohesive bed material, depending on its properties, may be dredged directly by a TSHD or by a CSD which loads to a TSHD or hopper barge.

Smith (2010) measured the composition of dredge plumes from TSHD overflow when dredging sand-silt-clay mixtures. The dredge plumes were comprised predominantly of dense bed aggregates (defined by densities of 1200 to 1800 kg m^{-3}) and larger flocs (with densities < 1200 kg m^{-3}) with primary sand particles (d < 100 µm) making up a very small proportion of the plume mixture. Smith considered that the bed aggregate particles present in the plume had most likely overflowed the hopper since their settling velocities did not exceed 5 - 7 mm s^{-1}, in general agreement with the settling velocities of the sand particles detected in the plume. He surmised therefore that the bed aggregates originated from the excavation process and were not completely disaggregated during their passage through the drag arm and hopper. A better understanding of the size, density and settling velocity distributions of bed aggregates produced during the dredging process would lead to improved predictions of material deposited in the hopper and released in the overflow. This in turn would improve predictions of dredge plume behaviour.

The literature concerning dredging operations in cohesive material has given little attention to quantifying the PSD of bed aggregrates, either in the mixture entering the hopper, within the hopper itself, or in the overflow. It would be useful to relate these PSD data to operational dredging parameters and *in situ* soil properties.

While recognising that shear may be high during some stages of the dredging process, Smith and Friedrichs (2011) suggested three possible sources of initial development of the flocs which were observed in the dredge plume: (a) the low density surficial sediment layer at the point of dredging; (b) the high-concentration, low-moderate turbulence conditions within the hopper; and (c) within the dredge plume very soon after material release from the overflow.

The occurrence and characteristics of material flocculation up to and including the stage of overflow discharge from the TSHD do not seem to have received much attention. Floc formation/break-up rates, floc-sizes, settling velocities, and shear stresses are extremely difficult to measure in-situ. However these data would complement and inform studies of floc development in the dredge plume and its influence on the extent and intensity of the plume.

5. Sediment release by TSHDs

5.1 Sources of sediment release from TSHDs

A TSHD producing relatively coarse material (e.g. sand, gravel or cut rock) will typically continue to load while overflowing. In this case the sources of released sediments are (HR Wallingford & Dredging Research Ltd 2003):

- hopper overflow discharge;
- propeller-induced erosion of material at the seabed; and
- disturbance of bed sediment by the drag head.

A TSHD dredging silts and soft clays may be required to stop loading in time to prevent overflow. In this case, the sources of sediment release are (HR Wallingford & Dredging Research Ltd 2003):

- discharge via the Lean Mixture Overboard (LMOB) system;
- propeller-induced erosion of material at the seabed; and
- disturbance of bed sediment by the drag head.

The LMOB system is used mainly at the start of the dredging run and during turning. It prevents low sediment concentration mixture from entering the hopper by discharging it to sea. Preventing the loading of low sediment concentration mixture helps to increase the amount of solids that can be stored in the hopper without overflowing (HR Wallingford & Dredging Research Ltd 2003). General guidelines for measuring sediment loss via the LMOB system are given in HR Wallingford and Dredging Research Ltd (2003), but there is very little in the literature on the actual magnitudes of those losses. Sediment loss via the LMOB system will not be dealt with further in this review.

It is common practice, when hopper loading is complete, for the TSHD to sail to a dredged material placement area at sea. Once on location, doors in the base of the hopper are opened, releasing the material as a dense plume which descends and impinges on the seabed. Alternatively, for land creation projects, the hopper material may be slurried and pumped through a pipeline to settling ponds. Suspended sediment is released into the water column as a result of these dredged material placement operations and may generate significant plumes. Information on sediment release from material placement operations is reviewed in section 7.

5.1.1 Hopper overflow source

It is generally recognised that hopper overflow is a major source of the fine sediments released from TSHD dredging activities. Section 4 reviewed laboratory-scale, full-scale and numerical model investigations of hopper processes which govern the discharge of sediments via hopper overflow. In some cases the mass rate of sediment release in hopper overflow may exceed other TSHD sediment sources by orders of magnitude (Van Rhee 2002b, HR Wallingford & Dredging Research Ltd 2003, Van Eekelen 2007), although propeller-induced erosion of bed material may also be a significant source of resuspension for operations conducted in shallow water (Spearman et al. 2007, HR Wallingford 2010b).

The suspended sediment load in the overflow discharge is composed mainly of relatively fine particles from material delivered to the hopper. Vlasblom (2005a) stated that all particles with diameter less than 75 µm can be considered to be lost in the overflow. Costaras et al. (2011) noted that particle sizes between 80 and 200 µm can make a significant contribution to the overflow. Van Rhee (2002b) stated that there is typically a range of particle diameters where a transition occurs between fine sediments which are completely overflowed and coarse sediments which are totally retained in the hopper. For sandy material this range is around 100 to 300 µm (Van Rhee 2002b). However, if bed aggregate and floc particles are present in the hopper during dredging of cohesive material, the size ranges across which these particles transition from complete overflow to complete retention is likely to differ from that of primary particles. This is because of the different relationships between settling velocity and particle size, due in part to the lower effective densities of these cohesive aggregates (Smith & Friedrichs 2011).

Van der Schrieck (2000), cited by Van Eekelen (2007), stated as a general guide that the solids concentration in the mixture that is sucked up by a TSHD is about 20 to 25 per cent by volume and that the solids concentration in the overflow leaving the hopper is about 5 to 15 per cent of the solids concentration in the mixture entering the hopper 'under normal conditions'. This would suggest that the overflow mixture has a solids concentration in the range 25 to 100 kg m^{-3} and a bulk density in the range 1040 to 1090 kg m^{-3} (well above the density of sea water). These calculations assume densities for solids and sea water of 2650 kg m^{-3} and 1025 kg m^{-3}, respectively.

Lloyd Jones et al. (2010) reported that sediment losses via the overflow can be up to 30 to 40 per cent of the total amount of sediment pumped into the hopper, depending on the sediment settling characteristics, the hopper geometry and other process parameters. In general, percentage overflow losses increase with the hopper inflow rate, the sediment concentration and proportion of fines in the mixture pumped to the hopper, and with the level of turbulent kinetic energy in the hopper.

It is clear from field measurements that the concentration, flux and PSD of sediment in the overflow all change with time during loading (Aarninkhof et al. 2010). This change is perhaps most obvious at the end of the loading period if the bed level in the hopper has risen almost to the level of the overflow structure. Then, for the same inflow rate, the horizontal velocity and concentration of the overlying mixture increases, enhancing hindered settling and scour of sediments at the bed surface, and this results in additional amounts of material being discharged in the overflow (Spearman et al. 2007).

The bulk density of the overflow significantly exceeds that of seawater on account of its suspended sediment load. The overflow discharge for a large TSHD is typically in the order of 10 m^3 s^{-1} (Van Eekelen 2007) and is directed downwards. The initial momentum flux and negative buoyancy flux from the overflow discharge typically give rise to a 'dynamic' plume which descends rapidly through the water column. This topic will be discussed further in following sections of this review.

When the flow over the hopper weir free-falls for some distance in the overflow pipe, it causes air entrainment. The presence of air bubbles in the overflow discharge is a significant issue because it can:

- cause malfunctioning of submersible pumps that are used to sample the overflow mixture deep within the overflow pipe (Aarninkhof 2008);
- drastically increase acoustic backscatter in the water column and mask underlying acoustic backscatter signals which can otherwise be correlated with suspended sediment concentrations in dredge plumes (Land & Bray 2000, HR Wallingford & Dredging Research Ltd 2003); and
- add buoyancy to (and strip sediment out of) the plume from the overflow, increasing suspended sediment concentrations near the surface (Aarninkhof et al. 2010, De Wit & Van Rhee 2013, De Wit et al. 2014a).

Air entrainment in the overflow may be significantly reduced by the installation of an 'environmental valve' in the overflow discharge pipe. The valve can be adjusted so that the overflow weir is fully submerged, which creates a smoother flow from the hopper into the overflow pipe with less entrainment of air (Lloyd Jones et al. 2010).

Source measurements

Difficulties of accessing and measuring under or very close to a working TSHD means that overflow discharges must be measured on-board before they exit the ship (HR Wallingford & Dredging Research Ltd 2003).

An efficient and reliable on-board method for measuring TSHD overflow source characteristics has been developed over several field measurement campaigns for a range of soil types and overflow configurations (HR Wallingford & Dredging Research Ltd 2003, Aarninkhof 2008, Aarninkhof et al. 2010). Samples of the overflow are taken from a well-mixed region near the lower end of the overflow pipe and are raised using a flexible airlift system. This sampling method minimises problems with pump failure or instrument error due the presence of air bubbles. The samples extracted from the overflow can be monitored in-line for mixture density and can be bottled and later analysed for bulk density, sediment concentration, PSD, particle specific gravity and organic content (Aarninkhof et al. 2010). It has been shown by Aarninkhof (2008) that estimates of the volumetric discharge rate of the overflow can be derived from the ship's on-board monitoring system (if properly calibrated). The overflow discharge rate is calculated as the flow rate into the hopper minus the rate of increase of water volume within the hopper. Overall, the on-board overflow measurement method outlined above yields data that are considered fit for use to estimate sediment source terms at the point of discharge of the overflow and to validate and/or further develop hopper process models (Aarninkhof 2008, Aarninkhof et al. 2010).

Lee et al. (2010) developed a method to quantify overflow spillway losses and screening losses during aggregate dredging with TSHDs. Many aggregate dredgers overflow via deck-level spillways and, while this is different to discharge of overflow via a pipe through the hull of the vessel, the following insights from Lee et al. (2010) are still of relevance to this review:

- transmissometers can provide effective on-board measurements of the concentration of silt in the overflow from dredger hoppers, even where large numbers of air bubbles are present; and
- multibeam sonar systems deployed around a TSHD can provide information on the location, form and extent of sediment overflow plumes but they have not yet been calibrated to provide sediment concentrations. Multibeam sonar measurements extend through the full range of depths beneath the sensor head. This is not the case for conventional Acoustic Doppler Profiler (ADP) backscatter measurement systems used to map suspended sediment concentration fields, for which valid data cannot be obtained close to the water surface and close to the sea bed (Land & Bray 2000).

Source models

For the purpose of near-field dredge plume prediction, the overflow source needs to be specified in terms of: suspended sediment concentration; particle size (and settling velocity) distribution; bulk density of the overflow mixture and volume rate of discharge, together with information on the location and cross-sectional dimensions of the discharge pipe.

A review of hopper processes and process-based models which predict hopper overflow source characteristics is provided in section 4. Hopper process (overflow source) models should include key features of the hopper geometry, a moving water surface level, an adjustable overflow level and a rising bed level. The models also need to accept variable inputs (flow rates, solids concentrations and particle size characteristics) that represent the input of dredged material slurry loaded to the hopper (Van Rhee 2002b, Spearman et al. 2007).

Air bubble content and flow rate pulsing are also important overflow source characteristics governing the behaviour of dredge plumes (De Wit & Van Rhee 2013, De Wit et al. 2014a, De Wit et al. 2014b) and their influence will be discussed in more detail in section 5.2.

5.1.2 Propeller-induced bed erosion source

Propeller-induced bed erosion may be a significant source of suspended sediment during TSHD operations in shallow water (Spearman et al. 2007, HR Wallingford 2013b). Bed erosion may occur both when the TSHD is dredging and when it is simply navigating. TSHDs also have bow thrusters which can generate bed erosion, for example, when the TSHD needs to hold position while being loaded by a CSD.

The rate of bed erosion depends on the shear stress exerted on the seabed and on the nature of the bed material (e.g. HR Wallingford 2010b, Hayes et al. 2012). Bed erosion rates per unit area of sea bed have been formulated in terms of the difference between the actual bed shear stress and a critical shear stress necessary for incipient motion (e.g. Soulsby 1997). Alternatively, tests on core samples can be conducted to develop site specific relationships between erosion rate and shear stress (e.g. Gailani et al. 2001, Jepsen et al. 2004, Hayes et al. 2012). Some of these tests can also provide data on the PSD of the eroded material.

The bed shear stress depends on the effective water velocity close to the bed and on a friction factor which varies with bed roughness (e.g. HR Wallingford 2010b).

The effective water velocity close to the bed is determined by a range of parameters (e.g. Maynord 2000, HR Wallingford 2010b), including:

- propeller diameter;
- applied power;
- distance from the propeller shaft to the seabed (depends on water depth and vessel draft);
- speed of the vessel; and
- ambient current velocity.

The normal setup for modern TSHDs is for there to be two propeller screws side by side, each with a rudder placed in front. The two propeller jets merge fairly rapidly and then can be treated as originating from a single propeller (HR Wallingford 2010b). Rudders have an effect on the flow behind a propeller by splitting the wash into two streams, one inclined upward and the other downward, with an angle of inclination from the horizontal of about 12 degrees (Fuehrer et al. 1987, HR Wallingford 2010b). Hence, for situations where the propeller jet impacts the sea bed, this occurs at distances behind the vessel of about five times the vertical distance from the propeller shaft to the seabed (HR Wallingford 2010b).

Propeller-induced erosion increases with propulsion power and as the propeller clearance (the distance between the propeller shaft and the seabed) decreases (HR Wallingford 2010b). For TSHDs the vessel draft increases as the hopper fills and the under-keel clearance may become as small as 0.5 m during some dredging operations (Mr Ron Hutchinson pers. comm. 2014).

Erosion is reduced when the dredger is moving with the current (rather than into it) because the ambient current is then flowing against the propeller jet (HR Wallingford 2010b).

Propeller-induced erosion tends to increase in shallow water locations with large quantities of fine, unconsolidated sediments (Aarninkhof et al. 2010).

Sediment that has deposited from dredge plumes may be resuspended by the propeller jet, particularly in shallow water and where the dredging path is aligned with the flow (Spearman et al. 2007).

A study of suspended sediment directly around a TSHD capital dredging operation in north-west Western Australia demonstrated that propeller wash was a major source of resuspension. Levels of resuspension were highly dependent on the under-keel clearance and on the PSD of sediments (Damara 2004, cited in Stoddart & Anstee 2004).

Stewart and Leaman (2013) analysed plume data collected near a small TSHD (3,700 m^3 hopper capacity, loaded draft 5.85 m) operating in an area of relatively shallow water with a bed of marine clays. Estimated sediment resuspension rates from the dredger under propulsion (but not dredging) showed a strong dependence on under-keel clearance within a range of 1.5 to 9 m, with little sediment resuspension measured for clearances greater than nine metres. These results illustrate the significance of under-keel clearance in the generation of propeller-induced suspended sediment plumes in shallow waters.

Source measurements

The rate of bed erosion due to the propeller jet may be estimated directly by measuring bed elevation before and after the passage of the vessel (not dredging) with simple depth sounding equipment, or indirectly by measuring the flux of resuspended sediment through transects of the bed erosion plume (e.g. Aarninkhof 2008).

A review of the effect of propeller wash (HR Wallingford 2006, cited in Aarninkhof 2008, HR Wallingford 2010b) indicated that the vertical erosion rate at the point of greatest erosion could be as much as 0.10 to 0.15 m s^{-1} in unconsolidated sediments.

Estimating propeller-induced bed erosion rates from plume transect data requires that the measurements be undertaken when the TSHD is navigating but not dredging, so that there are no sediment sources from either the overflow or the drag head. Plume transect measurements (including ADP backscatter, turbidity meter and water column samples) provide information on the PSD, mass flux and vertical distribution of suspended sediment in the propeller-induced erosion plume.

Large quantities of air bubbles are typically found in ship wakes and propeller jets. Propeller-induced scour may increase rates of degassing from the bed sediments. Both of these effects can severely compromise the use of acoustic backscatter and turbidity meter measurements for estimating suspended sediment concentrations and source strengths. It may take around 15 minutes after entrainment for the air bubbles to dissipate (HR Wallingford & Dredging Research Ltd 2003).

Source models

HR Wallingford (2010b) developed and tested a bottom velocity and bed shear stress model for propeller wash as part of the TASS model for TSHD operations. This model takes into account the size, draft, installed power and propeller specifications of the vessel, the propeller clearance above the sea bed, the relative speed of the dredger with or against the ambient current, the sediment characteristics and bed roughness.

The model uses an expression from Blaauw and Van de Kaa (1978) for the initial velocity at the propeller as a function of propeller diameter and installed power. A formula developed by Fuehrer et al. (1987) is used to calculate the attenuation of the propeller jet with distance. This formula takes into account the presence or absence of a central rudder that splits the jet. It also accounts for propeller clearance above the bed, and surface, bottom and lateral constraints on the jet flow. The propeller jet velocity calculated with this formula needs to be corrected to give an effective velocity at the bed that can be used to calculate bed shear stress. The corrections allow for the speed of the vessel and of the ambient current.

The bed shear stress depends on the effective water velocity close to the bed and on a friction factor which varies with bed roughness (HR Wallingford 2010b).

The model uses a standard formulation to calculate erosion rate from bed shear stress (e.g. Soulsby 1997). The rate of erosion of bed sediment per unit area varies with the magnitude of excess bed shear stress above a defined critical level. Values for an erosion rate constant and for the critical shear stress for sediment erosion are required.

Generally, the eroded bed sediment is assumed to form a passive plume immediately after its release. The calculated bed erosion flux and the particle size (settling velocity) distribution may therefore be input as source characteristics to a passive plume model. In model simulations reported by HR Wallingford (2010b), the eroded sediment was released into the lower portion of the water column at the location of largest erosion, a distance astern of the vessel of around five times the clearance of the propeller shaft above the bed.

The model was validated against dredge plume measurements at several locations with muddy or sandy sediments and with water depths in the range 16 to 23 m (HR Wallingford 2010b). The measurement trials involved two dredgers with distinct drafts and applied power, operating at different speeds, different water depths and in current speeds flowing both with and against the direction of heading of the dredger. Under these conditions propeller-induced bed erosion flux from both TSHDs was found to be relatively minor in comparison to a typical sediment flux from overflow discharge. HR Wallingford (2010b) reported satisfactory comparisons between model simulation results and field measurements of TSHD propeller-induced plumes. On this basis the model has been included as a component of TASS.

The model was also used to assess the relative importance of propeller-induced bed material resuspension during operations by a large TSHD dredging crushed rock material in water depths mainly less than 15 m in north-west Australia (HR Wallingford 2013b). The sediment flux and particle size characteristics predicted by the propeller-induced bed erosion model were released into the passive plume model within one metre of the sea bed at the location of largest erosion, typically about 25 to 75 m from the back of the dredger. Results of the passive plume simulations suggested that up to 30 to 40 per cent of the suspended sediment load measured across transects of the far-field dredge plume could have been due to the action of the propeller.

Maynord (2000) presented a propeller jet model (not specific to TSHDs) that calculates maximum velocity distributions across the seabed in water of any prescribed depth. This model considers important physical vessel characteristics including length, width, draft and the size, depth and spacing (for dual engines) of propellers. The model takes into consideration both forward speed and applied horsepower.

Using the Maynord (2000) model and a laboratory-derived, site-specific relationship between shear stress and erosion rate, Hayes et al. (2012) calculated resuspension flux values for a range of vessels and operating conditions, including propeller clearance, vessel speed and applied horsepower. The results of these simulations suggested that a clearance of about 10 propeller diameters between the propeller axis and the seabed is necessary to eliminate sediment scour. However these simulations require validation against field data.

5.1.3 Drag head source

Bed material that is suspended into the water column by drag head disturbance either settles rapidly back to the seabed or leaves the immediate dredging zone as a suspended sediment plume.

Estimation of the resuspended sediment source strength from the drag head can be made by measuring mass flux in the drag head plume when it is still close to source and distinct from other dredge-induced plumes (HR Wallingford & Dredging Research Ltd 2003, Aarninkhof 2008). Drag head plume measurements need to be conducted without overflow and in deep water where bed erosion due to propeller wash is minimised and where the drag head plume is not subject to turbulent mixing from the propeller jet. Under these circumstances the drag head plume can typically be identified in the lower part of the water column.

Primary measurements can be obtained with an ADP mounted on a stabilised tow fish which is made to traverse the drag head plume very close to the stern of the vessel and well below the influence of the propeller jet (Aarninkhof 2008). A detailed protocol for quantifying the drag head source strength is given in HR Wallingford and Dredging Research Ltd (2003).

Field measurements of sediment suspension induced by drag head disturbance were reported in Coastline Surveys Limited (1999) with an inferred source strength of less than 1 kg s^{-1}. Drag head sediment resuspension rates, estimated from measurements during dredging trials in Rotterdam, were found to be less than 5 kg s^{-1} (Aarninkhof et al. 2010). Sediment release rates from drag head disturbance are generally considered to be orders of magnitude smaller than sediment release rates from the overflow (e.g. Coastline Surveys Limited 1999, Burt & Hayes 2005, HR Wallingford 2013a).

