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Estimating source terms for far field dredge plume modelling

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ABSTRACT

Far field modelling of dredging induced suspended sediment plumes is important while assessing the environmental aspects of dredging. Realistic estimation of source terms, that define the suspended sediment input for far field dredge plume modelling, is key to any assessment. This paper describes a generic method for source term estimation as it is used in practice in the dredging industry. It is based on soil characteristics and dredge production figures, combined with empirically derived, equipment and condition specific 'source term fractions'. A source term fraction relates the suspended fine sediment that is available for dispersion, to the amount of fine sediment that is present in the soil and the way it is dredged. The use of source term fractions helps to circumvent modelling of complicated near field processes, at least initially, enabling quick assessments. When further detail is required and extra information is available, the applicability of the source term fractions can/should be evaluated by characterisation monitoring and/or near field modelling. An example of a fictitious yet realistic dredging project demonstrates how two different work methods can trigger two distinctly different types of stress to the environmental system in terms of sediment concentration and duration.

1. Introduction

Ongoing trends such as the urbanization of delta areas, growing global trade and energy demand, anticipated (accelerated) sea level rise, subsidence and climate change have triggered the development of large scale hydraulic infrastructure world wide, such as land reclamations, port development and a wide range of flood protection works. Growing environmental awareness and governance complexity (international, national and local regulations, active stakeholder involvement, etc) make the realisation of such hydraulic infrastructure projects increasingly challenging (Bray, 2008). Close attention to both the *process effects*, related to the project realisation process, and the *project effects*, related to the long term effect of the final project layout, is crucial for large scale economic developments to be integrated successfully into sensitive environments (De Vriend and Van Koningsveld, 2012; De Vriend et al., 2014a, b).

Suspended sediment plumes are one of the potential *process effects* of dredging projects inevitably associated with the (re)handling of sediment underwater. These plumes may cause environmental loss (light reduction and sedimentation at sensitive receptors, release of contaminants etc.) as well as environmental gain (release of nutrients, supply of fine sediments to silt rich habitats etc.), both of which need to be quantified. A common method to assess environmental response to dredge plumes involves hydrodynamic and suspended sediment transport modelling (either in 1D, 2D or 3D). The models simulate the processes driving sediment dispersion: advection, diffusion and settling (and sometimes re-suspension). The predicted water quality variations at the location of the sensitive receptors need to be interpreted and translated to environmental risk (Erftemeijer and Lewis III, 2006; Doorn-Groen, 2007; Becker, 2011; Erftemeijer et al., 2012; Dupuits, 2012).

Depending on the quality of the data available to drive the model (bathymetry, boundary conditions, etc.), the suitability of the numerical approach and the time available for calibration, general hydrodynamic and sediment transport patterns can be predicted with reasonable skill. Limitations in the understanding of ecosystem response to suspended sediment, and a lack of field data thereof, hinder an unambiguous translation of such water quality variations to environmental risk. Regardless of this uncertainty a crucial step in the modelling process is the estimation of a realistic 'dredge plume source term', or 'source term' for short, which

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defines the dredging related fine material input into the model (type of material, release rate and release location). Unrealistic 'source terms' will surely lead to unrealistic environmental assessments.

It is important to realise that 'source term' in this paper refers to the input for so-called far field models. Such models resolve continuity and momentum equations for fluid in combination with a continuity and transport equation for sediment, including processes of advection, diffusion and settling (and re-suspension), on a spatially and temporally specified grid. Far field models are suitable to assess the large scale spatial and temporal fate of dredge plumes. However, they do *not* resolve density currents, propeller wash effects and other dynamic processes associated with the near field development of dredge plumes. The source term thus does *not* relate to the sediment release directly at the dredger, but to the suspended sediment that remains available for passive transport at the end of the dynamic phase. The transition from the dynamic to the passive phase may be located as far as several hundred meters from the dredger. Source terms can be formulated either as a stationary source, such as an outflow from a dredged material deposit or settlement basin (De Lange, 2011) or (semi)stationary dredging equipment such as a Backhoe Dredger(BHD) and Cutter Suction Dredger(CSD), or as a moving source, such as non-stationary equipment like a Trailing Suction Hopper Dredger(TSHD).