5.2 Near-field plumes generated by TSHDs

Sediment plumes can be classified as dynamic, passive or transitional (Winterwerp 2002, De Wit 2010, Decrop et al. 2013). Dynamic dredge plumes arise from hopper overflow discharges of high concentration sediment-water mixtures that are denser than the surrounding water. The advection and mixing of these plumes is strongly influenced by the cross flow of water relative to the moving TSHD and by the fluxes of vertical momentum and negative buoyancy from the overflow discharge. The sediment particles and water in dynamic plumes tend to move together like a dense, bulk fluid and with a descent velocity that is typically much greater than the settling velocity of individual particles in the plume. Dynamic plumes retain their identity while they still have significant excess density and momentum, but they weaken as a result of turbulent entrainment and plume dilution, sedimentation and energy dissipation, and ultimately they are mixed into the surrounding water by the ambient flow, marking the completion of their transition to a passive plume. A strong external mixing influence, for example propeller-induced turbulence, may hasten the transition and mixing of the dynamic plume.

Passive plumes consist of low suspended sediment concentration mixtures that have minimal density differences relative to the surrounding water. Sediment transport in passive plumes is governed by the ambient hydrodynamics and by the vertical settling velocity of the suspended particles. Passive plume behaviour occurs when the plume has moved beyond any localised turbulent flow generated by the dredging equipment and beyond the extent of any dynamic plumes.

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 whilst being advected by the ambient currents; the initial stages may be dynamic but the plume becomes more passive with time'. Particle flocculation, in some cases, may significantly enhance differential settling in the near-field (e.g. Bundgaard et al. 2011). Horizontal sediment flux and PSD in near-field plumes will change significantly with distance from the source (or time since release). Depending on sediment type, source parameters, ambient hydrodynamic conditions and water depth, the near-field may range from a few hundred metres to several kilometres in horizontal extent (Spearman et al. 2007), and from a few minutes to a few hours in plume age (e.g. Land & Bray 2000, Bundgaard et al. 2011).

Once differential settling is complete, the suspended sediment plume reaches a stage at which 'only the fine fraction remains in suspension and is capable of being advected over long distances by the ambient currents as long as the velocity of that current remains above a critical threshold' (HR Wallingford & Dredging Research Ltd 2003). This stage of plume development is referred to as the *far-field*.

Clearly there is a quantitative difference between the near-field and far-field source terms. The ability to predict the far-field source term (i.e. the horizontal mass flux, settling velocity distribution and vertical distribution of suspended sediment supplied to the far-field plume) depends on a knowledge of sediment release from the immediate dredging zone and an understanding of the near-field plume processes.

5.2.1 Dynamic plume from the overflow

The mixture discharged via the overflow from a TSHD hopper or hopper barge is denser than the surrounding sea water and is therefore negatively-buoyant because it contains a high concentration of predominantly fine sediment. Also, the overflow mixture is discharged with downward momentum. Technically this gives rise to a buoyant jet or forced plume (Rodi 1982, Lee & Chu 2003). In this review, however, we shall refer simply to the dynamic plume from the overflow.

In dynamic plumes the suspended sediment and water tend to move together as a bulk fluid, and with a vertical velocity that can be much greater than the settling velocities of the individual sediment particles. The dynamic plume entrains surrounding seawater as it descends and, as a result, plume dilution occurs, plume cross-sectional area increases, its sediment concentration and excess density are reduced and its rate of vertical descent is diminished. In the presence of an ambient current, horizontal momentum is imparted to the plume by both shear and forced entrainment, causing the plume to bend in a downstream direction (Spearman et al. 2007). If, as a result of entrainment and dilution, the vertical velocity of the descending plume becomes less than the settling velocity of sediment particles within the plume, then these particles will start to settle out of the plume (Spearman et al. 2007).

Soon after its release from the TSHD, a proportion of the material in the dynamic overflow plume may be diverted and mixed with near-surface water to form a passive surface plume. This will be discussed in greater detail in section 5.2.2.

In coastal waters the descending dynamic plume from the TSHD overflow generally reaches the seabed. Some of the plume may be mixed with overlying seawater as it impacts the seabed (Spearman et al. 2007), while some may form a suspended sediment bed plume (i.e. a density-driven layer on the seabed). Gravitational spreading of the bed plume occurs and, in addition, it is carried downstream by the ambient current. As the bed plume spreads its layer thickness is reduced. Sediment progressively settles out of the layer, reducing the excess density and spreading rate of the bed plume. The bed plume persists while it retains a significant excess density and turbulent kinetic energy compared to the ambient seawater (Aarninkhof et al. 2010, Spearman et al. 2011). Eventually the plume collapses as it is mixed into the overlying water and a passive plume is formed. This mixing process may be driven by ambient currents and waves, or by the influence of propeller jets if the propellers are sufficiently close to the seabed (Aarninkhof et al. 2010).

The descending plume and the density-driven bed plume are different stages of the dynamic plume (e.g. Spearman et al. 2007).

The mass rate and size characteristics of suspended sediment mixed into the surrounding water when the dynamic plume collapses and transitions to a passive plume (and the location where this occurs) are of particular interest, since they act as a sediment source which contributes to the far-field plume.

Laboratory investigations

High quality field measurements of dynamic plumes from TSHD overflow are difficult to make for a range of reasons including access, safety and corruption of acoustic backscatter data by air bubbles entrained in the plumes (HR Wallingford & Dredging Research Ltd 2003). Laboratory experiments can be conducted to gain further understanding of the physical processes involved. Data sets from these experiments can be used to test the performance of predictive models of overflow plume behaviour.

Descending plume: In laboratory experiments conducted by Boot (2000), negatively-buoyant kaolinite-water mixture was discharged from a stationary pipe into cross-flowing water of uniform depth (equal to eight pipe diameters). The pipe opened flush with the hull of a partially-submerged model ship. Winterwerp (2002) analysed the results of these experiments to determine whether the plumes were still dynamic or had mixed and transitioned to passive behaviour by the time they reached the bottom. The plumes were classified as dynamic if a bed plume was observed to form, and if its measured rate of spreading was consistent with a density-driven current. The plumes were classified as passive if dragged with the main flow and mixed rapidly over the water depth. Plumes with behaviours that could not be defined unambiguously as belonging to either of the above categories were classified as transitional. The category to which the plumes belonged was found to depend on a bulk Richardson number (the ratio of the energy generated by buoyancy divided by the initial kinetic energy of the plume) and a velocity ratio (cross-flow velocity divided by overflow discharge velocity).

Van Eekelen (2007) conducted laboratory experiments to investigate the behaviour of sediment-laden, negatively-buoyant plumes in cross flow. He found that sediment stripping from the descending plume was negligible under quasi-steady experimental conditions, and that any significant removal of suspended material from the dynamic plume was due to external factors that give rise to unsteadiness, such as entrapped air in the overflow, abrupt changes in the discharge rate and/or density of the overflow, and unsteady movements of the discharge pipe. Van Eekelen (2007) also investigated the mechanism known as vortex divergence. As the plume descends and entrains ambient seawater in the presence of a cross current there is a transfer of horizontal momentum into the plume which sets up a sectional circulation pattern within the plume which takes the form of an opposing vortex pair. These vortices have a tendency to diverge (which potentially alters the surface area of the plume and entrainment rates) and there is a possibility that the plume itself may ultimately bifurcate (resulting in much more rapid mixing). The experiments of Van Eekelen (2007) yielded vortex divergence angles consistent with those previously cited in the literature, however vortex bifurcation was not observed in the experiment. The effect of vortex divergence on the overall entrainment rate of the plume was not considered to be important.

Van Eekelen (2007) noted that the descending plume became unstable when source conditions were unsteady, giving rise to large billows and cloud formation. Under these circumstances sediment from the plume was clearly mixed into the surrounding water column. There are a range of conditions and factors in play during dredging operations (e.g. wave-induced ship motions, fluctuations in pumping rates or mixture concentration, adjustments in the hopper overflow level) which could lead to unsteady source conditions for the overflow, and to overflow plume instability (Spearman et al. 2007, Van Eekelen 2007).

Decrop et al. (2013) conducted experiments with negatively-buoyant sediment plumes in cross-flow, issued from a pipe mounted in a hull-shaped model. Instantaneous images of the plume highlighted the large scales at which turbulent mixing and entrainment occurs.

The mean trajectories of the experimental buoyant plumes were compared by Decrop et al. (2013) to integral laws (Fischer et al. 1979) and to a Lagrangian model for buoyant jets (Lee & Chu 2003). Good agreement was found for cases where the plume discharge speed dominates the horizontal cross-flow speed. However significant differences occurred for cases where the negative buoyancy of the discharge is weak and the cross-flow speed dominates the plume discharge speed. Under these circumstances the plume behaviour is influenced by the boundary layer and wake of the model hull, where shear flow induces greater vertical mixing with the result that the plume axis is located closer to the surface compared to what is predicted by the integral laws. The experiments of Decrop et al. (2013) offer an extensive dataset on the mixing in this type of plumes, useful for calibration of numerical models.

Decrop et al. (2013) classified the negatively-buoyant plumes generated by their experiments on the basis of the vertical inclination of the bent plume centreline at a defined distance (thirty pipe diameters) downstream from the source. Plumes having a slope of 1:5 (or more) at this distance were classified as dynamic. Plumes showing limited or no vertical momentum were categorised as horizontal (passive) plumes, while intermediate cases were classified as transitional plumes. Decrop et al. (2013) demonstrated that the plumes, if mapped on a diagram of bulk Richardson number versus velocity ratio, fall into distinct zones according to their classification (either dynamic, passive or transitional).

Bed plume: In experiments by Hallworth et al. (1998) a fixed volume of relatively dense fluid (salt solution or particulate suspension) was suddenly released into stationary or steadily flowing water of uniform depth. The density excess of the released fluid resulted in gravity currents which propagated along the channel floor. For release into a zero ambient flow, the dense fluid spread symmetrically. For non-zero ambient flow, the dense fluid elongated rapidly in the downstream direction but developed an arrested wedge in the upstream direction before being swept downstream. For experiments with particulate suspensions the development of the arrested wedge was not as noticeable since particles quickly settled out, reducing the density difference and hastening the decay of the gravity current. The results of these experiments were used to validate the density-driven bed plume sub-module of the TASS dynamic plume module (HR Wallingford 2010b) and also a recently developed Computational Fluid Dynamics (CFD) near-field dredge plume model (De Wit et al. 2014a).

Numerical model investigations

Descending plume: Spearman et al. (2007) developed a model for the descent of the dynamic plume issued from a moving TSHD into flowing water. This model is included as a component of the TASS modelling system for TSHDs (HR Wallingford 2013a). The model employs a Lagrangian technique whereby a thin element of the released plume is tracked as it moves downwards under the influences of initial momentum and negative buoyancy (e.g. Koh & Chang 1974, Brandsma & Divoky 1976, Lee & Cheung 1990). The model includes both shear and forced entrainment terms, and represents plume dilution, bending in cross-flow, vertical deceleration and settling out of coarser particles. Simulations are terminated when the dynamic plume either loses its downward momentum, impinges on the bed, or is forcibly mixed with surrounding water. The model has been designed to provide rapid simulations by focusing on the mean behaviour (trajectory, dilution, sectional area) of the plume, and has been calibrated against the experimental results of Chu and Goldberg (1974) and Chu (1975). However the model does not resolve the large-scale turbulent mixing processes associated with the overflow plume (e.g. Decrop et al. 2013) and this may have implications for predicting rates of plume dilution and transition of the plume from dynamic to passive behaviour. Nor does the model fully represent other important TSHD-related processes and their interactions with the dynamic plume, such as the effects of air bubbles in the plume, boundary layer flow around the vessel and propeller-induced mixing.

Other models that have been used to simulate descending dynamic plumes include JET3D (e.g. Morelissen 2007, Deltares undated), PLUMES (USEPA 2014) and CORMIX (CORMIX 2015).

De Wit (2010) reported on the development of a three-dimensional Computational Fluid Dynamics (CFD) model to simulate near-field mixing of dynamic plumes from TSHD overflow. This model uses a Large Eddy Simulation (LES) approach and captures not only the mean trajectory of the plume but large turbulent eddies which are considered to be important for mixing between the plume and its surroundings. The experiments of Van Eekelen

(2007) were simulated with the CFD model and simulation results were generally found to compare favourably with experimental data.

De Wit (2010) then used the model to investigate descending overflow plumes in cross-flow and their depth of transition from dynamic to passive behaviour. A criterion for transition from a density-driven to a mixed plume was required for this investigation. De Wit (2010) used a locally determined plume Richardson number (Ri_l) and set the criterion for transition as $Ri_l < 0.15$, a range which indicates that excess density is no longer a significant driver of plume behaviour. The transition depth results were presented on a graph of bulk Richardson number versus velocity ratio and contours of plume transition depths drawn. The modelled plume transition depths were found to be consistent with the experimental findings of Winterwerp (2002). Furthermore, the model results enabled the depths of plume transition to be investigated more generally.

De Wit et al. (2014a) successfully tested the CFD model against two full-scale TSHD overflow plumes for which side scan sonar images were available, showing the under edge of the descending dynamic plume and the locations of touch down of the plumes on the seabed. The simulated under edges of the plumes revealed large eddy structures similar to those shown on the sonar images and the CFD model was able to accurately simulate the observed touchdown locations of the plumes. Bed shear stress, sediment deposition and mud erosion were represented in these model simulations.

Bed plume: Spearman et al. (2007) used a box-model approach to represent the gravitational spread and collapse of a sediment-laden density current (the bed plume) formed after impingement of the dynamic plume on the sea bed. This model is included as a component of the TASS modelling system for TSHDs (HR Wallingford 2013a). The model simulates gravitational spreading (transverse to the direction of the ambient current) which increases the width of the bed plume. For a thin, dense layer on a horizontal bed, the horizontal speed of propagation of the density front is related to the layer thickness and the gravitational acceleration modified for buoyancy (Hallworth et al. 1998). The model uses this relationship to calculate horizontal spreading of the layer, and mass conservation to calculate a corresponding reduction in the layer thickness. At the same time, sediment is allowed to settle out of the layer and deposit onto the bed, reducing the excess density and potential energy of the bed plume. After the bed plume collapses it is mixed into the overlying water and transitions to a passive plume. The bed plume model gives the location of collapse and transition of the dynamic plume, and the PSD and flux of sediment released as a passive plume.

The model was validated against the results of laboratory experiments by Hallworth et al. (1998) who used both saline solution and suspended particles in water to generate density currents. The model validation results are published in Spearman et al. (2007).

The bed plume model of Spearman et al. (2007) is designed for rapid simulations and does not accommodate or resolve large-scale turbulent mixing processes. This may have implications for predicting the timing and amount of suspended sediment released as a passive plume subsequent to the collapse of the bed plume.

5.2.2 Surface plume

Observations and measurements (Nichols et al. 1990, Whiteside et al. 1995, John et al. 2000, Aarninkhof et al. 2010, Spearman et al. 2011) suggest that, close to the TSHD, some of the dynamic plume from the overflow can be mixed into near-surface waters to form a passive plume. The surface plume contains predominantly fine sediments (with low settling velocities) that originated from the hopper overflow. The surface plume is transported passively by the ambient current and can remain suspended for hours while travelling considerable distances into the far-field.

From data collected during dredging operations in water depths greater than 20 m off the Dutch and German coasts, and in Hong Kong, it was estimated that the surface plume transports somewhere in the range of 5 to 15 per cent of the sediment flux released from TSHD overflow (Whiteside et al. 1995, Spearman et al. 2011, HR Wallingford 2013a). However, for a capital dredging project in the north-west of Australia, this percentage was seemingly much higher. The high concentration of material in the surface plume in this case may be a result of the dredger overflowing into shallower water so that the dynamic plume is more exposed to vigorous vertical mixing and entrainment. A greater suspended sediment contribution from propeller-induced bed erosion would also be expected in shallow water with small propeller clearances (HR Wallingford 2013b). The percentage of sediment flux in the overflow that is diverted into the passive surface plume has an important influence on the far-field flux; it can vary significantly from one case to another, and further work is required to enable better prediction of this percentage over a wide range of dredging situations.

Several factors associated with TSHD design and operation were thought to influence dynamic plume behaviour and the formation of passive surface plumes. It has been suggested that:

- significant air entrainment during hopper overflow could change the buoyancy of the discharge, slow the descent of the dynamic plume and increase its interaction with turbulent flow around the vessel hull and propellers. In addition, escaping air bubbles could lift fine particles out of the overflow plume (HR Wallingford & Dredging Research Ltd 2003, Spearman et al. 2007, Aarninkhof et al. 2010, Spearman et al. 2011);
- turbulent boundary layer flow around the hull could upwardly entrain some of the dynamic plume (Aarninkhof et al. 2010);
- turbulence generated by the ship's propellers could enhance mixing of the dynamic plume (Spearman et al. 2007, Lloyd Jones et al. 2010); and that
- unsteadiness in the rate or density of the overflow discharge could lead to instability of the dynamic plume and enhance the release of fine sediment into the surrounding water column (Van Eekelen 2007, Lloyd Jones et al. 2010). The unsteadiness could be caused, for example, by water oscillations inside the hopper compartment due to ship motions, or inhomogeneity in the sediments dredged.

Laboratory investigations

De Wit et al. (2014b) conducted laboratory experiments to investigate interactions between an operating TSHD and its overflow plume, including specific processes responsible for generation of the surface plume. The experimental data were used to validate a CFD model with particular emphasis on surface plume formation (De Wit et al. 2014b).

In the experiments, the vessel was towed in otherwise still water with a depth large enough to minimise the influence of the sea bed. The overflow plume was simulated by injecting saline solution from the keel of the moving vessel. The overflow discharge location could be set either toward the front or the back of the vessel. The experimental TSHD was fitted with a propeller and shaped with a rounded bow and a sloping aft. The propeller rotation speed was kept constant, independent of the tow speed. Measurements of the dynamic plume were taken at fixed cross-sections in the flume and each experimental setup was repeated three times to obtain averaged plume profiles.

The experiments were designed to systematically investigate surface plume formation due to the influences of vessel speed, propeller effect, overflow location and overflow discharge pulsing on a dynamic 'overflow' plume for which the buoyancy flux and discharge momentum flux were approximately equal (i.e. a bulk Richardson number Ri ~ 1). The influence of air bubbles entrained into the overflow was not included in this study.

The results of these experiments and parallel simulations of a CFD model were in satisfactory agreement. For this reason, the results of the study by De Wit et al. (2014b) will be summarised in the next section.

Numerical model investigations

A three-dimensional CFD model which uses a Large Eddy Simulation (LES) approach was developed to model near-field mixing of dynamic plumes from TSHD overflow (De Wit 2010). The model has been validated against laboratory and field data (De Wit 2010, De Wit & Van Rhee 2013, De Wit et al. 2014a, De Wit et al. 2014b).

De Wit et al. (2014b) used the CFD model to investigate the influence of dredging speed, overflow location, propeller action and overflow discharge pulsing (caused by ship motions) on near-field mixing of dredging plumes, including generation of a surface plume. The model was set up to simulate a TSHD sailing in water with no ambient current, and with a water depth large enough to minimise the influence of the sea bed. Buoyancy flux and initial momentum flux values of similar magnitude were input to the model to drive the dynamic plume. For all model simulations, therefore, the bulk Richardson number of the overflow discharge was approximately 1.

The model simulations were based on the experiments of De Wit et al. (2014b), described in the previous section. Once validated against experimental results, the model was run for many more combinations of the parameter values and provided data that was more comprehensive (and at finer resolution) than could be obtained from the experiments. De Wit et al. (2014b) provided a detailed discussion of the model results and their significance, which is summarised below.

For all simulations large-scale turbulent mixing is apparent and the dredging plume shows rapid vertical expansion. Although the majority of dredging plume material descends because of its initial downward momentum and excess density, some material is mixed upwards into near-surface waters as a result of interactions with flow around the hull, influence of the propeller and pulsing of the discharge. Examples are shown in Figure 8 for several simulations with normal dredging speed.