Estimation of source terms can be complex. A dredge plume resulting from a TSHD overflow, for example, has a complicated dynamic phase that is difficult to predict in detail due to several interacting processes. The most significant processes are entrainment of ambient water into the negatively buoyant plume, interaction of the plume with the cross flow due to currents and TSHD trailing speed, entrainment of air in the overflow mixture, mixing by propellers of the TSHD and influences resulting from flow around the hull (Van Eekelen, 2007; De Wit, 2010; De Wit et al., 2014b). The relative importance of these processes may differ further depending on equipment specifications, work methods and environmental conditions (under-keel clearance, currents, project progress etc). Similar complications exist for other types of dredging equipment. The dynamic effects around a CSD cutter head (cf. Hayes et al. (2000); Henriksen et al. (2012)) or the bucket drip of a BHD moving through the water column, are equally complicated to model in detail. Such complexities hamper the quantification of the near-field effects and consequently of the source term to be used as model input.

The primary objective of this paper is to document the state-of-the-art of source term estimation. Plume sources for various equipment types are discussed qualitatively. A step-by-step procedure for estimation is presented and illustrated by means of a practical example. The full details of a source term analysis depend on equipment specifications and the work methods used. Timely consulting of dredging companies is crucial if these are to be incorporated. A secondary objective of this paper is to promote a more uniform approach to source term estimation. This will further improve environmental impact assessments of dredging projects world wide.

John et al. (2000) have suggested four methods to estimate source terms. The first is based on a sediment concentration increase (in mg/L) in the vicinity of the dredging activity (Bray et al., 1997). It is site specific and not suitable for application with a universal scope. The second describes a sediment release rate (in kg/s) into the water column at the vessel (Whiteside et al., 1995; Spearman et al., 2011). The success of this approach depends on the translation of the sediment release rate to far field input, which is difficult to generalise. The 'S-factor' approach is the third, in which the total mass of sediment put into suspension (in kg/m^3) is expressed relative to the quantity of material that is dredged (Blokland, 1988). The factor depends on soil class, equipment and ambient conditions. According to Pennekamp et al. (1996) the S-factor depends strongly on the way the equipment is used. The fourth and final is the sediment flux method, which describes the sediment loss through the boundaries of a designated area within which the dredger is working. This method was developed as part of the Øresund Fixed Link project, Denmark, but it is a measuring method rather than a sediment re-suspension description (Jansen, 1999).

In terms of the classification of John et al. (2000), the current best practice presented here is a combination of the second, third and fourth method, where a rate of release of fine material (in kg/s) is specified for the passive plume. The source term is estimated based on soil characteristics and dredge production figures, combined with empirically derived, equipment and condition specific 'source term fractions'. A source term fraction relates the suspended fine sediment that is available for dispersion, to the amount of fine sediment that is present in the soil and the way it is dredged. The use of source term fractions helps to circumvent modelling of complicated near field processes, at least initially, enabling quick assessments. When further detail is required and extra information is available, the applicability of the source term fractions can/should be evaluated by characterisation monitoring (see VBKO, 2003; Aarninkhof et al., 2007; for more detail) and/or near field modelling. Mobile sediment flux monitoring combined with on-vessel measurements is a key verification method. Each measurement supplements the database underlying the empirical source term fractions (Van Koningsveld et al., 2010, 2013). The following sections illustrate step-by-step how source term estimations may be performed for various types of dredging equipment. First a brief qualitative description of equipment types and potential plumes sources is provided.

2. Plume sources for various equipment types

2.1. Trailing Suction Hopper Dredgers (TSHDs)

The plume source of a TSHD can be divided into three main parts: spill caused by the drag head, spill caused by the overflow, and re-suspension due to propeller wash. A graphical representation is shown in Fig. 1.

The overflow plume is the most complex term and is created when a water-sediment mixture is discharged from the hopper, forming a negative-buoyant jet, or a so-called dynamic plume (Dankers, 2002). Dispersion of the plume depends on hydrodynamic circumstances and sediment properties. The plume can either be mixed with the surrounding water to form a passive plume or impinge on the bottom as a result of its momentum and propagate as a density current. In situ particle size distribution, disaggregation properties during dredging and the amount of sediment that is discharged all affect the plume.