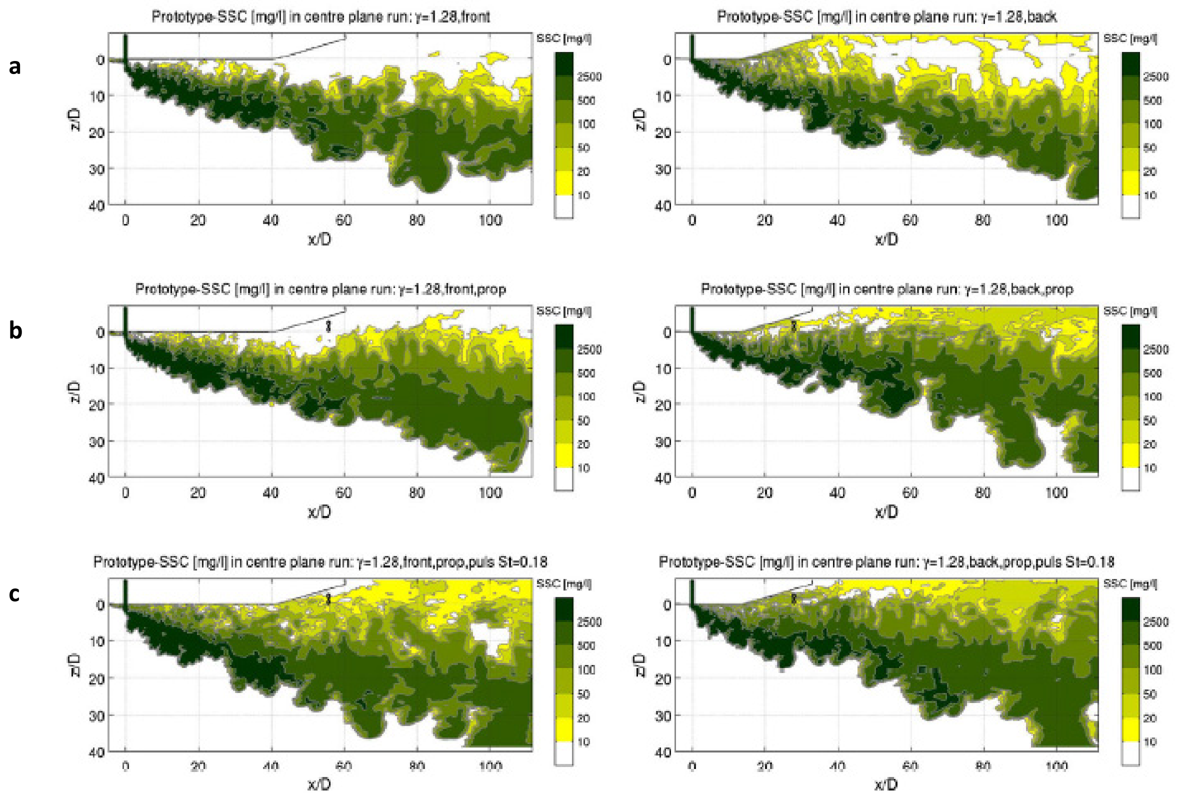

Figure 8. Simulated instantaneous prototype suspended sediment concentration at the centre slice of a TSHD overflow plume for different runs with normal dredging speed (from De Wit et al. 2014b, with kind permission from Springer Science and Business Media). The left (right) panels are for simulations with a front-mounted (back-mounted) overflow pipe. From top to bottom, the cases are: (a) no propeller action and no discharge pulsing; (b) propeller action; and (c) both propeller action and discharge pulsing. D is the discharge pipe diameter.

Dredging speed is a key parameter because it largely determines the horizontal slope of the plume trajectory relative to the moving vessel. For high dredging speed the vertical separation between the overflow plume and the TSHD remains small as the vessel passes. This strengthens the interaction of the overflow plume with the turbulent boundary layer around the vessel and with the turbulent propeller jet. Material from the dredging plume is drawn upward by entrainment when the vertical separation is small enough.

Likewise, the more the overflow is located toward the back of the vessel, the smaller the vertical separation and the greater the interaction between the overflow plume and the propeller jet. Sensitivity of the surface plume strength to the overflow location is more significant for normal than for high dredging speed.

Pulsing of the overflow discharge (represented as a sinusoidal fluctuation of the discharge velocity about a mean value) induces two effects on the dredge plume: a larger vertical spreading and a more rapid descent of the lower portion of the plume. Plume instability (with increased mixing) generated by the pulsing discharge may account for the larger vertical spreading of the plume. The more rapid descent of the plume may be due, at least in part, to the greater mean inflow of vertical momentum from a pulsing discharge compared to a steady discharge with the same average inflow velocity.

A pulsing discharge with the propeller in action enhances surface plume formation for normal dredging speed and reduces it for higher dredging speed. This is because the vertical spreading effect of pulsing dominates at normal dredging speed, whereas the rapid descent effect of pulsing dominates at higher dredging speed.

A TSHD is always under propulsion when dredging. De Wit et al. (2014b) found that for the CFD model runs with propellers there is always a surface plume with a horizontal sediment transport in the range 0.2 to 2 per cent (of the overflow source flux) for normal dredging speed and 11 to 18 per cent for high dredging speed. Hence, the dredging speed is the dominant factor of all investigated parameters governing sediment flux in the surface plume generated in the near-field.

De Wit and Van Rhee (2013) successfully validated the CFD model against measurements of two very different full-scale TSHD overflow plumes. The green valve in the overflow pipe was open for one of these cases and closed for the other, resulting in relatively high and low air bubble content in the overflow discharge, respectively. De Wit and Van Rhee (2013) then used the model to investigate the effects of air entrainment and pulsing of the overflow discharge on dynamic plume behaviour, including mixing of the plume with surface waters, and found that these effects can increase this mixing by a factor of 3–10.

De Wit (2015) found that the surface plume sediment flux is larger when dredging in shallow water, because the small water depth ensures a small separation between the overflow plume and the TSHD hull and propellers. When dredging in shallow water, the surface plume is strongly mixed in the vertical. As the surface plume is carried further away from the source, the plume flux still in suspension decreases relatively rapidly because the vertical settling distance is smaller.

It should be noted that the CFD model used for these near-field dredge plume mixing investigations is a very sophisticated model. The model is computationally intensive and is not currently intended for routine use to predict dredge plumes for environmental impact assessment purposes. However, De Wit (2015) used the results from many overflow dredge plume simulations to develop simple functions (of the basic dredging parameters) which predict the vertical distribution and flux of the overflow plume downstream of a TSHD. It is anticipated that the understanding and functional forms gained from this and other similar investigations will be incorporated into rapid assessment models such as the TASS model system (Aarninkhof et al. 2010).

5.2.3 Propeller-induced bed erosion plume

For TSHDs operating in shallow water, propeller-induced scour of weak, erodible bed material will form wide, initially very turbulent plumes in the lower part of the water column (HR Wallingford & Dredging Research Ltd 2003).

Bed material resuspended by propeller wash is assumed to behave as a passive plume. In TASS, the mass rate and PSD of bed material eroded by the propeller are used to calculate the release rate of fines (< 63 µm) for input to a passive plume model (HR Wallingford 2010b).

5.2.4 Propeller-induced mixing effects

Mixing of the dredge plume is enhanced when it interacts with the highly turbulent propeller wake of the vessel. This accelerates the transition of the dredge plume from dynamic to passive plume behaviour (Lloyd Jones et al. 2010).

Specific effects arising from interactions between the TSHD dredge plume and the turbulent propeller jet include:

- partial mixing of the descending dynamic plume with near-surface waters to form a passive surface plume (Aarninkhof et al. 2010, De Wit et al. 2014b);
- further mixing of the surface plume by the propeller jet and surface wake of the vessel (Aarninkhof et al. 2010, De Wit et al. 2014b); and
- accelerated mixing of the dynamic bed plume (particularly in shallow water), leading to increased resuspension and vertical diffusion of sediment that had originally been discharged from the TSHD overflow, (HR Wallingford & Dredging Research Ltd 2003, Spearman et al. 2007, HR Wallingford 2010b).

5.2.5 Drag head plume

The rate of sediment resuspension from the drag head is reported to be minor (e.g. Coastline Surveys Limited 1999, Aarninkhof et al. 2010). The resultant drag head plume originates near the seabed, is of low suspended sediment concentration and is generally considered to transition rapidly to a passive plume (HR Wallingford & Dredging Research Ltd 2003, HR Wallingford 2013a, b).

5.3 The far-field source term

Sections 5.1 and 5.2 have reviewed available information on the individual sources of sediment release from TSHDs and on the near-field behaviour of the suspended sediment plumes generated by these sources. It has been seen that each of these plumes, either sooner or later, transitions to passive plume behaviour. Passive plume behaviour is governed by advection and diffusion driven by the ambient hydrodynamics, and by settling rates of suspended material. As the passive plumes are transported further from their individual sources they tend to mix, merge and become one. Sand and coarser sediment settles out. Fine cohesive particles (silt and clay) released by dredging processes may form larger, low density conglomerations (flocs) with settling velocities higher than those of primary silt and clay particles. If flocculation occurs, the material will gradually develop natural distributions of floc sizes and settling velocities (Bundgaard et al. 2011) and some of this material may settle out in the near-field. Beyond the near-field, the remaining fine fractions tend to stay in suspension as long as the bed shear stress remains above a critical threshold for deposition. At this stage of its development the dredge plume is said to have entered the far-field (HR Wallingford & Dredging Research Ltd 2003, Spearman et al. 2007, Aarninkhof et al. 2010).

Models of dredge-induced sediment plumes are required when assessing the spatial extent of dredge-induced pressures and their effects on marine biological communities. DELFT3D (Deltares 2015) and MIKE (DHI 2015) are examples of passive models used for far-field dredge plume simulations. For a proper assessment of far-field dredge plume transport it is essential to have realistic estimates of suspended sediment source terms for input to these passive plume models. These source terms include contributions from the surface plume, bed plume and propeller erosion plume. They vary with time and are defined by the horizontal mass flux, settling velocity characteristics and spatial distribution of the suspended sediments that supply the passive plume.

Bekker et al. (2015) describe a method, used in the dredging industry, for estimating source terms prior to commencement of a dredging project. They discuss in detail the estimation of source terms from TSHD operations. The method requires geological, geotechnical and hydrographic survey data for the proposed dredging site. It also requires empirical resuspension data or validated near-field models for like dredging operations involving similar soils, site and environmental conditions.

It is sound practice to conduct dredge plume sediment flux monitoring and on-vessel measurements when the proposed dredging project has commenced (Bekker et al. 2015). These data can be used to (a) provide direct empirical estimates of the far-field source term, (b) test the far-field source term predictions made prior to the commencement of dredging and (c) either confirm or improve the source term prediction method. Collection of such datasets adds to the range of dredging circumstances for which resuspension data are available for application to future dredging proposal assessments.

HR Wallingford and Dredging Research Ltd (2003) and Breugem et al. (2009) report protocols for estimating suspended sediment mass flux in the dredge plume produced by a TSHD. The survey vessel is installed with an acoustic doppler current profiler (ADCP), an optical backscatter (OBS) meter and a Siltprofiler. The "perpendicular" protocol measures across the full width of the plume by sailing transects that are perpendicular to the path of the TSHD. After calibration, this method yields data for suspended sediment concentration (SSC) and current speed over the plume cross-section. With these data (and with the background SSC) estimates can be made of the suspended sediment mass flux in the dredge plume and this can be expressed in a frame of reference moving with the TSHD to derive an effective suspended sediment release rate from the dredger.

During the channel deepening project in Port Phillip Bay, Melbourne (Provis & Aijaz 2009) the dredge plume was measured following the methodology of Hydronamic (2005). The turbidity was measured at three different depths from a survey vessel following a zig-zag path across the track of the dredger while maintaining a constant distance astern.

Multiple transects should be monitored at several distances astern of the TSHD to determine the decay curve of the dredge plume mass flux and the degree of differential settling that has occurred. The transects should be located sufficiently far astern of the TSHD so that air bubbles released from the vessel into the water column have been able to dissipate and do not degrade the instrument data.

If the source term for the far-field plume is to be estimated a priori, using a process-based approach, then an integrated modelling system is required that simulates the release rates of suspended sediment from individual sources and the behaviours of the near-field plumes that are generated. These models enable prediction of the total suspended sediment mass flux to be input to a passive plume model to simulate the far-field dispersion of the dredge plume. As illustrated in Figure 9, this mass flux consists of contributions from: the surface plume; re-entrainment of the collapsing bed plume; the drag head plume (generally considered to be negligible); and the propeller-induced bed erosion plume (Spearman et al. 2007, Aarninkhof et al. 2010, HR Wallingford 2013a).

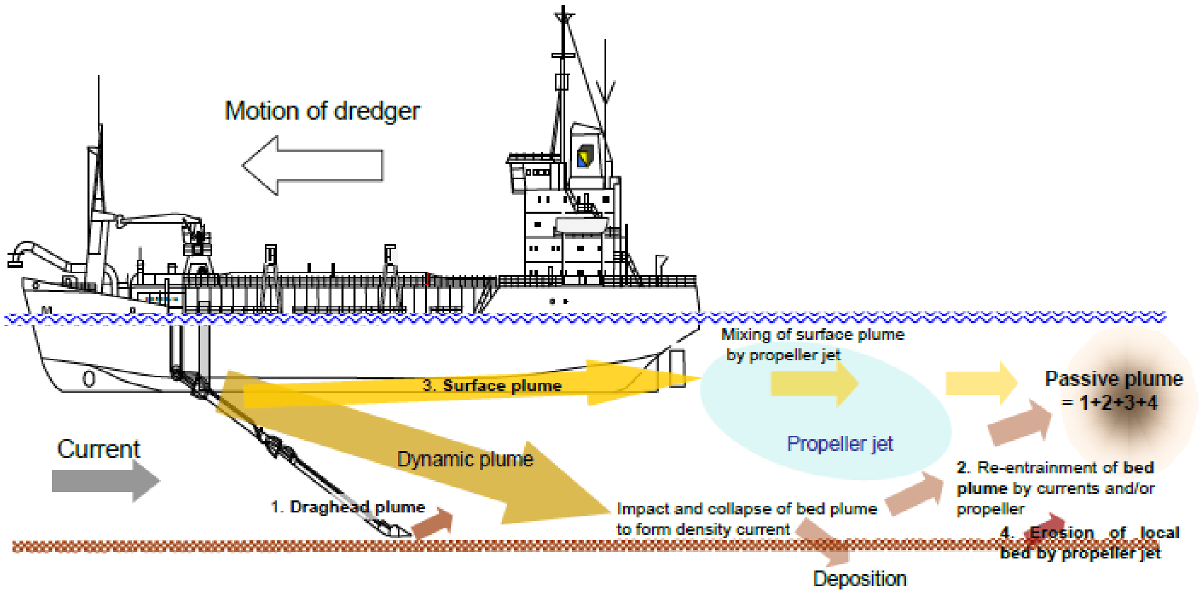

Figure 9. Release of sediment arising from dredging by TSHD and contributions to the suspended sediment source term for a passive plume model (from HR Wallingford 2013a, with kind permission from HR Wallingford and Ecoshape).

5.4 The Turbidity Assessment Software (TASS) model for TSHDs

The Turbidity Assessment Software (TASS) version 4.0 for TSHDs (HR Wallingford 2013a) was developed in collaboration between HR Wallingford, Stichting Speurwerk Baggertechniek (SSB) and the Dutch-funded Ecoshape project (Building with Nature 2013). It is an integrated modelling system that adopts a process-based approach to the estimation of: (a) the rates and characteristics of sediments introduced to the water column by dredging processes; (b) near-field plume behaviours; and (c) suspended sediment contributions from the near-field that together provide the sediment source term for input to a far-field dredge plume model. High-quality data have been collected during several TSHD operations and have been used for TASS validation and to guide further model development (Aarninkhof 2008). TASS has been designed as a tool for the rapid assessment of dredge plume generation that will ultimately be available to a wide range of users.

5.4.1 TASS structure

As shown in Figure 10, the TASS model (version 4.0) for TSHDs consists of several sub-modules (HR Wallingford 2013a):

- a hopper process module that predicts the concentration, flux and PSD of solids in the hopper overflow discharge. The module requires input data specifying the flow rate of the mixture entering the hopper, the solids concentration and particle size (settling velocity) distribution in that mixture, and the level of the overflow weir. With the exception of PSD, the input parameters can be calculated from the on board measuring system of the dredger (HR Wallingford 2013a). Section 4.1.3 contains further details on this module;
- a dynamic plume module that represents key processes arising from the discharge of a negatively-buoyant overflow from a moving TSHD into flowing seawater. This module includes two sub-modules: one for the descending plume and one for the spreading density current (or bed plume) that forms after the descending plume impacts the seabed. The dynamic plume module predicts the mass flux, PSD and location of sediment released into surrounding water as the dynamic plume transitions to passive behaviour. Transition may occur either before the plume has reached the seabed or after it has formed a density-driven bed plume. Section 5.2.1 contains further detail on the descending plume and bed plume sub-modules;
- a propeller-induced bed erosion module that predicts the bed erosion source term arising from impingement of the propeller jet on the sea bed. Section 5.1.2 contains further detail on this module. The suspended material eroded from the bed is assumed to form a passive plume immediately upon release (HR Wallingford 2013b). This module can be incorporated into the passive plume module which makes it easier to access the appropriate water depth and propeller clearance in cases of variable bathymetry; and
- a passive plume module. Source contributions from the surface plume, the transitioning dynamic plume and the propeller erosion plume are input to the passive plume module which is used to simulate far-field plume dispersion.

Sediment resuspension by the drag head is not currently included in the TASS model (HR Wallingford 2013a) because this source is generally considered to be negligible.

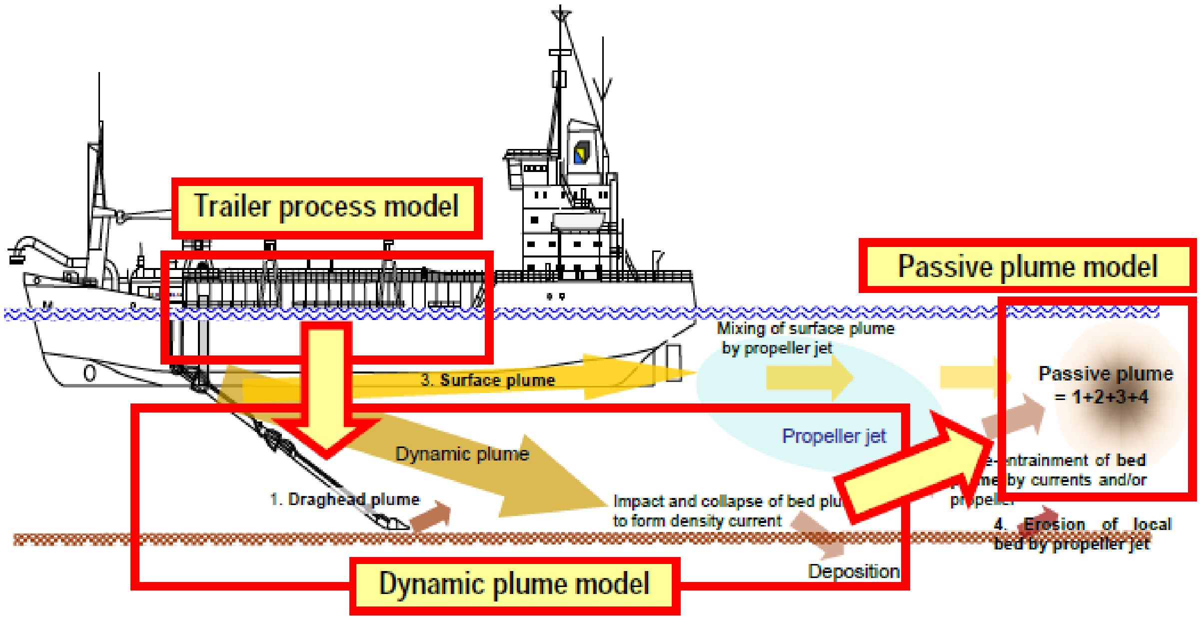

Figure 10. Structure of the TASS model for TSHDs (version 4.0) showing the sub-modules and underlying processes (from HR Wallingford 2013a, with kind permission from HR Wallingford and Ecoshape).

TASS Version 4.0 has no module for predicting the surface plume source contribution, but allows for a user-defined percentage of sediment to be diverted from the dynamic overflow plume and released near the surface as a passive plume (Spearman et al. 2007). Field and laboratory studies suggest that this percentage may vary strongly from one situation to another (HR Wallingford 2013a, b, De Wit et al. 2014b), depending on factors such as air bubble entrainment and pulsing in the overflow discharge, vessel speed, hull shape, mixing action of the propellers and under-keel clearance. Recently, an advanced numerical CFD model has been developed to investigate the influence of these factors on surface plume generation (De Wit 2010, De Wit & Van Rhee 2013, De Wit et al. 2014a, De Wit et al. 2014b) and it is anticipated that the knowledge gained through these investigations will be applicable for further development of TASS. Section 5.2.2 contains more detail on surface plume modelling.

5.4.2 Learnings from validation of the TASS model

Hopper process module

The TASS hopper process module was validated against overflow data collected during field trials in Bremerhaven, Rotterdam and Den Helder. The results for simulated overflow loss rates showed fairly realistic variations as loading progressed (Spearman et al. 2011) and mean absolute errors of about 10 to 15 per cent in the predicted total overflow losses (Aarninkhof et al. 2010).

Overflow measurements from field trials in north-west Australia provided a further opportunity to assess the performance of the TASS hopper process module (HR Wallingford 2013b). The local *in situ* material largely consisted of rock which required cutting by CSD before being removed by TSHD. The module was able to predict the right order of sediment concentration and flux from the overflow. A formal validation procedure was not possible, however, due to uncertainties surrounding both the density and solids PSD of the mixture entering the hopper. Both of these variables are required as input data to the module. This highlights the importance of having a functional, well-calibrated TSHD measurement system that can deliver good quality data on the flow rate and density of the solid-water mixture entering the hopper. Except when dredging non-cohesive, granular bed sediments of known characteristics, the PSD of the incoming mixture is difficult to estimate and it appears that currently there is no widely accepted and practiced measurement procedure in place to support this estimation.

Propeller-induced bed erosion module

Field measurement data for propeller-induced plumes from TSHD operations were used to test the predictive ability of the TASS propeller-induced bed erosion module (HR Wallingford 2010b). The dredge plume measurement trials involved two dredgers with distinct drafts and applied power, operating at different speeds, different water depths and in current speeds flowing both with and against the direction of heading of the dredger. Above background suspended sediment fluxes were calculated from measurements across propeller-induced plume transects located about 80 to 200 m astern of the dredgers. Bed erosion was estimated to occur somewhere in the range 25 to 75 m astern of the dredger. Most of the trials were conducted over predominantly fine, muddy substrate, so that the calculated sediment fluxes in the plumes were expected to reflect the magnitude of erosion flux from the bed. The results of the propeller-induced bed erosion module simulations provided estimates in reasonable agreement with the observations of propeller-induced plumes.

For the range of operations conducted, the results of the propeller erosion calculations suggest that the propeller-induced erosion flux is relatively minor compared to typical values of overflow flux. Unfortunately the clearances between the propeller shaft and the seabed are not reported in HR Wallingford (2010b). The erosion rate can be further reduced if the dredger is operating in deeper water, is of shallower draft or is moving in the direction of the current. However, when operating with small under-keel clearance there is potential for greater propeller-induced erosion as well as earlier mixing of the dynamic plume into the upper part of the water column (HR Wallingford 2010b).

Further TASS model testing against field measurements was conducted in north-west Australia (HR Wallingford 2013b). For this application the propeller erosion module was included within the passive plume model to better account for propeller erosion in areas of variable water depth. With the aid of model simulations it was estimated that, depending on the parameters of the dredging operation, from 5 to 10 per cent up to 30 to 40 per cent of the mass in the measured plumes was caused by propeller wash.

TASS as an integrated simulation package

The predictive ability of TASS as an integrated software system was assessed against field data obtained during the Rotterdam and den Helder field trials (Aarninkhof et al. 2010). The hopper process and dynamic plume modules were used to estimate source contributions (from the surface plume and the transitioned bed plume, respectively) for input to a three-dimensional passive plume dispersion model. Suspended sediment mass flux results from the passive plume model simulations were then compared against corresponding field data from transects across the passive plume at some distance from the dredger.

For dredging in water depths of greater than 20 m at Rotterdam and Den Helder, the best agreement between field measurements and model results (for the passive plume, based on TASS-derived sediment source terms) was achieved by assuming a diversion to the surface plume of 5 to 15 per cent of the sediment flux in the overflow (Aarninkhof et al. 2010, Spearman et al. 2011, HR Wallingford 2013a). However, to achieve reasonable comparisons between field measurements and simulations of passive plumes from capital dredging in water depths of 10 to 18 m in north-west Australia (HR Wallingford 2013b), the assumed percentage of overflowed sediment released into the surface plume needed to be set at values up to 50 per cent, or even higher. This result suggests that much more sediment is diverted to the surface plume when dredging with small under-keel clearance. However the physical reasons for this are not explicit in the model. It seems reasonable to expect that, as under-keel clearance is reduced, higher levels of turbulence (including propeller-induced turbulence) may result in (a) an increase in vertical mixing of the dynamic plume and (b) an increase in the rate of erosion of bed material.

These model validation exercises demonstrate the considerable progress that has been made in developing an integrated set of process-based modules for suspended sediment release, near-field plume dynamics and transition to passive plume behaviour. However they also reveal that there are still important physical processes that are not as yet well represented in TASS. Therefore, considerable caution should be applied to predictions made for circumstances and conditions beyond those for which the modules have already been validated (Spearman et al. 2011).

The proportion of the overflow that forms a surface plume is at present a focus for study in the EcoShape Project, including research using advanced CFD modelling at Delft University of Technology (De Wit 2010, De Wit & Van Rhee 2013, De Wit et al. 2014a, De Wit et al. 2014b, De Wit 2015). Published results from this research have been summarised in section 5.2.2. The CFD model is computationally intensive and is not currently intended for routine use to predict dredge plumes for environmental impact assessment purposes. However it is anticipated that the fundamental process-based understanding gained from this and other similar investigations would be incorporated in an appropriate form into the TASS model system (Aarninkhof et al. 2010) and that the updated TASS model system would then be re-validated against existing and future field trial data sets.

5.5 Knowledge gaps

Research on sediment release and near-field dredge plume behaviour arising from TSHD operations has made considerable progress in the last decade in terms of measurement and characterisation, detailed process understanding, numerical modelling and prediction.

This progress has been spurred by:

- the development of protocols for the field measurement of sediment release from dredgers (HR Wallingford & Dredging Research Ltd 2003);
- the execution of on-board and plume flux measurements during full-scale dredging to further test and develop measurement techniques and to obtain data sets for analysis and numerical model validation (e.g. Land & Bray 2000, Aarninkhof 2008, Aarninkhof et al. 2010, Smith & Friedrichs 2011, Spearman et al. 2011);
- the performance of laboratory experiments to investigate near-field plume behaviour under repeatable, controlled conditions and to examine parameter sensitivity (e.g. Van Eekelen 2007, Decrop et al. 2013, De Wit et al. 2014b); and
- the development and validation of numerical simulation models, either to improve understanding of dredge-induced sediment release mechanisms and near-field plume processes or to provide rapid predictions of sediment source terms for particular dredging operations (Van Rhee 2002b, HR Wallingford 2013a, De Wit et al. 2014a).

The number of field measurement data sets and the range of site and operating conditions they encompass is still limited. In some cases uncertainties and gaps in the data collected have reduced the value of the data sets for model calibration and validation. Further full-scale dredging measurement trials and high quality data sets are needed for model validation purposes, particularly for site and operating conditions that have not yet been adequately represented.

There does not appear to be a widely accepted method for measuring the solids PSD of dredged material entering the hopper. Such data are required for input to hopper process models used for predicting overflow source terms. The lack of these data gives rise to considerable uncertainty in overflow predictions, particularly for the dredging of cohesive soil or crushed rock material.

The aim of the TASS software system for TSHDs is to make process-based estimates of initial sediment release and near-field plume behaviour and to use these estimates to derive sediment source terms for input to far-field dredge plume models (HR Wallingford 2013a). The intent of TASS is to provide a tool that can be made accessible to a broad range of users to facilitate the rapid assessment of dredge plumes from proposed dredging scenarios.

TASS (version 4.0) does not explicitly represent large-scale turbulent mixing processes that are apparent in field observations of dredge plumes. Nor does it provide a detailed representation of interactions between the descending dynamic plume from the overflow and the operating characteristics of the TSHD, such as flow pulsing and air entrainment in the overflow discharge and propeller-induced turbulent mixing of the plume with surface waters. This may have implications for predicting the amount of suspended sediment released to the far-field as a passive plume.

The CFD model developed by De Wit (2010) uses a Large Eddy Simulation (LES) approach and captures both the mean trajectory of the near-field plume and the large turbulent eddies which are thought to be important for mixing between the plume and its surroundings. Furthermore, a range of TSHD-specific effects has been implemented into the model. These include: the effects of vessel speed; water depth; the location of the overflow discharge; pulsing of the overflow discharge; air entrainment in the overflow discharge; propeller-induced mixing, and the presence of the sea bed (De Wit & Van Rhee 2013, De Wit et al. 2014a, De Wit et al. 2014b, De Wit 2015). The model has been found to perform satisfactorily during simulations of laboratory and full-scale dredging plumes. In particular, the model results reasonably represent the mixing of the overflow dynamic plume and the strength of the passive surface plume The CFD model is being used for an ongoing set of investigations to improve understanding of the behaviour of dredge plumes close to the vessel.

It is suggested that the CFD/LES model be applied to further investigate:

- the conditions of formation and decay of the dynamic bed plume, its transition to a passive plume and its contribution to the far-field source term; and
- the influence of the propeller on bed erosion and resuspension, with a particular focus on TSHD dredging operations in shallow water.

It should be noted that the CFD model used for these near-field dredge plume mixing investigations is a very sophisticated model. The CFD model is computationally intensive and is not currently suited for routine use to predict dredge plumes for environmental impact assessment and management purposes. However it is anticipated that the fundamental understanding being gained from this and other similar investigations will be incorporated in an appropriate parameterised form into rapid assessment models such as the TASS model system (Aarninkhof et al. 2010).

6. Sediment release by CSDs

CSDs use a rotating cutter head equipped with blades and teeth to break and excavate *in situ* soil or rock material (see Figure 3). The cutter head is swung back and forth along a series of transverse arcs as it cuts. 'Overcutting' ('undercutting') occurs when the direction of swing of the cutter head coincides with (opposes) the direction of tangential movement of the rotating blades at the top of the cutter head.

The blades guide the material into the cutter head where it is mixed with sea water and hydraulically removed through the suction line and centrifugal pumps. The solids-water mixture produced by the CSD may be pumped directly to a bunded area with settling ponds for land reclamation. Alternatively it may be pumped to an attendant hopper barge or TSHD for transport to a designated disposal site when hopper loading is complete.

Other work methods are sometimes employed when CSDs are used to cut hard rock. The CSD either pumps the cut material to a submerged discharge location or simply allows it to deposit on the bed directly behind the cutter. In both of these cases the cut material is picked up from the seabed at a later time by other dredging equipment.

Depending on the work method employed, sources of sediment release from dredging operations involving CSDs may arise from:

- cutter head action;
- pumping or placement of cut material to the seabed;
- overflow during hopper loading from CSDs;
- hopper load discharge at sea; and

- settling pond overflow.

The main focus of this section is on sources of sediment release from cutter head action and, to a lesser extent, material pumping or placement to the seabed. Hopper overflow as a source of suspended sediment release has been reviewed in detail in section 5. However the particular case of overflow when a CSD is loading to a hopper barge or TSHD is considered in section 6.4. Published information on suspended sediment losses from hopper load discharge at sea and settling pond overflow will be reviewed in section 7.

6.1 Cutter head source

Typically, in the order of 20 to 30 per cent of material cut by the cutter head is not drawn into the suction pipe and this may increase up to around 50 per cent when cutting hard formations (Dekker et al. 2003, Den Burger et al. 2005, Vlasblom 2005b). Some of that material is expelled from the rotating cutter head while some may never even have entered the cutter head. Of the cut material that avoids the suction intake, a proportion will remain in suspension for some time causing turbidity in the surrounding water column while the remainder (mainly coarser particles) will deposit locally on the seabed (Hayes et al. 2000, Bridges et al. 2008). Those proportions will depend upon a range of factors, including cutter head specifications, operating parameters, material type, PSD and settling characteristics of the cut material and ambient hydrodynamic conditions (Lorenz 1999, Henriksen 2010).

The material that is not entrained into the suction line is referred to as spillage and the two categories of spillage are referred to as the resuspended and residual material, respectively (following Henriksen 2010). The term residual is sometimes used in the context of environmental dredging of contaminated sediments (e.g. Palermo et al. 2008). For this review, however, this is not the case. Here the term residual simply refers to any material disturbed by dredging that is rapidly deposited on the seabed within the area being worked by the dredger.

For CSDs pumping to a remote placement area, most of the sediment resuspension and turbidity around a CSD comes from the action of the cutter head (Huston & Huston 1976, Brahme 1983, HR Wallingford & Dredging Research Ltd 2003). Further sources of sediment resuspension from CSD operations may arise from disturbance and erosion of the sea bed due to dragging of the ladder (when dredging in very shallow water), anchor manipulation, side wire movements, spud operations, and scour induced by large-scale turbulence around the ladder. Furthermore, when dredging with minimal under-keel clearance and a strong cross-flow, water is diverted around the bow and stern of the vessel; this may create large eddies which enhance sediment release, both directly from the cutter head and from seabed erosion (Lorenz 1999). While there is little published information on the magnitude of these other sources, they are generally considered to be occasional and/or minor compared to the ongoing sediment flux released by the action of the cutter head (Huston & Huston 1976, HR Wallingford & Dredging Research Ltd 2003).

6.1.1 Flow induced by the cutter head

Den Burger (2003) discussed the water flow induced by a rotating cutter head. The dredger pump creates suction which induces a region of inflow toward the suction pipe intake located at the back of the cutter head. The shape and rotation of the blades propels water in an axial direction from the front toward the back of the cutter head from where it may either be drawn into the suction pipe or expelled in a radial direction due to centrifugal forcing.

Dekker et al. (2003) conducted laboratory and numerical modelling investigations of the flow of water in a freely rotating cutter head. Consistent with findings from earlier experiments by Mol (1977b) and Moret (1977a) it was concluded by Dekker et al. (2003) that for each value of flow speed in the suction line there is a transition value for the rotational speed of the cutter head. When the cutter head rotates more slowly than this transition value the water flow is inward along the entire contour of the cutter head. However for cutter head rotational speeds above the transition value a radially outward water flow occurs near the back of the cutter head. The ratio of cutter head rotational speed to suction line speed at the point of flow transition was found to be fairly constant for a given cutter head.

Dekker et al. (2003) suggested that these water flow regimes would not be greatly changed for dilute mixtures of sediment and water. He further suggested that the slip between very small particles and water could be neglected and that the conditions for spillage from the cutter head of fine-grained sediment at low concentration could be understood on the basis of the flow regimes induced by a working cutter head. The trajectories of large particles, however, would be influenced by inertial as well as drag forces and so they would not follow the water flow. Their spillage would depend not only on the flow regimes but on parameters such as particle size, density and the frequency of collisions.

Mol (1977b) and Moret (1977a) also found that when the cutter-suction head (with inclination angle of 30 degrees) is placed in a sediment bank the water exits the cutter head more readily (i.e. the water starts to move outwards when the ratio of cutter head rotational speed to suction line flow speed is at a lower value). Mol (1977b) found that swing velocity increased the movement of water out of the cutter head (Den Burger 2003).

High ambient currents and turbulence levels enhance the ejection of water from the cutter head and reduce the influence of suction near the suction mouth (Lorenz 1999).

Dismuke et al. (2012) summarised previous investigations of the inflow region around the suction pipe inlet and presented new experimental results. They concluded that this area of research is incomplete and is yet to fully determine the extent and magnitude of the inflow field as a function of suction flow rate, cutter head rotational speed and swing speed.

6.1.2 Spillage from the cutter head

Spillage when dredging sediment

Laboratory tests have been conducted to investigate the mechanisms by which sediments are released from the cutter head of a CSD. These experiments have been summarised in detail by Den Burger (2003) and Henriksen (2010).

Many of the laboratory experiments conducted have focussed on measuring production (i.e. material removed via the suction pipe) and expressing it as a percentage of the total amount of material dredged (or supplied). From the value of production percentage it is possible to infer the spillage percentage (since they add to 100 per cent) and therefore the temporal spillage rate from the cutter head.

A number of the experiments were conducted by injecting sediment into a freely-rotating cutter head. These tests showed that the trajectories of small particles deviate less from the patterns of water flow within the cutter head than do the trajectories of larger particles (Moret 1977b, Den Burger et al. 2005, Dismuke et al. 2012). Fine-grained sediments are transported axially toward the rear of the cutter head but are not necessarily all captured by the inflow to the suction pipe. For a given suction pipe velocity and for cutter speeds higher than a transitional value, some of the sediment is expelled by radial flow at the rear of the cutter head. Laboratory tests using light plastic particles (Mol 1977c) and fine sand (Moret 1977b) demonstrated that the proportion of sediment supply spilled is mainly determined by the ratio of the cutter blade tip speed to the suction pipe velocity.

Other experiments investigated the effects of placing the cutter into a sediment bank. Mol (1977a) conducted cutting tests on sand with a d_{50} of 120 µm while varying the cutter head rotational velocity, the swing speed and the suction velocity. For undercutting he found that the production rate was proportional to the swing velocity, but that the production percentage (the mass of sediment suctioned up divided by the mass cut) was insensitive to the swing velocity. This suggests that the spillage rate increased with swing velocity, while the spillage percentage was not much affected. For overcutting he found that the production (spillage) percentage increased (decreased) with swing speed.

Miltenburg (1983) performed cutting tests on sand with a d_{50} of 180 µm while varying the rotational velocity of the cutter head, the suction velocity and the swing speed. He found that the spillage percentage increased significantly with the ratio of the cutter blade tip speed to the suction flow velocity and that the spillage percentage for overcut was always greater than for undercut.

Hayes (1986) suggested that the majority of sediment resuspended during cutter head dredging operations is due to the 'washing' of particles that cling to the cutter blades during excavation. The washing occurs once the rotating blades emerge from the sediment bank and are exposed to the water column.

Excessive swing speed or excessive rotation speed of the cutter head may also result in increased sediment spillage. If the rate of advance of the cutter head swing exceeds the capability of the suction to remove dislodged material, the dredge head is essentially ploughing through the sediment, with increased spillage (Palermo et al. 2008).

Over-burial of the cutter head will usually result in increased sediment spillage since more sediment will be disturbed but not captured (Palermo et al. 2008).

Other factors such as increased ambient currents and turbulence may increase the rate of sediment released from the cutter head (Lorenz 1999).

Spillage when dredging hard material

Spillage from the cutter head can be up to about 50 per cent of the cut volume when hard formations are dredged (Den Burger et al. 2005). CSDs cutting hard rock can produce particle sizes ranging from fine silts to rock pieces of up to 30 cm diameter and can generate significant amounts of suspended fines (e.g. Jansen 1999, Lorenz 1999, Fitzpatrick et al. 2009, Mulligan 2009). The disintegration of intact rock by the cutter head and the amount of fine material generated as a proportion of cut production will depend on a range of factors, including rock composition and strength, mode of rock failure (either brittle or ductile) and the cutting power available (Verhoef 1997, Vlasblom 2005b, Barber et al. 2012). However the ability to quantitatively predict this disintegration and fines generation in advance of actual dredging is still limited (Barber et al. 2012).

Den Burger (2003) conducted laboratory experiments to investigate mixture formation and material spillage mechanisms relevant to a cutter head dredging hard rock, but his experiments focused on the behaviour of gravel-sized rock pieces. The physics of release from the cutter head of fines (generated as part of a mixture of different sized rock fragments) has not been fully addressed in the literature.

Spillage when dredging cohesive material

Spillage and resuspension of cohesive material from the cutter head will vary depending on cutter head specifications, operational parameters, site conditions and the properties of the material (e.g. its friability, strength, cohesion and adhesion). The size of particles dislodged from the bed by the cutter head can vary significantly depending on the failure modes that occur (Van der Schrieck 2009, Barber et al. 2012). Highly adhesive clays may stick to the cutter blades. Aggregation of highly plastic clay particles will reduce the amount of fines available for resuspension into the water column.

6.1.3 Resuspension from the cutter head

Investigations of sediment resuspension from cutter head dredging have been conducted over many years using field trials and laboratory experiments. The motivation for this work has been two-fold: firstly, to reduce sediment resuspension through better design and operation of dredging equipment; and secondly, to improve the prediction of sediment resuspension rates and source terms for dredge plume models.

Resuspension results from CSD field measurement trials have been reported and discussed by Yagi et al. (1975), Huston and Huston (1976), Hayes et al. (1984), Hayes (1986), McLellan et al. (1989), USACE (1990), Crockett (1993), Collins (1995) and Hayes et al. (2000). Hayes and Wu (2001), Palermo et al. (2008), Henriksen (2010) and Henriksen et al. (2012) are amongst those who have reviewed these investigations. Important details of these field measurement trials, including operational parameters, soil types and site conditions are given in Henriksen (2010).