For the characterisation of plumes in a cross flow, it is helpful to consider two dimensionless parameters: the plume Richardson number and the velocity ratio (Winterwerp, 2002). They are defined as follows:

$$Ri = \frac{g\Delta\rho_0/\rho_a D}{W_0^2}, \tag{1}$$

$$\zeta = \frac{U}{W_0}, \tag{2}$$

where g is the acceleration due to gravity, $\Delta\rho_0 = \rho_0 - \rho_a$ is the difference between initial plume density and ambient water

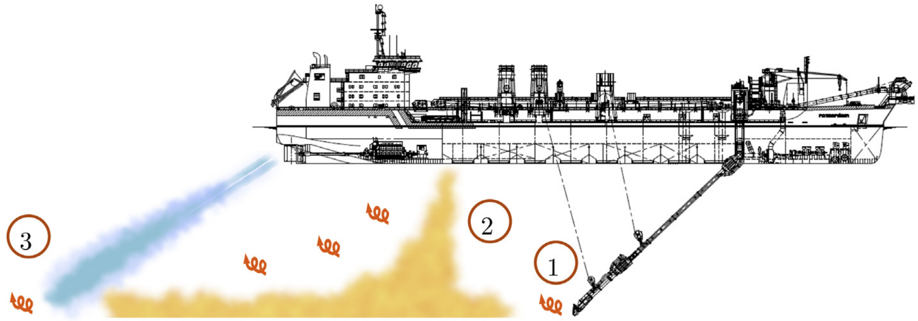

Fig. 1. Sources of a dredge plume for a Trailing Suction Hopper Dredger(TSHD): 1. drag head, 2. overflow and 3. propeller wash.

density, D is the initial plume diameter, W_0 is the initial vertical plume velocity and U is the ambient velocity of the cross flow. The Richardson number compares buoyancy with kinetic energy and the velocity ratio compares cross flow velocity with vertical plume velocity. Using these two parameters, Winterwerp (2002) devised the classification diagram as shown in Fig. 2.

A system where mixing is dominant will lead to a higher availability of fine sediment for the passive plume and hence a higher source term. Graphical representations of a situation where mixing is dominant and a situation where the density current is dominant are given in Fig. 3 and Fig. 4 respectively.

The spilled material from drag head or overflow (especially in case of a density current) may be forced (partly) into re-suspension due to propeller wash. In addition, previously spilled layers and naturally existing bottom sediments might erode as well. The propeller wash term is therefore difficult to describe and is usually included in the term related to overflow. Varying ambient conditions (e.g. water depth, current velocity) complicate matters further.

2.2. *Cutter Suction Dredgers (CSDs)*

The plume source of a CSD is the rotating cutter head. This source is shown in Fig. 5. The amount of material that is brought into suspension can be quite significant, depending on production, installed power, etc. Although detailed measurements are not available, the main cause for cutter head spill is related to the centrifugal dispersion of sediment. Rotation rate, swing speed and cut depth influence the amount of sediment brought into suspension. The suspended sediment is generated close to the bed and a large portion will stay low in the water column and settle near to the dredger.

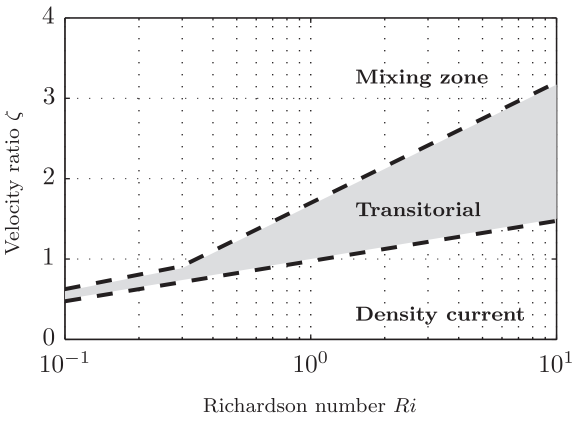

Fig. 2. Ri, ζ diagram with the classification by Winterwerp (2002).

2.3. *Backhoe Dredgers (BHDs), Bucket Ladder Dredgers (BLDs) and Grab Dredgers (GDs)*

TSHDs and CSDs make use of the so called hydraulic dredge method; they rely on diluting the dredged sediment with water to enable subsequent transport. The alternative is the so called mechanical dredge method; it relies solely on mechanical transport of dredged material and does not mix the dredged sediment with water. The main sources for suspended sediment for mechanical dredge methods are related to the hauling of the dredged material from the bed to the water surface. During this hauling process part of the dredge material may fall off creating a so-called drip pattern throughout the water column (e.g. Fig. 6).

Mechanical methods have a benefit over hydraulic methods in that the maintained integrity of the material in the bucket reduces the amount of fine material available for suspension. A down side is that production rates are generally lower leading to lower yet longer lasting stress. What is environmentally preferred depends on local ecosystem characteristics.