The advantages of field trials are that they involve full-scale dredging equipment and real operating and environmental conditions. The disadvantages are that field trials are not controlled, repeatable experiments and that measurements can be difficult to obtain and the data limited. There are always a number of confounding variables. For example, operating parameters, turbulence levels and water currents may fluctuate, *in situ* material characteristics may vary spatially and the measurements may be influenced by unrelated sources of turbidity. Other issues include expense, availability of dredgers, coordination and safety matters.

Most of the CSD field measurement trials referred to above were conducted during maintenance dredging of soft sediments ranging from sandy silts to clays. Water samples were taken from sampling points in the near-field (within a few metres of the cutter head) and far-field dredge plumes and also at locations unaffected by the plume. The samples were analysed for total suspended solids concentration and particle size distribution. These data were used to investigate resuspended sediment fluxes and concentration levels close to the cutter head and their dependence on CSD operational parameters, such as suction flow rate, cutter rotational speed, cut type (overcutting or undercutting), thickness of cut, ladder swing speed and direction, as well as the ambient current speed.

Resuspension results from cutter head experiments in the laboratory have been reported and analysed by Mol (1977a, 1977c, 1977b), Moret (1977a, 1977b), Slotta et al. (1977), Miltenburg (1983), Brahme (1983), Hayes (1986) and Herbich and DeVries (1986). Den Burger (2003) and Henriksen (2010) are amongst those who have reviewed these investigations. Important details of the experimental set up, measurements, operational parameters, soil types and results for each of the laboratory experimental programmes are given by Henriksen (2010).

Laboratory experiments are more able to be controlled and repeated. Dependencies on one or a few variables can be studied while holding other parameters constant. The scaling involved in designing the model tests and the methods of relating the laboratory data to prototype dredging situations presents challenges and difficult choices. For example, scaling can focus either on the processes of excavation/disintegration or those of production/resuspension, but not the two aspects simultaneously (Henriksen 2010).

Most cutter head resuspension experiments have used fine to medium sands. They have been conducted in a closed tank (i.e. with no water through-flow) and therefore the intensity and spatial distribution of suspended sediment concentrations developed about the cutter head depend largely on the resuspension mass flux, the particle settling velocity distribution and the local turbulent flow field induced by the cutter head.

Fines resuspension from a cutter head is dependent on (Hayes 1986, Palermo et al. 2008, Henriksen 2010):

- the nature of the *in situ* material;
- site conditions, including currents and waves;
- characteristics and distribution of impediments, such as debris, cobbles, boulders and obstructions;
- the design of the cutter; and
- dredger operating parameters (including cutter rotation speed, suction intake speed, depth of cut, swing speed, and ladder angle).

Soil type, grain size distribution and *in situ* solids concentration are important parameters for resuspension when dredging sediments (Hayes et al. 2000). For rock or other cohesive material, the proportion of fines generated as a result of the cutting and mixture formation processes strongly influences the rate of resuspension from the cutter head (e.g. HR Wallingford 2010a). Numerous authors have stated the importance of the settling rates of sediment particles when determining resuspended sediment concentration sources at the origin of dredging (e.g. Brahme 1983, Hayes 1986).

The design of the cutter is important. For example, cutter diameter and cutter length play a significant role in relationships between resuspension and the thickness of cut (Collins 1995).

Having reviewed previous field measurement trials and laboratory experiments, Henriksen (2010) provided an overview of the influence of dredge operating parameters on sediment resuspension from a cutter head. Key points of his overview are given below.

- For cutter rotational speeds above a critical level (which depends on the suction line flow speed), sediment particles are released from the cutter head and the rate of release increases with cutter speed (Huston & Huston 1976, Mol 1977a, Brahme 1983, Herbich & Brahme 1983, Miltenburg 1983, Hayes 1986, Herbich & DeVries 1986, USACE 1990, Crockett 1993, Collins 1995). An increase in cutter speed can also increase the turbulence in the vicinity of the cutter head. Increased sediment release rates and increased turbulence about the cutter head together contribute to an increase in sediment resuspension as the cutter speed increases (Henriksen 2010).
- An increase of the suction (negative) pressure in the suction pipe increases the suction velocity field which removes sediment particles from the cutter region. It is generally agreed (Huston & Huston 1976, Brahme 1983, Herbich & Brahme 1983, Miltenburg 1983, Hayes 1986, Crockett 1993, Collins 1995, Den Burger 2003) that a stronger suction pressure will remove the particles more efficiently and decrease the amount of resuspended sediment.
- The cutter tip speed to suction line speed ratio has been identified as a key non-dimensional parameter governing the release of fine to medium sand from the cutter head (Mol 1977a, c).
- Resuspension was found to depend on swing velocity (Herbich & Brahme 1983). Experimental results for cutter heads dredging sand (Mol 1977a) demonstrated that sediment release from the cutter head was greater for overcutting than for undercutting (Henriksen et al. 2012). A similar trend was found from field trial results (Hayes 1986).
- Thickness of cut (the vertical displacement of the cutter head relative to the top of the material being dredged) is an important factor governing the amount of sediment resuspension from the cutter head. The thickness of cut that minimises resuspension is approximately equal to the diameter of the cutter head (Hayes 1986, Herbich & DeVries 1986). This is often referred to as a full cut. Hayes (1986) and McLellan et al. (1989) noted an increase in resuspension as the thickness of cut decreased from a full cut to a partial cut less than one cutter diameter. Crockett (1993) hypothesized that this is due to an increase in the amount of sediment washed from the cutter blades when more of the blade surface area is exposed to the water. For very shallow cuts, the material picked up by the blade is still available to washing but the amount of material picked up is less (Crockett 1993, Henriksen 2010). Over-burial of the cutter head will usually result in increased sediment spillage since more sediment will be disturbed but not captured. This could result in a thicker residual sediment layer and an increase in the amount of sediment resuspended into the water column (Palermo et al. 2008).
- The ladder angle determines the orientation of the cutter with respect to the *in situ* sediment surface and influences the amount of material that the cutter excavates. This in turn affects the rates of production and of sediment resuspension (Huston & Huston 1976, Herbich & DeVries 1986, Crockett 1993, Collins 1995, Hayes et al. 2000).
- Both Hayes (1986) and Collins (1995) recognised that variables such as the thickness of cut, the ladder angle, the cutter radius, and the cutter length influence the cutter blade surface area that is exposed to a washing mechanism where sediment resuspension may occur. Crockett (1993), Collins (1995) and Wu and Hayes (2000) developed alternative geometric analyses of the cutter head that could be used to calculate the exposed washing area of a cutter blade and thus provide a parameter that might be correlated with field-derived cutter head sediment resuspension factors.

Significant developments in the technology of measuring suspended sediment concentrations in the field (e.g. Land & Bray 2000, Taylor et al. 2014) have occurred since the time of the CSD field measurement trials referred to above. Furthermore, HR Wallingford and Dredging Research Ltd (2003) have provided field measurement protocols for estimating the magnitude of suspended sediment release from semi-stationary dredgers, including CSDs. However the published literature on cutter heads does not seem to include suspended sediment source estimates derived from field data where these technologies and protocols have been applied.

Further cutter head laboratory experiments were conducted by Den Burger (2003) and Den Burger et al. (2005) to investigate mixture formation and spillage of coarse (gravel-sized) rock particles. For coarse particles they noted the added significance of the gravitational and centrifugal forces acting directly on the particles, resulting in altered particle trajectories and changed relationships between spillage and the cutter head operating parameters. However the generation and release of fines as a consequence of cutter head action was not part of their study. The physics of release of fines (as part of a mixture of different sized rock fragments) from the cutter head does not appear to have been widely addressed in the literature.

More recently Henriksen (2010) and Henriksen et al. (2012) reported experiments with a carriage-mounted cutter-suction head dredging sand in a tank with no through-flow current. The purpose of the experiments was to:

- investigate the release of sediments from the cutter head;
- quantify the spatial distributions of resuspended solids concentrations, water velocities and turbulence levels surrounding the cutter ring;
- investigate the dependence of these distributions on operational parameters of the cutter-suction system; and
- support the development of a process-based near-field cutter resuspension model.

The experiments were controlled for suction flow rate, cutter rotational speed, cut type (overcutting, undercutting), cut depth and ladder swing speed. Ladder angle was kept constant. Fourteen different combinations of these parameters were tested and, overall, ninety cuts were made during the experiments.

In preliminary testing the highest turbidity was consistently observed around the cutter ring at the back of the cutter head. High frequency turbidity and water velocity data for the experiments were therefore collected at multiple locations on a plane perpendicular to the cutter head axis and coincident with the cutter ring. The turbidity data were calibrated and converted to suspended sediment concentration.

Henriksen (2010) reported that the maximum point specific turbidity value was usually greater for undercutting than for overcutting in his laboratory experiments, although the overall resuspension percentage was generally greater for overcutting. Typically, an increase in suction flow rate was shown to increase production and decrease turbidity around the cutter head, but at the highest suction flow rate turbidity was shown to actually increase at some points around the cutter. In general an increase in cutter speed led to an increase in turbidity, however, the increase in turbulence with cutter speed may also have led to a greater turbulent diffusion rate for some areas surrounding the cutter. The turbidity produced for a partial cut was greater than for either a full cut or a 'shallow cut'. Cross correlation of high frequency velocity and turbidity measurements were used to determine the diffusion field surrounding the cutter head for each specific laboratory test case.

6.1.4 Numerical source models

Three main approaches have been taken to provide predictive estimates of resuspended sediment source strength for an operating cutter head.

Empirical source models

The first approach is data-based and applies regression analysis to fit a functional relationship between CSD operational parameters and resuspended sediment mass flux data derived from field measurements close to the cutter head. Caution should be exercised in applying the derived relationships and they should only be used for similar dredging cases and where values of the independent variables fall within the ranges for which the relationships were validated. Henriksen (2010) and Henriksen et al. (2012) provide a detailed summary of empirical source models developed for cutter head operations by Hayes (1986), Crockett (1993), Collins (1995) and Hayes et al. (2000).

Resuspension factor

Hayes and Wu (2001) proposed a semi-empirical model to estimate the mass rate of suspended sediment from dredging operations that reaches the far-field. The model assumes that all size fractions of the released sediments are initially suspended into the water column by the mechanical and mixing actions of the dredger, but that sand (and larger) particles resettle relatively quickly and locally, except under extreme current conditions, leaving only fine particles (< 74 µm) in suspension and therefore able to be transported further away from the dredging location. The model requires a value for the 'resuspension factor' which is defined by Hayes and Wu (2001) as the mass of sediment suspended into the water column relative to the mass of sediment removed via dredging, expressed as a percentage. The resuspension factor may also be considered (Palermo et al. 2008) as the mass rate of suspended fines that reach the far-field expressed as a percentage of the mass rate of fines removed by dredging. The resuspension factor will vary with dredger type and size, operating characteristics, sediment properties and other site conditions (Hayes & Wu 2001).

Numerical values for resuspension factors are calculated from field trial data and these values can in principle be used as estimates of resuspension factors for other dredging works with the same type of dredger, provided that the dredger size and operational parameters, the characteristics of the sediments dredged and relevant site conditions are similar.

Hayes and Wu (2001) and Hayes et al. (2000) showed resuspension factors for cutter head dredging operations in mainly silt/clay sediments at five different sites. The site-averaged resuspension factors ranged from 0.003 to 0.13 per cent, and the overall maximum of the 388 resuspension factor values derived from measurements was 0.51 per cent.

The wide range in the calculated resuspension factors suggests that it is very difficult to assign a 'typical' resuspension factor value, even for relatively similar dredging operations. However, based on these data sets, Hayes and Wu (2001) concluded that a conservative resuspension factor for small cutter heads dredging fine-grained sediments is about 0.5 per cent.

On the basis of dredge plume measurements during cutter head dredging of variable strength limestone, Lorenz (1999) suggested that the release of fines to the water column, expressed as a percentage of the total dry weight of material dredged, was higher for low production rates (i.e. for hard limestone). Palermo et al. (2008) stated that low production rates and shallow cuts for hydraulic dredgers can increase the fines percentage of material spilled but not necessarily the concentration of resuspended sediment.

There is typically considerable uncertainty in predicting the extent to which hard material will disintegrate under the action of the cutter head and what the resultant fines fraction will be (Barber et al. 2012). Furthermore, relatively few resuspension data sets have been published for a cutter head dredging hard material. Empirically-derived resuspension factor values for large cutter heads used on CSD capital dredging operations have not been found in the published literature.

Process-based source models

Henriksen (2010) and Henriksen et al. (2012) reported the development of a process-based numerical simulation model of sediment release and near-field mixing about the cutter head. They used an expression by Miedema (1995) to calculate the volume of sediment excavated for each cut. Experimental data from Mol (1977c) were used to determine the point along the blade radius where suction and tangential forces are in balance. The sediment located beyond this point was assumed to escape the influence of suction and to be released progressively as the blade moved through the water. Using the number of blade cuts per second the flux rate of sediment released from the cutter head was calculated and applied as the source term for an advection-diffusion model to simulate the suspended solids concentration distribution across a small region of highly turbulent flow around the cutter head. This turbulent region was typically found to extend a few diameters around the cutter head.

The model was set up to simulate resuspended sediment concentration data from the laboratory experiments of Henriksen (2010). These data were measured around a model cutter head dredging sand in a closed laboratory tank with no net through flow. The resuspended sediment concentration and velocity data were collected at multiple (coplanar) points surrounding the back ring of the model cutter. The advection and turbulent diffusion fields used in the advection-diffusion model were derived from processing the measured velocity data and interpolating onto a computational grid in the plane of the measurements. The advection-diffusion model (including a settling velocity term) was therefore implemented in two-dimensions in the plane of the measurements.

Operating parameters incorporated into the model included: cutter rotational velocity; suction flow rate; cut type (overcutting, undercutting); thickness of cut; ladder angle; and swing speed.

The results of the numerical model have been tested against the laboratory data of Henriksen (2010) and have been scaled for comparison against CSD field measurement trials for situations where the natural current speed was close to zero. As detailed by Henriksen (2010) the scaling focused on processes of sediment production and resuspension. Particle settling velocity provided the fundamental scaling variable. Cutter tip speed provided a direct relationship to scale the advective field and the Peclet number scaled the diffusive field.

Henriksen et al. (2012) showed that the results from the model simulations were broadly comparable to the results from laboratory testing and empirical models based on selected field trial resuspension data.

He recommended that further work be undertaken to investigate:

- turbidity generation over a wider range of soil and dredger operating conditions;
- particle-particle dynamics during the mixture forming process and its influence on sediment release from the cutter head; and
- the three-dimensional distribution of the turbulent flow and turbidity fields induced by the cutter head. This would assist the development of a three-dimensional near-field model that would ultimately include ambient water currents. Such a model would provide a more realistic cutter head source term for input to passive sediment plume models to simulate far-field plumes.

6.2 Plumes from sediment resuspension by the cutter head

Usually, most of the sediment spillage from CSDs occurs near the seabed due to the action of the cutter head (Huston & Huston 1976, Brahme 1983, HR Wallingford & Dredging Research Ltd 2003, Fitzpatrick et al. 2009).

Very coarse fractions of the spillage are deposited on the seabed almost immediately, while finer fractions are resuspended and mixed over a localised zone of highly turbulent flow generated around the working cutter head. As a result of this mixing the resuspended sediment forms an 'initial' spatial concentration field which is reported 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). In the transverse horizontal direction the 'initial' concentration field is reported to extend no more than ten to fifteen suction pipe diameters away from the cutter (Brahme 1983). The proportion of the material spillage from the cutter head that leaves the immediate dredging zone in suspension will depend on (a) the particle size (and settling velocity) distribution of the spilled material and (b) the intensity of the turbulent flow field generated around the cutter head.

Little is understood about the way the turbulent zone around the cutter head interacts with and is modified by ambient currents. Presumably the zone is extended downstream to a point where the flow characteristics are no longer dominated by the action of the cutter head but again resemble those of the ambient flow.

Once resuspended sediment in the dredge plume has moved beyond the zone of dredge-induced turbulence its subsequent transport is governed only by the ambient currents and waves and by its particle settling characteristics. When differential settling has occurred the suspended sediment plume reaches a stage at which only fine fractions remains in suspension that are capable of being advected over long distances by the ambient current as long as the velocity of that current remains above a critical threshold. The plume has then reached the far-field stage of its development. The source term for the far-field dredge plume will depend on (a) the temporal spillage rate from the cutter head, (b) the particle size (and settling velocity) distribution of the spillage material, (d) initial mixing due to a local zone of turbulent flow near the cutter head, and (e) subsequent passive transport due to the ambient hydrodynamics combined with differential particle settling.

Some of the dredge plume sediment that settles to the bed may subsequently be resuspended, either by later dredging activity or by an intensification of wave and current conditions in the area (Lorenz 1999).

6.3 Source from pumping or placement of cut material to the seabed from a CSD

Alternative work methods when dredging hard material with a CSD are for the cut material to be:

- pumped to a nearby seabed location; or
- deposited to the seabed directly behind the cutter.

The cut material is then picked up at a later time by other dredging equipment.

In the first case the cut material mixture is drawn into the suction pipe, passed through the underwater pump and then discharged to the water column either directly from the CSD ladder or through a pipe and submerged diffuser opening near the seabed. The material discharged descend rapidly to the seabed. A proportion of the descending material may be mixed into the surrounding water depending on a range of factors, including the cross-flow velocity, turbulence intensity, the height of the discharge above the seabed and whether the discharge flow rate and density are steady or unsteady. Coarse particles will come rapidly to rest after impacting the seabed, while some of the finer material will be resuspended into the water column.

It is still generally difficult to predict the extent of material attrition and fines generation that will occur during cutting and mixture formation by the cutter head and hydraulic transport through the suction line, pump and discharge pipe (Barber et al. 2012).

Furthermore, in project-specific studies, there appears to be considerable uncertainty about what percentage of the total fines in cut material discharged to the seabed is actually resuspended and transported away from the work area in the short term. This topic does not seem to have been addressed in the published literature.

In the second case the cutter head is operated with no suction so that the cut material is left on the seabed directly behind the cutter. With no material removal through the suction line a greater spillage from the cutter head would be expected compared to a similar cutter head operation with suction. In this case, however, the overall potential for fines generation and release is reduced because material attrition only occurs at the cutter head, there being no hydraulic transport through the suction line, pump and discharge pipe.

6.4 Hopper overflow source for loading from a CSD

The subject of hopper overflow as a source of suspended sediment has been reviewed in some detail in section 5, mainly in the context of TSHD operations. There are some cases, however, when CSDs dredge material and pump it to an attendant hopper barge or TSHD for transport and disposal at sea. For these cases it becomes apparent that differences in operational characteristics of CSDs compared to TSHDs may lead to significant differences in the rates of sediment released in the overflow.

For a CSD dredging unconsolidated sediment, the solids content of the mixture in the suction line ranges typically from 10 to 20 per cent by weight (Herbich & Brahme 1991, Palermo et al. 2008). On this basis, the dry solids concentration in the suction line of the CSD would typically be in the range 117 to 234 T m^{-3}, assuming a solids density of 2.65 T m^{-3} and a sea water density of 1.025 T m^{-3}.

For a TSHD dredging unconsolidated sediment, the solids content in the suction line mixture is typically about 20 to 25 per cent by volume (Van der Schrieck 2000, Spearman et al. 2007, De Wit 2010). On this basis the dry solids concentration in the suction line of the TSHD would typically be in the range 530 to 662 T m^{-3} for the solids density and seawater density values assumed above.

In the case of a CSD loading to an attendant hopper barge or TSHD, therefore, the solids concentration of the mixture pumped into the hopper may be less than half of what would be expected of a TSHD in self-loading mode. The action of the cutter head entrains a greater proportion of water into the dredged sediment mixture compared to the action of the TSHD drag head.

Furthermore, the pumping rate of a large CSD is typically in the order of 3 m^3 s^{-1}, whereas a large TSHD, operating with two drag heads could have a combined pumping rate in the order of 10 m^3 s^{-1}.

From the above comparisons of typical mixture solids concentrations and flow rates it follows that the mass rate of dredged sediment loaded by a CSD to an attendant hopper barge or TSHD is likely to be significantly less than the mass rate of self-loading for a large TSHD. If the same sediment (i.e. with the same percentage fines content) is assumed, then the mass rate of fines loaded to the hopper should also be significantly less for the case of loading from the CSD. Further, if the same hopper specifications are assumed then the smaller flow rate and lower solids concentration in the incoming mixture from the CSD is likely to result in a greater percentage of the incoming material being retained in the hopper, compared to a self-loading TSHD. Overall, it follows that there is potential for a significantly smaller sediment mass flux rate in the overflow for the case of a CSD loading to a TSHD hopper compared to the case of the same TSHD in self-loading mode. In the latter case, however, the duration of the hopper overflow period is likely to be smaller.