The plume source for a Bucket Ladder Dredger(BLD) is very similar to the Backhoe Dredger(BHD), as shown in Fig. 7. The same goes for a Grab Dredger(GD), see Fig. 8. The BHD, Bucket Ladder Dredger(BLD) and Grab Dredger(GD) have the possibility to be equipped with closed buckets, ladders or grabs, further reducing the release of sediments into the water column. This reduction is paid for with a decrease in production rates and thus again lower yet longer lasting stress.

2.4. *Placement operations*

Placement operations also create suspended sediment plumes. The magnitude of the source depends on placement method (split barge, bottom doors, rainbowing, pumping ashore), water depth, ambient conditions, soil properties, amount of water involved, etc.

A Split Hopper Barge(SHB) placement is shown in Fig. 9. The placement of the barge load creates a cloud of high density water falling onto the seabed. The bulk of the material will stay on the bed, but a part of the material will go into suspension. Bottom door placement by TSHD creates a similar source.

3. Estimating source terms for TSHD

To illustrate the process of quantification, this section elaborates on the estimation of TSHD source terms. The main reasons to treat TSHDs separately first, are that (1) they are responsible for the largest portion of dredging works by far and thus most relevant for the Environmental Impact Assessment(EIA), and (2) the near field processes are more complex than for other equipment types. The steps for other equipment types are similar though. Generally

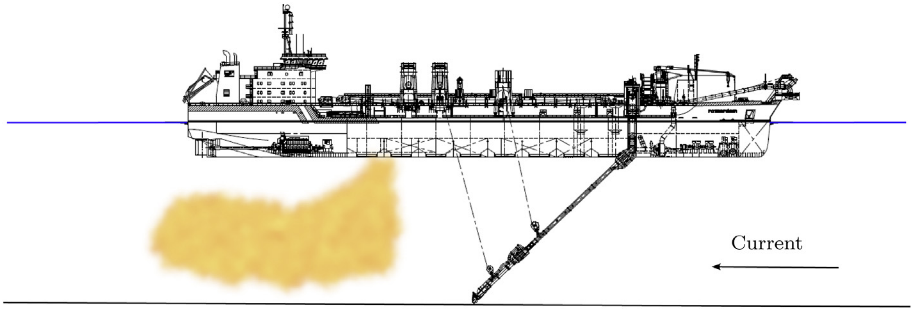

Fig. 3. Trailing Suction Hopper Dredger(TSHD) overflow plume when mixing is dominant.

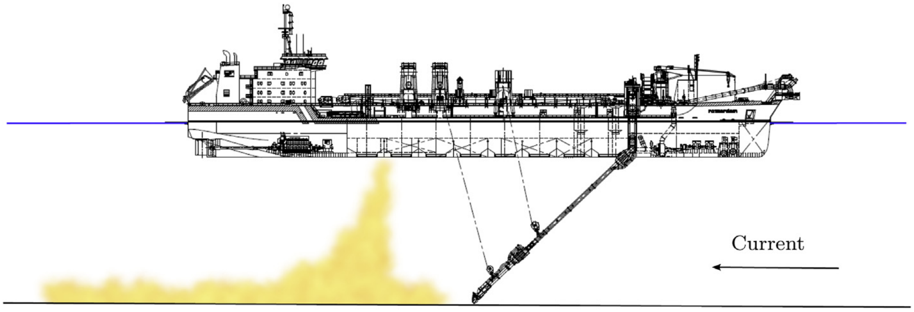

Fig. 4. Trailing Suction Hopper Dredger(TSHD) overflow plume when a density current is dominant.

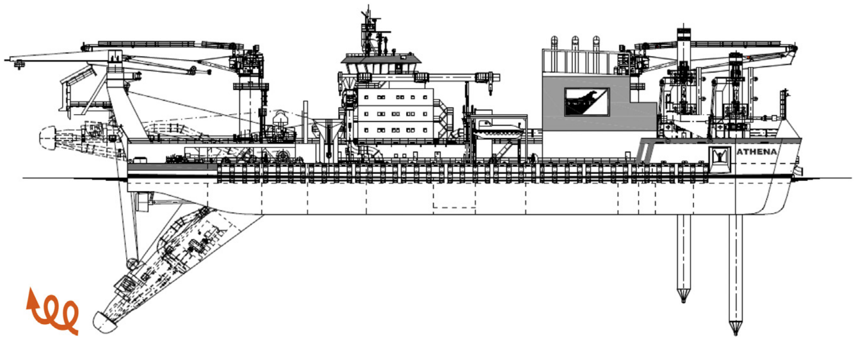

Fig. 5. Sources of a dredge plume for a Cutter Suction Dredger(CSD).