6.5 Knowledge gaps

The resuspension and near-field dispersion of material from a CSD cutter head has been the subject of considerable study over many years yet, despite the knowledge and understanding acquired, major gaps in knowledge still persist.

Very few cutter head resuspension field trial data have been published in the open literature in the past decade, despite recent advances in measurement technologies (e.g. Land & Bray 2000, Smith 2010, Taylor et al. 2014) and field data collection protocols (HR Wallingford & Dredging Research Ltd 2003). There is also a lack of resuspension data for cases where cut material is either pumped or placed to a seabed location. There is a need for such data sets for a range of different soil and rock types, dredger specifications and operating conditions. The data sets are needed to: provide empirical estimates of sediment resuspension source terms from CSD operations; improve understanding of resuspension processes; and develop, calibrate and validate improved models of sediment resuspension and dredge plume generation from CSDs.

There is also a need for further laboratory-scale testing to improve the understanding of processes leading to resuspension during cutter head dredging.

Dismuke et al. (2012) found that the extent of the water inflow field about the suction intake is not yet fully determined as a function of cutter head operational parameters such as suction pipe flow rate, cutter head rotational speed, swing speed and placement of the cutter head in sediment. He recommended further laboratory investigations to address this knowledge gap. He also recommended the addition of sediment into such experiments and the use of particle image velocimetry and high speed cameras to provide a more accurate model of the region of sediment inflow.

Den Burger (2003), Dekker et al. (2003) and Henriksen (2010) recognised that the concentration of particles could be important for the processes taking place inside the cutter head. The role and importance of fluid-particle, particle-particle and particle-blade interactions will change in response to increased particle concentrations;

furthermore, the flow patterns inside the cutter head will be altered. An additional factor to be considered is the PSD of the material in the cutter head, since the dynamics of particle trajectories and their interactions varies with particle size. The relationships between resuspension and the cutter head operating parameters may therefore be significantly influenced by an increase in the concentration or a change in PSD of solids within the cutter head. Little work appears to have been done to clarify these influences on resuspension from a cutter head.

Spillage rates can be up to 50 per cent when hard formations are cut (Den Burger et al. 2005). The fines content in this spillage is potentially available for resuspension. CSDs cutting hard rock can generate significant amounts of resuspended fines (e.g. Lorenz 1999, Fitzpatrick et al. 2009, Mulligan 2009). However, as discussed in section 3.1.2, there is still very limited ability to provide quantitative predictions of the extent to which hard material will disintegrate under the action of the cutter head and what the resultant fines fraction will be (Barber et al. 2012). Only limited resuspension data have been published for a cutter head dredging hard material. The physics of release of fines from the cutter head (as part of a mixture of different sized rock fragments) has not been fully addressed in the literature.

The zone of turbulent flow surrounding the working cutter head has not been studied in three-dimensions (Henriksen 2010). The interaction of that turbulent flow with an ambient current and the resultant change in the zone size and configuration is not known. Sediment released from the cutter head is mixed by the surrounding turbulent flow zone and develops a concentration distribution that also depends on the mass flux and settling velocity characteristics of the released material. Once the dredge plume has moved beyond this highly turbulent zone it continues to be transported by the ambient hydrodynamics while differential settling of particles occurs. When differential settling is complete the plume will exhibit far-field behaviour. High frequency measurements of resuspended sediment concentration and water velocity around and downstream of a cutter head dredging sediment in the presence of an ambient current are required to address these issues and to develop models for predicting far-field dredge plume source terms related to cutter head action. This work could be conducted both in the laboratory and in the field.

7. Suspended sediment loss from dredged material placement

Proposals for port infrastructure development are required to consider the potential for avoidance or minimisation of environmental impacts that could arise from disposal of dredged material. For example, unconfined, open disposal of clean dredge spoil in Western Australian waters should only be considered after the environmental costs and benefits of alternatives have been evaluated (Environmental Protection Authority 2011).

Such alternatives might include (SKM 2013):

- engineered and product uses such as land creation, beach nourishment, fill material for future infrastructure projects, park creation, shoreline stabilisation and erosion control;
- agriculture and related uses such as enhancement of soils in agriculture, forestry and aquaculture, and related uses such as mine rehabilitation; and
- environmental enhancement such as habitat development, restoration of tidal flats, mud flats, salt marshes, wetlands and nesting habitats.

This section will focus mainly on suspended sediment sources arising from disposal of dredged material at sea. These sources consist mainly of fine-grained sediment and represent that part of the disposed material that is entrained into the surrounding water column rather than accumulating as a mound on the seabed. They are also sometimes referred to as suspended sediment losses in the sense that they represent disposed material that is suspended and not retained at the placement site. These suspended sediment sources generate turbid plumes which may be transported considerable distances away from their source locations by ambient currents and waves and thereby may pose a risk to living marine resources outside of the material placement area (Ferry 2003). The review will also touch briefly on suspended sediment sources from land creation and fill activities.

7.1 Disposal at sea

Subject to regulatory conditions, dredged material may be loaded to a hopper barge or TSHD for transport and discharge at a designated offshore placement site. The vessel is unloaded by opening doors or valves in the base of the hopper. In the case of a split hull barge, the hull of the whole barge splits longitudinally between the end bulkheads to discharge the load. The unloaded vessel then returns to the dredging site to reload. This cycle is repeated many times during the course of a dredged material disposal campaign giving rise to a series of discrete discharges at the placement site which typically occur at intervals of several hours.

There are a number of processes and time scales that need to be considered in relation to the release and transport of suspended sediment from dredged material discharge operations at sea. Some of these are listed below.

- Individual disposal events may last from a minute to half an hour (e.g. Vlasblom 2005a, SKM 2013) depending on the volume and characteristics of the material load and the hopper discharge configuration and method. A proportion of the fine sediment in the disposed material is entrained into the surrounding water from the rapidly descending bulk load and from a bottom sediment suspension layer which forms when the disposed material impacts the seabed (e.g. Johnson et al. 1992, Aarninkhof & Luijendijk 2010, SKM 2013). These suspended sediment sources contribute to the formation of turbid plumes which are transported away from the site by prevailing currents. The magnitude of these sources varies depending on the quantity, type and sediment size characteristics of the material dumped, the rates and mechanisms of its release from the hopper, the water depth and the prevailing oceanographic conditions (waves and currents).
- The interval between successive disposal events is typically a few hours and the sequence of disposal events may last for weeks to months depending on the duration of the dredging operations. This will give rise to a sequence of suspended sediment sources generating turbid plumes at intervals of a few hours over this extended period.
- Some fine material will not be lost immediately as suspended sediment plumes but will be deposited and will accumulate on the seabed at the disposal site along with coarser material. Elevated levels of silts and clays may therefore develop in the sediments of the disposal area.
- Under typical moderate to low energy conditions, fine material deposited on the bed may initially be winnowed from the sediment surface leaving an upper layer of coarse material that protects underlying fines from being resuspended. Once the bed has been 'armoured' in this way it will take a high energy event to mobilise the sediment and expose more of the underlying fine material so that it is again susceptible to resuspension.
- Other bed processes (e.g. consolidation of dredged material after placement and wave-induced fluidization) may make the sea bed more or less resistant to erosion and affect the time scales of sediment resuspension.
- Increased levels of fines may be found beyond the disposal area, both during and subsequent to the disposal campaign, due to transport, settling and accumulation of fines from disposal event plumes and bed erosion of deposited dredged sediments.
- Ferry (2003) reported a significant reduction after three years from the levels of fines recorded in the placement area at the conclusion of a four month disposal campaign. He concluded that bed erosion had resulted in the transport of potentially large quantities of fine dredged sediments outside of the material placement site boundaries. He also concluded that the erosion and dispersal of fines in dredged material disposed to placement sites may occur over a period of several years in response to a combination of

infrequent high intensity storms, occasional localised storm activity and more typical wave and current conditions.

SKM (2013) noted in relation to maintenance dredging that placement of the dredged material has the potential to increase sediment mobility and suspended sediment concentrations, even if not representing a new sediment input to the system, by making the sediment more susceptible to resuspension.

While all of the above-mentioned processes and their associated time scales are potentially important, this review will focus primarily on the short-term fate of material released from individual disposal events.

7.1.1 Processes

The processes which operate during the disposal of dredged material from a TSHD or hopper barge have been described and discussed by a number of authors (e.g. Johnson et al. 1992, Wolanski et al. 1992, Ruggaber 2000, Dankers 2002, Vlasblom 2005a, Aarninkhof & Luijendijk 2010, Van Rhee 2010, Gensheimer et al. 2012, Nguyen et al. 2012).

Vlasblom (2005a) and Van Rhee (2010) discussed the rate of material discharge from the hopper and its dependence on soil type and hopper design. Full disposal of the load can be achieved within minutes for free flowing soils but for some cohesive soils it may take around half an hour. For efficient discharge of silt slurries it has been found that a total discharge area of at least 10 per cent of the horizontal section area of the hopper is required. This requirement may increase up to 50 per cent for very cohesive soils some of which tend to adhere to hopper surfaces making it difficult to fully empty the hopper. In this case high pressure pumps may be used to erode or fluidise the material (Vlasblom 2005a).

The quasi-steady release from the hopper of unconsolidated fine sediment or highly liquid mud generates a negatively-buoyant fluid-like jet (e.g. Aarninkhof & Luijendijk 2010, Van Rhee 2010). The particles and water in the jet move downward with a vertical velocity typically in the order of 1 m/s (Van Rhee 2010), far greater than the individual particle settling velocities. Sea water is entrained into the descending jet, reducing its excess density and increasing its volume. Once the jet impacts the seabed it forms a dense, suspended sediment layer which spreads out from the impact zone. Bed material may also be resuspended as a result of the impact. Particle deposition occurs while the dense layer spreads across the sea bed, leading to reductions in the suspended sediment concentration, excess density, thickness and spreading velocity of the layer. Ultimately the density layer breaks down and is mixed with surrounding water.

Fine sediment particles are stripped from the negatively-buoyant jet as it descends through the water column. Fine material is also released as the collapsing bed density layer is mixed with overlying water by ambient turbulence. These mechanisms entrain a proportion of the discharged sediment load into the surrounding water column where they form passive plumes whose behaviour is governed by the ambient hydrodynamics and the particle settling velocities (e.g. Aarninkhof & Luijendijk 2010).

Wolanski et al. (1992) investigated hopper discharge of fine sediment from both a stationary and a moving TSHD. They noted a considerable increase in the initial dilution of the discharge in the turbulent wake of the dredger when under way during disposal. This could have a marked effect on the amount of sediment entrained into the surrounding water column and lost from the disposal site.

During laboratory experiments which modelled the disposal of fine disaggregated sediments at sea, Johnson et al. (1992) observed a series of discrete particle clouds convecting downward, with fine material being stripped into the surrounding water column. During convective descent the horizontal velocity of the clouds tended to approach that of the ambient fluid. Provided these clouds impinged on the bed with sufficient momentum they generated radial 'surges' of suspended material prior to collapse. Johnson et al. (1992) and Johnson and Fong (1995) attributed the formation of the particle clouds to inhomogeneities in the material stored in the hopper and to unsteadiness in the material release rate. Johnson et al. (1992) also found that moving disposal vessels tend to create suspended sediment plumes as a result of a shearing effect around the level of material release from the hopper that can leave extremely fine material suspended in the upper water column.

Dankers (2002) cited several mechanisms for the formation of particle clouds: discontinuous or unsteady release rates; the stretching and breaking up of a continuous dynamic plume as it encounters sheared flow; and the entrainment of lighter particles by heavier particles during initial rapid descent.

In some cases the dredged material falling through the water column may contain large clumps of material and these may be subject to erosion (and generation of fine particles) during their rapid descent through the water column (Van Rhee 2010).

It is beyond the scope of this report to provide a detailed review of the dynamics of particle clouds. Instead, the reader is referred to the works of Li (1997), Ruggaber (2000), Bühler and Papantoniou (2001), Gensheimer (2010), Gensheimer et al. (2012) and Nguyen et al. (2012).

Most authors have identified three distinct stages in the evolution of a particle cloud:

- convective descent;
- dynamic collapse / horizontal spreading; and
- passive diffusion.

The convective descent of the particle cloud is driven by its negative buoyancy. As it descends the particle cloud entrains ambient seawater and decelerates due to a reduction in its negative buoyancy. The particle cloud collapses either when it has entrained sufficient seawater and has reached a level of neutral buoyancy or when the cloud impacts the bottom. As the cloud collapses it spreads horizontally. Passive diffusion occurs when the dynamic (density-driven) spreading of the cloud has ceased and when the dominant mechanisms transporting the particles are advection and diffusion by the ambient hydrodynamics and the settling velocities of the particles themselves.

The convective descent stage can be divided into three phases according to descent velocity of the cloud:

- the initial acceleration phase;
- the thermal phase; and
- the dispersive phase.

A brief description of these phases, drawn from Gensheimer (2010), is given below.

Upon release, the closely packed sediment or sediment/water mixture accelerates and expands rapidly as it entrains ambient water. The entrainment of water reduces the density difference between the cloud and the ambient environment and, after reaching its maximum velocity, the cloud begins to decelerate and enter its second phase. Experimental investigations have demonstrated that the length scale for the initial acceleration phase of particle clouds is around one to three initial cloud diameters (Li 1997).

As the particle cloud continues into its second phase, it behaves as if there has been a sudden release of negative buoyancy; this is called a ‘dense thermal’. Ongoing entrainment of water reduces the excess density of the cloud and the descent of the cloud is decelerated. As eddies on the cloud boundary grow and more ambient fluid is entrained into its top side, the descending cloud may evolve into an axisymmetric vortex ring or spherical vortex. The spherical vortex continues to entrain water and particles from the trailing stem (an elongated set of particles that were not originally incorporated into the cloud). This leads to greater horizontal spreading or flattening of the particle cloud which assumes the form of an inverted mushroom-shaped thermal.

Eventually, if there is sufficient depth of water, the vertical velocity of the descending cloud reduces to an extent where it is similar to the settling velocity of individual particles in the cloud. The internal circulation of the thermal is suppressed and not able to hold particles in suspension. Particles individually settle out of the neutrally-buoyant cloud and form what is referred to as a ‘swarm’. This phase is referred to as the dispersive phase. In the thermal stage the fluid inside the cloud moves more or less in unison with the particles, whilst the interstitial fluid in the dispersive or swarm stage remains nearly motionless as the particles rain through (Bühler & Papantoniou 2001).

The thermal phase of convective descent and the collapse of particle clouds on the seabed are generally of primary interest in relation to the 'loss' of suspended material from dredged material disposal operations .

In the thermal phase most of the sediment is incorporated into the mushroom-shaped cloud (or parent cloud). However some sediment is also contained in an irregular trailing stem. The material in the trailing stem is generally finer and is more readily dispersed by currents and waves (Gensheimer 2010). Discharge of hopper load material into ambient currents causes more mass to be left out of the ambient cloud and be part of the trailing stem. Gensheimer (2010) concluded that this effect increases rapidly with increasing current speed. Releases above or below the water surface caused more material to form part of the trailing stem compared to releases at the water surface. For larger particle sizes more of the released mass is incorporated in the parent cloud.

Drapeau et al. (1999) observed that bed density currents formed only when the descent velocity of the particle cloud at impact was significantly greater than a representative particle settling velocity. On this basis they developed a kinetic energy index which correlated with the proportion of sediment that formed into a density current. This provides a measure of the amount of sediment potentially available for resuspension from the collapsing density current. Because the descent velocity of a cloud decelerates as it descends, this proportion decreases as water depth increases.

7.1.2 Field measurements

Short- term resuspension losses

Gensheimer (2010) described eight field investigations (Gordon 1974, Sustar & Wakeman 1977, Bokuniewicz et al. 1978, Tavolaro 1982, Science Applications International Corporation 1984, Tavolaro 1984, Truitt 1986, Science Applications International Corporation 1988, Truitt 1988) which sought to estimate the quantity of material (expressed as a percentage of the dredged material load released) that is entrained into the water column and remains in suspension following the disposal event. These estimates were made either by direct measurements of turbidity, suspended sediment concentration and current velocity in the water column, or by adopting a mass balance approach based on dry masses and bathymetric data, taken before and after disposal. Reported fines contents of the material loads were high, dumped volumes were in the range 840 to 2780 m^3, water depths at various disposal sites ranged from 14 to 94 m and currents were 0.3 m s^{-1} or less. Estimates of resuspension losses from dredged material disposal events monitored during these investigations ranged from about one to six per cent of the sediment released.

Land and Bray (2000) reported resuspension losses from six dredge spoil disposal events: two from a split hull dredger and four from a twin hopper dredger with bottom valves. The discharged material was a mixture of clay (30%), silt (55%) and fine sand (15%). Water depths ranged from 30 to 45 m. Plume transect measurements were conducted at about 300 m downstream of the disposal location using ADPs to quantify the net amount of suspended sediment leaving the disposal area. Resuspension losses for the split hull dredger disposal events ranged from 0.86 to 2.09 per cent, whereas losses from the twin hopper disposal events were generally larger, ranging from 5.33 to 8.74 per cent. The capabilities of the split hull dredger to dredge mud at high density and to rapidly discharge its hopper load were invoked by Land and Bray (2000) as reasons for the relatively low resuspension losses associated with disposal from this dredger. They noted that the twin hopper dredger discharged its load of low density material relatively slowly and had to flush its hoppers to fully empty them of soil, giving rise to much larger resuspension losses.

Land and Bray (2000) also reported percentage loss rate estimates for six barge disposal events. The mixture volumes in the hoppers ranged from 400 to 1000 m^3 and the dry densities of the mixtures ranged from 0.75 to 1.23 T m^{-3}. Ambient current speeds during the disposal events were in the range 0.07 – 0.4 m s^{-1}. Estimated loss rates to resuspension were found to range from 1.1 to 3.1 per cent and were greatest for fine material loads of low mixture density. Dump events involving large volumes had smaller measured percentage losses than dump events involving small volumes. No clear relationship was found between measured percentage loss and current speed.

Dispersion of sediment clouds generated by the disposal of dredged material

Wolanski et al. (1992) monitored the disposal of mud (silty clay material with high water content) from a TSHD in a water depth of 12 m. The material descended rapidly to the seabed as a negatively-buoyant jet and then formed an elevated concentration suspension layer on the bottom. Acoustic soundings during a stationary disposal event under relatively quiescent conditions showed that the negatively-buoyant jet, on impacting the seabed, took the form of a rapidly spreading bottom suspension layer with an internal hydraulic jump at its leading edge. For the other monitored disposal events the TSHD discharged material while underway at around 2.5 m s^{-1} and no hydraulic jump was observed. For disposal from a moving vessel under calm conditions acoustic sounder transects perpendicular to the direction of the flow at 1, 6 and 10 minutes after disposal showed that an initial vertical column of turbid water (left in suspension following the disposal event) settled down in the form of a dome-shaped bottom suspension.

Wolanski et al. (1992) also observed that mud flocs settled out of the bottom suspension layer within about 15 minutes of the disposal event in calm weather and that the suspension did not move out of the dump site. In rough weather the settling of mud flocs was inhibited by wave-induced turbulence, the suspension was mobile and was transported away from the dump site.

Morris et al. (undated) investigated the dispersion of discrete suspended sediment plumes associated with dredged material disposal events from split hull hopper barges. The dredged material was predominantly unconsolidated silts and clays with a high water content. The material was released into water depths of 36 to 39 m and currents were generally weak to moderate (speeds of around 0.1 to 0.2 m s^{-1}). ADP, transmissometer and optical backscatter instruments were deployed from a survey vessel to gather background and plume transect turbidity data extending throughout the water column. The trajectories of the discrete plumes were tracked from a few minutes to several hours after release and multiple plume transects were conducted to investigate changes in the cross-section and relative turbidity of the plumes as they moved away from the release point. Water column samples were collected and analysed for suspended sediment concentration.

For a short period (10 to 15 minutes) after each disposal event, the sediment plume typically occurred as a vertical column of turbid water in the vicinity of the dredge material placement site (Morris et al. undated). The sediment plume was subject to advection by ambient currents, turbulent diffusion between different levels of the water column and particle settling. Horizontal dispersion of the plume was enhanced by vertical variations in both current speed and direction. Suspended sediment concentrations in the plume decreased with distance from the release location due to plume dispersion and mixing as well as particle settling. This reduction in concentration occurred more rapidly for portions of the plume in the upper and mid water column. The most turbid part of each sediment plume was located within 3 to 5 m of the seabed and the suspended sediment concentration in this part of the plume remained an order of magnitude greater than background for about an hour before decreasing toward background levels after a further three to four hours. Some additional extension of the sediment plume in near-surface waters occurred due to washing of residual sediment from the open disposal barge as it was towed away from the designated disposal area. Morris et al. (undated) does not provide any estimation of the percentage resuspension loss from the documented disposal events.

Van Parys et al. (2001) studied the evolution of turbidity plumes formed by hopper discharge of dredged material at two designated disposal sites off the Belgium coast. ADP and optical backscatter instruments were deployed on moorings at fixed locations and mounted on mobile survey vessels to gather water current and backscatter intensity data. Water samples were collected to calibrate the backscatter data to suspended sediment concentrations. A tidally-driven cycle of background turbidity was monitored and subtracted from the test data in order to determine the structure of turbidity plumes generated by the disposal events.

Data collected shortly after a disposal event revealed the presence of a vertical column of turbid water, the result of lighter sediment fractions that were released into the surrounding water column during the descent of the disposed material to the sea bed. Figure 11 shows the evolution of the initial column of turbidity as it moved down-current, dispersed and settled to form of a cloud close to the sea bed. Moored turbidity sensors registered the passage of the turbidity cloud as it was transported downstream of the release location. The near-surface moored sensors recorded a turbidity increase during 3 minutes only. Near the bottom it took 25 to 30 minutes before the turbidity returned to its background value.

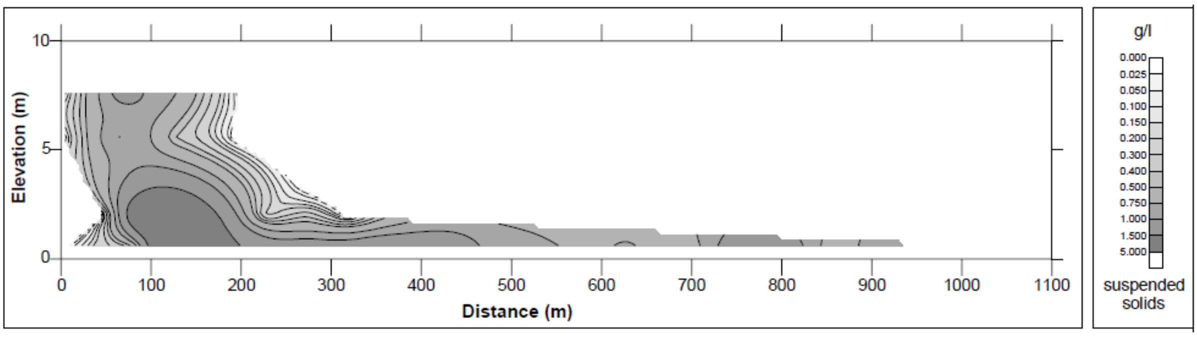

Figure 11. Tracking a turbidity cloud after a dredge spoil disposal event (from Van Parys et al. 2001). The cloud dispersed and settled as it was transported downstream. The data are corrected for background turbidity.

Density-driven bed currents

Drapeau et al. (1999) conducted field investigations of dredged sediment clouds impacting the sea bed following disposal events, and their potential to form density-driven bed currents (Gensheimer 2010). For different grain sizes, water depths and disposed volumes, they examined the proportion of sediment that settled upon impact versus the sediment that remained in suspension as a bed current. They reported the formation of density-driven bed currents with velocities of up to 0.5 m s^{-1} for disposal events conducted during slack water (tidal currents of around 0.02 m s^{-1}). They noted that bed currents formed only when the descent velocity of the particle cloud at impact was significantly greater than a representative particle settling velocity and they developed a kinetic energy index which correlated with the proportion of sediment that formed into a density-driven bed current.

With increased tidal current speeds it is probable that the bed current layers resulting from disposal events would, after some period of decay, be mixed into the overlying water column (e.g. HR Wallingford 2013a). Sediment resuspended as a result of this mixing would then behave as a passive plume.

7.1.3 Laboratory measurements

Johnson et al. (1992) conducted 1:50 scale laboratory tests to simulate sediment disposal from a split-hull barge and a multi-bin hopper vessel. Disposal tests were conducted from stationary and moving vessels. A series of small negatively-buoyant clouds was observed to form as the material was released into the water column. The average speed of descent of the clouds decreased with increasing test water depth. This was as a result of turbulent entrainment of ambient water which reduced the excess density of the particle clouds. From observations and measurements it was concluded that fine material was being stripped from the descending clouds into the surrounding water column. When the particle-laden clouds impinged on the bed they spread horizontally as a bottom suspended sediment 'surge'. It was also found that vessels that are moving during disposal tend to create near-surface plumes as a result of a shearing effect that can leave fine material suspended in the upper water column.

Gensheimer (2010) and Gensheimer et al. (2012) reported laboratory experiments to study the convective descent of particle clouds generated by the rapid release of sediment mixtures into a water body with cross-flow. This study focussed particularly on the 'thermal phase' of convective descent. Here the downward velocity of the cloud, driven by its excess density, is much greater than the settling velocity of its constituent particles. Entrainment of surrounding water reduces the negative buoyancy of the cloud leading to its downward deceleration. This phase of convective descent is often characterised by the development of an axisymmetric vortex ring which can take the form of an inverted mushroom-shaped cloud, referred to here as the 'parent cloud'. The parent cloud usually contains most of the released material, while the remainder forms a thin 'trailing stem' that is located above the parent cloud. Gensheimer (2010) states that the material in the trailing stem generally is composed of finer particles and is more susceptible to dispersion by currents and waves.

Gensheimer (2010) found that particle clouds exhibit three behavioural regimes which depend upon the strength of the ambient currents. Particle clouds are advected downstream in weak ambient currents and the behaviour and structure of the cloud is similar to that in still water: the vortex rings form at a similar depth and grow to a similar size. For clouds in transitional currents there is a delay and a distortion of vortex ring formation. In strong currents vortex rings never form and the structure of the particle clouds is destroyed. Gensheimer (2010) showed that the ambient current threshold values between the three regimes are dependent on particle size.

Gensheimer (2010) scaled his experimental results to represent two practical applications: disposal of 1 m^3 of 'field particles' (predominantly in the range 0.1 to 1 mm diameter) such as from a backhoe dredger; and disposal of 1000 m^3 of 'field clumps' (predominantly in the range of about 30 to 450 mm) such as from a split hull barge loaded with moist cohesive material. The scaled results of the experiments suggest (Gensheimer 2010, Gensheimer et al. 2012) that, for material released rapidly into 'weak' currents:

- the mass contained in the trailing stem (more susceptible to dispersion) may range up to 30 per cent of total material released for the 'field particles' and up to 15 per cent for the 'field clumps'; and
- the proportion of material transported beyond a circle of radius equal to the water depth and centred on the predicted landing location was found to be up to 28 per cent for 'field particles' and up to 3.5 per cent for 'field clumps'.

While these conclusions are of considerable interest, they do not directly address the rates of resuspension of fines (mainly silts and clays) from full-scale dredged material disposal events and their transport into the far-field. From an environmental perspective resuspended fines have a significant potential to generate widespread turbidity.

With respect to the practical applications of this work, Gensheimer (2010) recommended that 'losses' of particles and clumps could be reduced by timing disposal to coincide with weak currents and by encouraging the clumping of cohesive materials prior to release.

7.1.4 Numerical modelling

Suspended sediment plumes arising from dredged material disposal operations at sea may extend well beyond the boundaries of the material placement zone. The sediment transport in far-field plumes is governed by advection and turbulent diffusion from ambient currents and waves and by particle settling and resuspension from the seabed. Passive plume models are required together with input data on water currents, waves and suspended sediment source terms in order to predict the extent and intensity of environmental pressures from disposal events. The source terms incorporate information on the mass rates, settling characteristics, spatial distributions and the times and locations of introduction of the suspended sediments which give rise to the far-field plumes. In the case of predictions for environmental impact assessment these source terms need to be estimated or predicted prior to the commencement of the dredging and material placement campaign.

There are several approaches that can be employed to estimate these source terms. The first approach relies on field measurements from other similar disposal operations. The mass of sediment that remains suspended as it is transported away from the disposal location can be expressed as a percentage of the total mass discharged from the hopper. For example, Land and Bray (2000) derived percentage 'losses' for various types of disposal operations by running repeated ADP transects across the disposal plume at a distance of 300 m downstream of the disposal site.

Passive plume models do not include all of the important physical processes represented in the near-field. They are therefore unable to simulate resuspension processes that are activated directly by the rapid descent and bed impact of the hopper load material. The source terms for passive models of the far-field plume therefore need to represent the outcomes of these initial resuspension processes, namely the mass flux, settling characteristics and vertical distribution of the suspended sediment leaving the disposal area.

SKM (2013) assumed that, as the dredged sediment descends, the finest 5 to 10 per cent are released into suspension and move away from the disposal site as a passive plume. This was represented as a source term in the passive model by distributing these fine sediments through the water column beneath the hopper. The high proportion of dredged material reaching the seabed was represented as a source term in the model by distributing it within a few metres of the seabed. Typically the coarser fractions of the material released near the seabed would be rapidly deposited and would not contribute to the far-field plume.

Another approach to predicting source terms is to model the near-field dynamics associated with the disposal event and thus to derive the resultant source characteristics of sediments resuspended into the water column. Those source characteristics can then be input to a passive dredge plume model for far-field simulations. In reality there is a two-way dynamic interaction between the near-field and its surroundings; coupling of near-field and far-field models can best represent this interaction (Aarninkhof & Luijendijk 2010).

It is beyond the scope of this report to provide a detailed review of models used to predict the near-field dynamics and sediment resuspension from dredged material disposal events at sea. Instead we shall present some examples of the development of different types and classes of near-field models and their application to the prediction of the short term fate of material from disposal operations.

Johnson and Fong (1995) developed a numerical model (STFATE) based on the concept of the release and convective descent of multiple hemispherical particle clouds. The release of multiple clouds provided a better representation of the effects of prolonged discharges (particularly from a moving vessel), discharges from multiple hopper bins and discharges of dredged material with heterogeneities. The model allowed particles to be stripped from the convecting clouds and to be transported as passive plumes by ambient currents while settling.

In order to calculate the dynamic collapse of the clouds on the seabed Johnson and Fong (1995) assumed that the total energy of the cloud at the moment of impact becomes available to drive a bottom density current and that the density current collapses as this energy is dissipated. The collapse phase of the model is terminated when the rate of spreading of the density current becomes less than an estimated rate of spreading due to background turbulent diffusion.

Finally, the particles entrained into the water column from the descending clouds and from the top of the bed density current were assumed to form passive sediment plumes transported by ambient currents. During validation of the STFATE model against laboratory test data the model calculated that about two to three per cent of the original material for silt and clay disposals was stripped from the parent cloud during descent (Johnson & Fong 1995).

Aarninkhof and Luijendijk (2010) modelled the resuspension rates and dispersion of fine sediments discharged from a TSHD within a designated material placement zone. The purpose of their investigation was to develop release strategies that would account for the variability of tidal currents and ensure that water quality criteria for suspended solids concentrations were able to be met at a specified distance beyond the boundaries of the placement zone. For this purpose they used a jet integral model coupled with a passive far-field model. The jet integral model, Jet3D (e.g. Morelissen 2007) was applied to simulate the release, descent and collapse on the seabed of the dynamic plume. Jet3D is based on a step-wise solution of the equations for the conservation of mass, momentum and buoyancy along the curved trajectory of the descending plume. The dispersion and entrainment parameters in the model are adjusted for sediment-laden plumes on the basis of an experimental database. Jet3D treats the sediment-water mixture in the dynamic plume as a bulk fluid whose density is related to the suspended sediment concentration. Because of its negative buoyancy the plume descends much more rapidly than the normal settling velocity of its individual particles. Jet3D can also represent complex processes involved in the formation, propagation and collapse of the density-driven bed current plume.

For the dredged material placement operations investigated by Aarninkhof and Luijendijk (2010), Jet3D simulations predicted that approximately 10 per cent of the discharged material was resuspended into the surrounding water during vertical descent of material from the hopper; the remaining 90 per cent of the material formed a density current after impact on the seabed. The contributions of resuspended sediment from the vertical descent and the collapse and mixing of the bed density current both served as inputs for the Delft3D passive plume dispersion model used by Aarninkhof and Luijendijk (2010).

Nguyen et al. (2012) and Wang et al. (2013) provide recent examples of research on numerical modelling of open water sediment disposal. Nguyen et al. (2012) developed a two-phase model which is able to correctly simulate the generation and vertical descent of a discharged material plume and the propagation of a density-driven current on the bottom as monitored in a large physical model testing facility by Villaret et al. (1998). The two-phase model takes into consideration fluid–solid and solid–solid interactions which become very important at high suspended sediment concentrations. The model allows the fluid and solid phase velocities to differ. Nguyen et al. (2012) states that these differences cannot be represented by classical single-phase numerical modelling based on the passive-scalar hypothesis which stipulates that the solid particles move at the same speed as the fluid ones, except for the vertical component of velocity. Wang et al. (2013) reported investigations of the settling of particle clouds using a three-dimensional CFD model via a series of multi-phase, large eddy simulations (LES), with individual particle tracking and particle-fluid interactions. LES can be used to resolve the larger turbulent eddies in a descending sediment disposal plume. These eddies possess the majority of the turbulent kinetic energy and may play an important role in releasing discharged material into the surrounding ambient water column.

7.2 Disposal on land

Land reclamation for construction of port and associated infrastructure may, in some circumstances, be the most suitable option for beneficial use of dredged material. The dredged material can be pumped to the reclamation area either directly or from a hopper barge or TSHD (SKM 2013). The reclamation area typically includes retaining walls, settling ponds and discharge points that allow for controlled release of excess water.

The dredged material - water mixture is pumped into the reclamation area. As the mixture transits through a series of settling ponds the coarser particles settle more readily leaving increasingly finer particles in suspension. Small water velocities and low turbulence levels are desirable to facilitate settling. Ultimately, however, the ponds need to be shallow enough to allow the material to dry out and form soils that can be used for their intended purposes. In managing the settling ponds a balance is therefore required to ensure that most of the material does settle but that the material drying time is not too long. Settling is also critical from an environmental point of view to limit the release of suspended sediment in the discharge to the marine environment and to ensure that the resultant suspended sediment plumes do not pose unacceptable risks to marine beneficial uses or environmental values.

Current design practice is to comply with a conservative upper limit for the suspended sediment concentration in the discharge. This concentration together with an estimate of the discharge flow rate (generally assumed to be equal to the rate of pumped inflow) can be used to calculate the suspended sediment source strength for input to a passive dredge plume model. The source PSD is estimated on the basis of measurements from other similar discharges and generally consists predominantly of fine silt or clay-sized particles. The source vertical distribution of suspended sediments from the discharge is typically assumed to be distributed throughout the water column, particularly where the depth of water into which the discharge occurs is small.

The settling and resuspension of particles and their rates and pathways of transport toward the discharge points of the reclamation area are important in determining the load of suspended sediments discharged back to the ocean. These processes are influenced by the concentration and settling characteristics of solids in the dredged material slurry inflow and its volume rate of inflow. Other important factors include the dimensions and configuration of the settling ponds, their exposure to wind, the material accumulation and bed evolution of the settling ponds and controls on pond outlet discharges (BMT Group 2014).

Existing design guidelines are based on previous experience and monitoring of the performance of dredged material settling pond arrays, however they do not account in sufficient detail for the physical processes at work and, in particular, the way that these processes operate under local conditions and in response to alternative design options (BMT Group 2014).

To address this situation process-based numerical models are being developed to simulate the performance of settling pond systems, including their overall capacity, evolution of the movable sediment bed and loadings of suspended sediment to the marine environment from tail water discharge (e.g. BMT Group 2014). These models will take into account project-specific dredged sediment types and local meteorological conditions. They will be used to explore alternative designs, including basin geometry, internal bund walls and overflow weir arrangements, in order to optimise the performance of the land reclamation facility while limiting its footprint (BMT Group 2014).

7.3 Knowledge gaps

Considerable attention has been given to evaluating sediment resuspension during individual dredge spoil disposal events at sea. However the processes involved are still not fully understood.

Most of the reviewed field and laboratory investigations of fine sediment resuspension rates from disposal events did not quantify the distinct contributions to the far-field plume which arise from the descending dredged material plume or cloud, and from the density-driven bed current.

When the descending plume or particle cloud from the dredged material disposal event impacts the sea bed there is potential for resuspension of sediment that was on the bed prior to the dredge spoil release. However this contribution to the density-driven bed current has not been investigated.

Attention also needs to be given to sediment resuspension from the erosion of bed material containing elevated levels of fines that have accumulated during the course of extended dredged material placement campaigns. These sources may continue to contribute to the suspended sediment and turbidity regimes in areas surrounding the disposal site over longer time scales of months to years. They may be influenced by a range of factors, including: the characteristics of the bed and the dredged material; the variability of the bed shear stress (as determined by ambient current and wave variability); and various bed processes (e.g. armouring, consolidation, bioturbation and wave-induced fluidisation) which render the bed more or less susceptible to erosion. The influence of these processes requires further study and may vary significantly between sites.

Process-based models are being developed to simulate the performance of settling pond systems and to evaluate alternative designs and management strategies. Fit-for-purpose data sets will be required to evaluate the process representation and predictions of these models. The models will need to be validated for a number of case studies encompassing a range of dredge material types, input characteristics, pond layouts, management controls and meteorological conditions. Model validation will need to encompass various aspects of the performance of the settling pond system, including the need to meet acceptable suspended sediment release rates to the marine environment. Monitoring programs need to be developed to meet the requirements for a thorough validation of these process-based settling pond models.

8. Conclusions

This review addresses the generation and resuspension of sediments by hydraulic dredgers and the development of dredge plumes within the near-field. The dredger types considered here are the trailing suction hopper dredger and the cutter suction dredger. These dredger types typically remove the bulk of material for major dredging projects. The review is motivated by the need to specify suspended sediment source terms as inputs to passive dredge plume models to be able to simulate and predict the extent and severity of far-field dredge plumes and their environmental impacts. The source term inputs to the passive dredge plume model are generally specified in terms of a resuspended sediment mass flux, settling velocity distribution and a vertical concentration distribution through the water column, and are applied at specified locations and times depending on the activities and movements of the dredger.

Dredge plume predictions for environmental impact assessment are required before commencement of actual dredging. The source term estimates therefore need to be derived either empirically, using existing resuspension data from similar dredging operations, or from calibrated source models based on an understanding of the processes of sediment generation and near-field resuspension by dredging. Ideally the two approaches can be used to increase confidence in the source term estimates.

This literature review identifies sources of empirical data and studies which focus on process understanding relevant to the estimation of dredge plume sediment source terms. Process understanding can be developed through carefully-designed field measurement trials and laboratory-scale experiments. Process understanding supported by adequate data sets is required to build and validate predictive models. Comprehensive, high quality data sets can be developed by the application of effective measurement technologies and rigorous measurement protocols applicable to dredging. In order to thoroughly test and maximise the utility of the predictive models there is a need to develop an extensive data base which covers a representative range of dredging equipment, operating characteristics, work methods, soil types and site conditions.

The information in this review has been arranged according to five main topics:

- dredge-induced sediment generation, which relates to the development of the PSD of dredged material during excavation, mixture formation and hydraulic removal and transport (section 3);
- sedimentation in the hopper and suspended sediment release via hopper overflow when dredged material is loaded to a hopper barge or TSHD (section 4);
- sources of sediment release, near-field plume behaviour and far-field sediment source terms from TSHDs (section 5);
- sources of sediment release, near-field plume behaviour and far-field sediment source terms from CSDs (section 6); and
- suspended sediment losses from dredged material placement operations (section 7).

Each of these sections concludes with a sub-section that discusses key issues and critical knowledge gaps.

Dredge-induced sediment generation

Break down and development of the PSD of dredged material during excavation, mixture formation and hydraulic removal and transport is an important issue. From an environmental perspective it influences the settling characteristics and mass flux of sediment resuspended into the water column by dredging operations and thereby influences the development, extent and intensity of suspended sediment dredge plumes.

Currently there is a general understanding of the failure modes of intact rock and clay material and of the influence of key geotechnical parameters on the breakdown of these materials when cut by dredgers (Barber et al. 2012). However detailed predictive estimates of PSDs from the cutting action of dredge heads still appear to be based on empirical data and professional judgements.