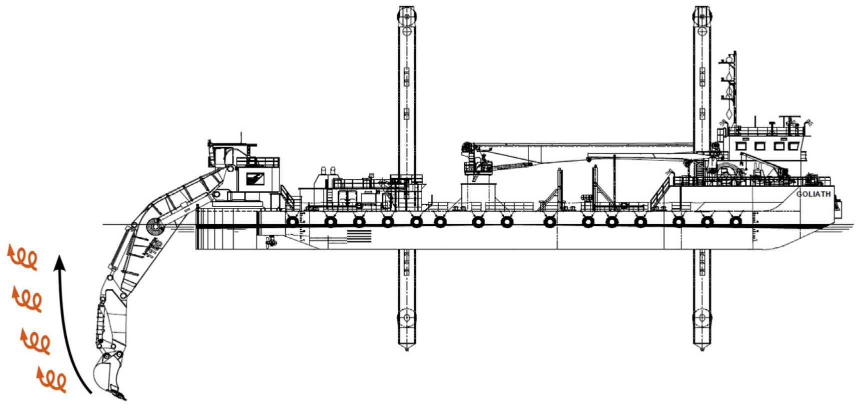

Fig. 6. Sources of a dredge plume for a Backhoe Dredger(BHD).

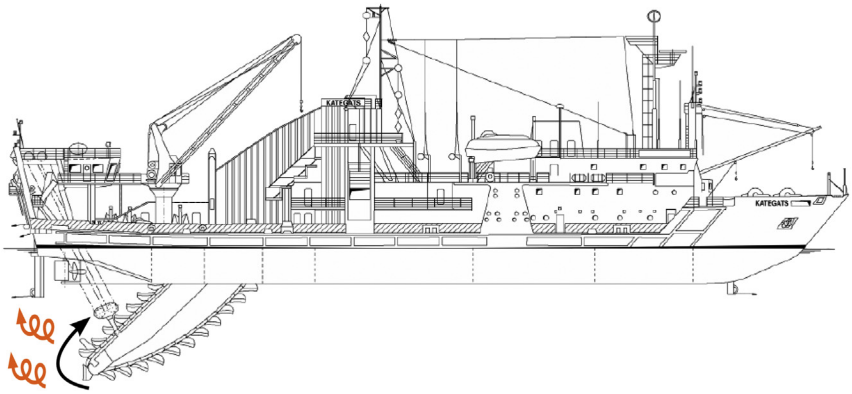

Fig. 7. Sources of a dredge plume for a Bucket Ladder Dredger(BLD).

speaking the estimation of source terms involves the following steps:

1. Analyse the work method for plume sources
2. Assess the total amount of available fines
3. Distribute available fines over work method elements, applying source term fractions to derive far field model source terms
4. Ensure appropriate application of source terms on the computational grid

3.1. *Analyse the work method for plume sources*

The estimation of source terms is explained for a TSHD dredging material nearshore and placing it offshore. The cycle consists of loading, with overflowing, sailing full, dredge material placement using the bottom-doors and sailing empty. The plume sources at the dredging location are related to drag head stir-up and overflow losses (see Subsection 2.1). For practical reasons propeller wash is not included in this example. At the placement site the plume source is related to the bottom-door placement activity (see Subsection 2.3). For reference, Fig. 10 is added, indicating qualitatively the changes in the amount of fines in the hopper during the dredge cycle.

In Fig. 10, t_0 represents the beginning of the dredging cycle and the start of the loading process. At t_1 the hopper reaches full capacity and overflowing starts. During overflowing the amount of sediment inside the hopper can be increased. At t_2 the loading process is stopped and consequently so is the overflowing. Next, the placement of the material in the hopper is started at t_3 and stopped at t_4. The dredging cycle stops at t_5. Intervals $t_3 - t_2$ and $t_5 - t_4$ are the sailing full and sailing empty periods respectively.

Practical considerations:

- Conservation of mass must apply to the available fines. To keep track, include the plume sources at both the dredging and the placement location in the analysis.
- Following the conservation of mass principle reducing the amount of fines released at the dredge area (e.g., through limited overflow) will lead to an increased amount of fines transported to the placement area.