Some weak to moderate strength sedimentary rocks are considered to be vulnerable to attrition during mixture formation in the cutter head even though the cutting action itself may not have generated a significant proportion of fines. The attrition of these materials during mixture formation has been attributed to turbulent, abrasive flow and particle collisions within the cutter head (HR Wallingford 2010a).

Barber et al. (2012) discussed key aspects of hydraulic transport that influence material attrition, including flow regimes, particle settling velocity, pipe inclination, the effects of the solids on the hydraulic gradients and the passage of solids through the centrifugal pump. However understanding and ability to predict particle attrition during hydraulic transport is still limited.

None of the standardised laboratory-scale tests commonly used to assess material attrition (in industries such as road construction engineering) represents well the conditions found in dredging applications and little information is available regarding the calibration of laboratory-scale test parameters or scaling test results to actual dredging situations. More representative, specifically-designed, tests are required to properly represent the physical processes to which materials are subject during dredging (Costaras et al. 2011).

There is currently very little published field data that documents PSD development in dredged material at various points along the full-scale dredging production line. Standard protocols for the collection of such data are required; the data are needed to validate the interpretation of laboratory tests and to fine tune test parameters.

Sedimentation in hoppers and overflow

When dredged material is hydraulically pumped into a TSHD hopper or hopper barge, coarse particles settle inside the hopper to form a material bed while fine particles tend to remain in suspension in a solid-water mixture overlying the bed. As dredging continues the hopper fills to a level at which the mixture overflows and is discharged to sea. The fine particles contained in this mixture are thereby released to the marine environment where they form turbid dredge plumes.

The processes at work during hopper loading and overflow have been investigated both in the laboratory and during full-scale TSHD dredging operations (e.g. Van Rhee 2002b, Ouwerkerk et al. 2007). These investigations revealed the importance of density effects on the hopper flow field. The dense, inflowing dredged material slurry descends, impacts the sediment bed, forms a scour hole and then spreads horizontally across the hopper bed as a density-driven current. Sediments are deposited from this spreading density current causing the bed level to rise (and helping to maintain mixture density gradients). The largest horizontal velocities occur just above the bed within the generated density current. Horizontal shear stress at the bed is an important factor controlling net sediment deposition rate. Velocities above the density current (and away from the inlet zone) are small and upwardly directed throughout most of the hopper volume. Finer fractions of the incoming sediment move into suspension within the hopper and develop a suspended sediment concentration profile through the water column with reduced concentrations near the surface. This profile represents a balance between net upward flow in the hopper, particle settling velocity and vertical turbulent diffusion. The near-surface mixture flows toward the overflow weir and is discharged.

Van Rhee (2002b) developed a two-dimensional (2DV) numerical model to simulate the density gradients, flow fields, deposition of sediment, development of the bed and transport of suspended particles within the hopper as well as the discharge and sediment flux in the overflow. The 2DV model was validated using laboratory-scale test results and hopper measurements during full-scale dredging of sandy material.

Other less computationally-intensive models have also been used to estimate sediment flux in the overflow (e.g. Camp 1946, Miedema & Vlasblom 1996, Ooijens 1999). However a model which more accurately represents the key physical processes should be used to investigate the sensitivity of the overflow to factors such as loading and overflow system configurations and hopper geometry (Lloyd Jones et al. 2010).

Most process-based investigations of hopper dynamics, sedimentation and overflow have been carried out in relation to the dredging of unconsolidated *in situ* sediments (Van Rhee 2002b, Ouwerkerk et al. 2007, Miedema 2008). However it is not uncommon for TSHDs and hopper barges to be loaded with crushed / cut rock or cohesive bed material. For these cases the detailed understanding of hopper processes and the ability to predict retention and overflow of solids from the hopper is less well developed.

There is a need to establish techniques for measuring the PSD of material entering the hopper, since these data are required as inputs to hopper process and overflow models (Van Rhee 2002b, HR Wallingford 2013a). Such measurements are not currently available and an assumed PSD has to be used.

When the dredged material entering the hopper consists of a mixture of particles ranging from large rock pieces through to fines it has been suggested (HR Wallingford 2013b) that the rapid fall of the large particles may increase turbulence levels in the hopper, thereby enhancing the range of particle sizes that are able to remain in suspension. The hydraulic lifting of the large rock pieces requires a larger suction pipe velocity and therefore a greater incoming mixture flow rate which will reduce hopper residence time and further increase the level of turbulence. Turbulence in the hopper and its influence on sediment flux in the overflow may require further investigation in this context.

Predictions of sediment source characteristics in the overflow when dredging cohesive bed material require a better understanding of the size, density and settling characteristics of bed aggregates loaded to the hopper. In this connection it would also be useful to investigate the potential occurrence and characteristics of flocculated material within the hopper and the overflow (Smith 2010).

Sediment release from TSHDs

Hopper overflow discharge is generally acknowledged to generate the largest potential source rate of sediment resuspension from TSHD dredging activities. Propeller-induced erosion of bed material may also constitute an important source of resuspension when the TSHD is operating with limited under-keel clearance (Spearman et al. 2007, HR Wallingford 2013b). Sediment release rates from drag head disturbance are reported to be orders of magnitude smaller than sediment release rates from the hopper overflow discharge (e.g. Burt & Hayes 2005, HR Wallingford 2013a).

The mixture discharged from the overflow pipe typically contains high concentrations of predominantly fine sediment and its bulk density significantly exceeds that of seawater. The overflow discharge occurs from a moving TSHD into a flowing water body. It forms a negatively-buoyant, dynamic plume which descends through the water column while being forced downstream by ambient cross-flow. In dynamic plumes the suspended sediment and water tend to move together like a bulk fluid and the vertical velocity can be much greater than the settling velocities of the individual sediment particles. The descending dynamic plume is diluted by the entrainment of surrounding seawater and this reduces the sediment concentration, excess density and rate of vertical descent of the plume.

When discharged into very strong cross-flow and water of sufficient depth the negatively-buoyant dynamic plume will at some stage be rapidly mixed with surrounding water as it transition from dynamic to passive plume behaviour. However when the excess density of the overflow is strong, the cross-flow weak and the water sufficiently shallow, the plume will remains dynamic till it reaches the sea bed.

In coastal waters the descending dynamic plume from TSHD hopper overflow generally reaches the seabed and forms a bed plume (i.e. a density current layer) on the seabed which undergoes gravitational spreading while also being advected downstream by the ambient current. As the bed plume spreads its layer thickness is reduced. Sediment progressively settles out of the layer, reducing the excess density and the spreading rate of the bed plume. Eventually the plume collapses as it is mixed into the overlying water and a passive plume is formed. This mixing process may be driven by ambient currents and waves, or by the influence of propeller jets if the propellers are sufficiently close to the seabed (Aarninkhof et al. 2010).

Observations and measurements (Nichols et al. 1990, Whiteside et al. 1995, John et al. 2000, Aarninkhof et al. 2010, Spearman et al. 2011) suggest that, close to the TSHD, some of the dynamic plume from the overflow can be mixed into near-surface waters to form a passive plume. This is now understood to occur due to interactions between the operating TSHD and its overflow plume, including the influence of the turbulent boundary layer around the vessel and the propeller jet.

Surface dredge plumes from TSHDs contain predominantly fine sediments (with low settling velocities) that originated mainly from the hopper overflow. As such, they are transported passively by the ambient currents and can remain suspended for hours while travelling considerable distances into the far-field.

In recent years there have been several investigations of overflow source characteristics, near-field behaviour of the dynamic plume from the overflow and the contributions of overflowed sediments to the far-field. These investigations have included full-scale field measurement programs, laboratory experiments and validated numerical model simulations.

Major issues that have been addressed by these investigations include:

- the compilation of reliable data on overflow source characteristics and their use to validate hopper process and overflow models (e.g. Aarninkhof 2008, Aarninkhof et al. 2010);
- criteria for the transition from dynamic to passive plume behaviour during descent of the overflow plume (Winterwerp 2002, De Wit 2010, Decrop et al. 2013);
- the formation and decay of density currents on the bed after the impact of the dynamic plume (e.g. HR Wallingford 2010b);
- the generation of a passive surface plume due to interactions between an operating TSHD and its overflow plume, including specific investigations of factors such as dredging speed, water depth, overflow location, propeller action, pulsing of the overflow discharge and air entrainment in the overflow (De Wit et al. 2014a, De Wit et al. 2014b, De Wit 2015); and
- contributions to the far-field from the passive surface plume and from the decaying density current on the seabed (e.g. Spearman et al. 2007).

TASS (Turbidity Assessment Software) is a process-based modelling system for the prediction of sediment resuspension rates from various dredging activities and the development of dredge plumes as they move away from the source (Burt et al. 2000, Aarninkhof et al. 2010). In recent years the TASS program has focused on developing rapid assessment predictive models for TSHDs (e.g. HR Wallingford 2013a).

More recent advances have occurred in the ability to accurately simulate the early stages of dredge plume development, including interactions between an operating TSHD, its overflow plume and the seabed (e.g. De Wit & Van Rhee 2013, De Wit et al. 2014a, De Wit et al. 2014b, Decrop et al. 2014, De Wit 2015). This has required the use of sophisticated CFD models. These models are well suited for scientific research to improve process understanding but they are computationally-intensive and are currently not intended to be routinely used for sediment resuspension and far-field dredge plume predictions for environmental impact assessment purposes. However, De Wit (2015) showed how the results of multiple dredge plume simulations could be converted into functional forms which can be used (with little computational effort) to predict the vertical distribution and flux of the overflow plume downstream of a TSHD. It is anticipated that the understanding and functional forms gained from this and other similar investigations will be incorporated into rapid assessment models such as the TASS model system (Aarninkhof et al. 2010).

The rate of bed erosion depends on the shear stress exerted by the propeller jet impinging on the seabed and on the nature of the bed material. The bed shear stress depends on the effective water velocity close to the bed and on a friction factor which varies with bed roughness. The effective water velocity close to the bed is determined by a range of parameters, including: propeller diameter; applied power; distance from the propeller shaft to the seabed; speed of the vessel; and ambient current velocity. Sediment resuspended as a result of bed erosion is generally considered to behave as a passive plume.

Sediment release from CSDs

For a CSD dredging soil, up to about 30 per cent of the cut material is spilled (i.e. not drawn into the suction intake). This may increase up to 50 per cent for a CSD dredging rock. Of the cut material that avoids the suction intake, a proportion will go into suspension causing turbidity in the surrounding water column while the remainder (mainly large particles) will deposit locally on the seabed. For normal CSD operations with offsite placement most of the sediment resuspension and turbidity around a CSD comes from the action of the cutter head.

Hayes (1986), Den Burger (2003), Palermo et al. (2008) and Henriksen (2010) have reviewed previous field measurement trials and laboratory tests of sediment resuspension from a cutter head. From these studies they found that the resuspension from a cutter head is dependent on:

- the nature of the *in situ* material;
- site conditions, including currents and waves;
- the type and distribution of impediments, such as debris, cobbles, boulders and obstructions;
- the design of the cutter head; and
- dredge operating parameters (including cutter rotation speed, suction intake speed, depth/thickness of cut, ladder angle, swing speed, cut type and production).

In situ solids concentration, grain size, grain shape, plasticity and soil classification are important parameters for resuspension when dredging sediments (Hayes et al. 2000, Henriksen 2010). For rock or other consolidated material, the proportion of fines generated as a result of the cutting and mixture formation processes strongly influences the rate of resuspension from the cutter head (e.g. HR Wallingford 2010a).

Hayes (1986) suggested that the majority of sediment resuspended during cutter head dredging operations is due to the 'washing' of particles that cling to the cutter blades during excavation. The washing occurs once the rotating blades emerge from the sediment bank and are exposed to the water column. Variables such as the thickness of cut, the ladder angle, the cutter radius, and the cutter length contribute to the amount of surface area exposed to washing.

Henriksen (2010) and Henriksen et al. (2012) conducted laboratory experiments to study resuspension from a cutter head dredging sand. In preliminary testing the highest turbidity was consistently observed in the area around the back of the cutter head. High frequency velocity and turbidity data were therefore collected on a plane coincident with the cutter ring. The variables of suction flow rate, cutter speed, and the thickness of cut were investigated to understand their specific effect on turbidity generation and turbulence production around the cutter head. There was no ambient current throughflow in these experiments.

Henriksen (2010) and Henriksen et al. (2012) reported the formulation of a numerical simulation model of sediment release and initial mixing around the cutter head. The model calculates the rate of sediment excavated by the cutter head and the proportion that escapes the influence of suction so that it can be released as the blades move through the water. The sediment release rate is then applied as the source term for a two-dimensional advection-diffusion model to simulate the suspended sediment concentration distribution which was typically found to extend up to a few diameters around the cutter head.

Operating parameters incorporated into the model included: cutter rotational velocity; suction flow rate; cut type (overcutting, undercutting); thickness of cut; ladder angle; and swing speed.

Resuspended sediment concentration simulations from the numerical model were compared directly against the results of laboratory tests by Henriksen (2010) and were scaled for comparison against CSD field measurement trials where the natural current speed was close to zero. The numerical model simulation results were found to be broadly comparable to the results from laboratory testing and the selected field trial data.

In reality the transport of sediment resuspended from a cutter head occurs in three-dimensions. Future laboratory and field investigations should therefore collect data in three-dimensions (Henriksen 2010). This will facilitate the development of a three-dimensional near-field cutter resuspension model and the incorporation of an ambient current. There is also a need to investigate resuspension for a wider range of material types and cutter head designs.

Suspended sediment loss from dredge material placement

Subject to regulatory conditions, dredged material may be loaded to a hopper barge or TSHD for transport and disposal at a designated offshore placement site. Part of the dredged material discharged from the base of the hopper is resuspended into the surrounding water column rather than accumulating on the seabed. The resuspension occurs in association with the rapid descent of the dredged material through the water column and also following impact of the dredged material with the sea bed and the formation and ultimate collapse of a density-driven bed plume. Both of these mechanisms contribute to a resuspension source of fine sediment that generates the turbid plume from the disposal event.

Gensheimer (2010) and Gensheimer et al. (2012) reported laboratory experiments to study the convective descent of particle clouds generated by the rapid release of sediment mixtures into a water body with cross-flow. The 'thermal phase' of convective descent is often characterised by the development of an axisymmetric vortex ring which can take the form of an inverted mushroom-shaped cloud, or 'parent cloud'. The parent cloud usually contains most of the released material, while the remainder forms a thin 'trailing stem' that is located above the parent cloud. Gensheimer (2010) states that the material in the trailing stem generally has a finer particle composition and is more susceptible to dispersion by currents and waves.

Drapeau et al. (1999) observed that density-driven bed plumes formed only when the descent velocity of the particle cloud at impact was significantly greater than a representative particle settling velocity. On this basis they developed a kinetic energy index which correlated with the proportion of sediment that formed into a density-driven bed plume. Because the descent velocity of a cloud decelerates as it descends, this proportion decreases as water depth increases. The proportion provides an upper estimate of the amount of sediment potentially available for resuspension from the collapsing density current.

Several approaches have been taken to modelling sediment resuspension and dredge plume generation from disposal events. Passive models used to simulate the transport of dredge plumes well beyond the placement site require source terms which specify the mass flux, PSD and vertical distribution of the sediment resuspended as a result of the disposal event. The source terms are estimated either from empirical data or by modelling / simulating the sediment release and evolution of the near-field plume to the point where it transitions to a passive or far-field plume.

Factors affecting sediment resuspension from dredged material disposal events include:

- soil type;
- volume, density and PSD of the hopper load;
- hopper discharge rate;
- discontinuous or unsteady release rates, leading to large turbulent billows and cloud formation;
- disposal from moving vessels (including shearing effects that can suspend fine material into the water column, and mixing effects of the turbulent wake);
- the speed and vertical shear of ambient currents;
- clearance between the vessel hull and the seabed; and
- the formation and decay of a density current at the seabed.

Gensheimer (2010) described eight field investigations which made estimates of the quantity of material resuspended into the surrounding water column during the disposal event. Estimates of resuspension losses from dredged material disposal events monitored during these investigations ranged from about one to six per cent of the sediment released.

Land and Bray (2000) reported resuspension losses from one to nine per cent from twelve disposal events involving a split hull hopper dredger, a twin hopper dredger with bottom valves and various hopper barges. They found that the loss rates for the split hull hopper dredger were less than for the twin hopper dredger and attributed this to the capability of split hull dredgers to dredge mud at high density and to rapidly discharge their hopper load. For the hopper barge disposal events the estimated loss rates to resuspension were found to range from 1.1 to 3.1 per cent and tended to be greater when disposing of fine materials of low mixture density. Hopper barge dump events involving large volumes had smaller measured percentage losses than dump events involving small volumes.

A typical work method with a TSHD consists of loading the hopper with dredged material, sailing to the placement site, discharging the material from the hopper and returning to the dredging area. This cycle is repeated many times during the course of a dredging campaign giving rise to a series of discrete discharges at the placement site at intervals of perhaps one to several hours.

Not all fine material will be lost from the disposal site immediately as turbid plumes; some will accumulate on the seabed as it is deposited along with coarser material.

The dispersal of accumulated fines in material disposed at placement sites may occur over longer periods (e.g. years) in response to a combination of infrequent high intensity storms, occasional localised storm activity and more typical wave and current conditions. In this context it is important to understand bed processes such as burial and armouring of potentially resuspendable material, consolidation and wave-induced fluidisation.

9. Recommendations

Each of the major sections of this review concludes with a sub-section that contains a discussion of the key issues and identifies critical knowledge gaps. Here we list key recommendations for further research which have arisen from this review.

- The level of attrition and PSD development in dredged material at various points along the full-scale dredging production line is not well documented. Alternative measurement methods should be trialled as a prelude to developing standard protocols and quality assurance procedures for the collection and reporting of these data.
- There is currently no widely-accepted, laboratory-scale test method of representing particle attrition processes experienced during full-scale dredging and more work is required to develop, calibrate and validate such tests.
- Methods should be trialled and standard protocols developed to appropriately characterise the PSD of solids entering the TSHD hopper, since this is a key input parameter for hopper process and overflow source models.
- Hopper processes should be investigated for situations where a mixture of coarse (e.g. rock pieces) and fine particles (e.g. silts) are pumped into the hopper.
- These investigations should include parameterisation of the increase in turbulence in the hopper due to enhanced flow rates and the rapid descent of large particles (e.g. rock pieces) to the hopper bed. Enhanced turbulence in the hopper may lead to an increased sediment flux in the overflow.
- The role of density effects on flow, bed shear stress and sediment transport in the hopper should be re-evaluated for cases where solids in the incoming mixture range from large pieces to fines particles.
- When dredging cohesive sediments, a better understanding of the size, density and settling velocity distributions of bed aggregates produced during the dredging process would lead to improved predictions of material deposited in the hopper and released in the overflow. This in turn would improve predictions of dredge plume behaviour.
- When dredging cohesive sediments, the occurrence and characteristics of flocculated material up to (and including) the stage of overflow discharge should be investigated to determine whether this has an influence on flocculation within the dredge plume.
- The zone of turbulent flow surrounding the working CSD cutter head should be studied in three-dimensions. The interaction of that turbulent flow zone with an ambient current should be investigated with a view to including the influence of the ambient current in sediment source and near-field plume models for the cutter head.

- Sediment resuspension from dredged material disposal events may be derived from both the descending dredged material plume and the density-driven bed current. When the descending plume or particle cloud from the dredged material disposal event impacts the sea bed there is potential for resuspension of sediment that was on the bed prior to the dredge spoil release. To address these issues, and to improve process understanding, dredged material disposal may be studied by conducting laboratory experiments in a recirculating water channel with a natural sediment bed.
- In assessing potential ecological impacts on marine biological communities surrounding a dredge spoil placement site, attention should be given, not only to plume generation from individual disposal events, but also to longer-term sediment resuspension from bed material containing elevated levels of fines that have accumulated during the course of extended dredged material placement campaigns.

Fundamental field and laboratory data are vital to empirical estimates of sediment source terms, process understanding and the development of validated dredge plume models. Many of the data sets that have been collected over the years are relevant to dredgers operating in relatively unconsolidated sediments. Only a few are relevant to other conditions, such as dredging harder materials, dredging with low under keel clearance, or with transverse currents. Yet conditions such as these are frequently encountered in large, capital dredging projects associated with port construction. Further measurement programs during full-scale dredging, and high quality data sets, are needed for source estimation and model validation purposes, particularly for site, material and operating conditions that are not currently well represented. It is sound practice to conduct mobile sediment flux monitoring of the dredge plume combined with on-vessel measurements once a dredging project has commenced (Bekker et al. 2015), as this provides a unique opportunity to test the initial source term predictions and assess source term estimation methods under a broader range of dredging conditions.

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