3.2. *Assess the total amount of available fines*

The calculation of the amount of fine material that is available for release into the environment starts with the total *in situ* volume (in m^3) to be dredged. From this volume, and available soil information (soil density, grain size distribution, percentage fines), can be calculated the available total mass of fine material (dry solids, in *kg*). Fine material in this case is defined as sediment consisting of particles with a diameter $d < 63\ \mu m$. The mass of solids in the *in situ* material is calculated using the dry density:

$$\rho_d = (1 - n) \cdot \rho_s \tag{3}$$

where n is the porosity and ρ_s is the grain density. When the *in situ* density ρ_{situ} is known, the dry density can be calculated with the following relation:

$$\rho_{\text{situ}} = \rho_d + n \cdot S_r \cdot \rho_w \tag{4}$$

where $S_r = V_w/V_p$ is the degree of saturation (generally $S_r = 1$), V_w is the volume of water, V_p is the volume of pores and ρ_w is the density of water. For dredging projects the *in situ* dredge volume is generally known. The following equation may be used to calculate the total mass of fines (dry solids):

$$m_t = \rho_d \cdot V_{\text{situ}} \cdot f_{<63\ \mu\text{m}} \tag{5}$$

where m_t is the total available mass of fines (in *kg*), V_{situ} is the *in situ* dredge volume and $f_{<63\ \mu\text{m}}$ is the fraction of fines. Note that the fraction of fines may be a composite of the fines available in the soil and those created or removed by the work method. Additional fines can be created due to degradation during dredging (Ngan-Tillard et al., 2009). Hydraulic transport, pump impeller impact, but also crushing by cutter head, drag head or bucket can cause a significant creation of fines. Development of clay balls, on the other hand, may reduce the amount of fines available. Work method related fines should be added to, or subtracted from, the fines available in the soil at the correct stage in the dredge cycle. Details on estimating the amount of fines created or removed by the work method are outside the scope of this paper.

When the *in situ* material is inhomogeneous, which it generally is, the dredged volume should be subdivided into a number of representative soil types with similar properties. The above stated procedure should then be repeated for every soil type, summing the resulting masses of fines in the end.

NB: in the remainder of the text *mass of fines* will refer to the mass of the dry solids.

Practical considerations:

- It is important to start the analysis process from the in-situ dredged volume. Taking the hopper volume as a starting point will not produce correct results when bulking is not taken into account.

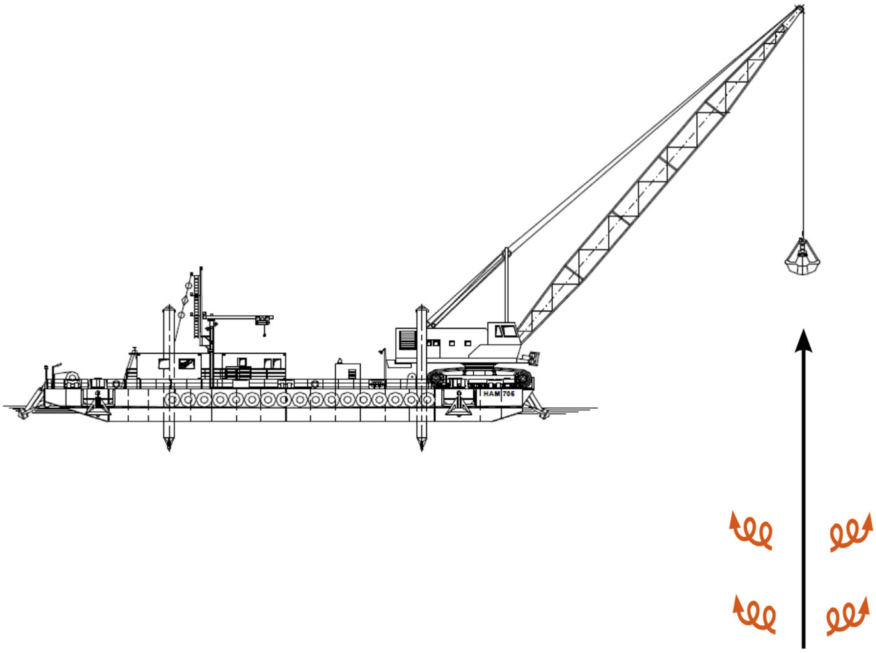

Fig. 8. Sources of a dredge plume for a Grab Dredger(GD).

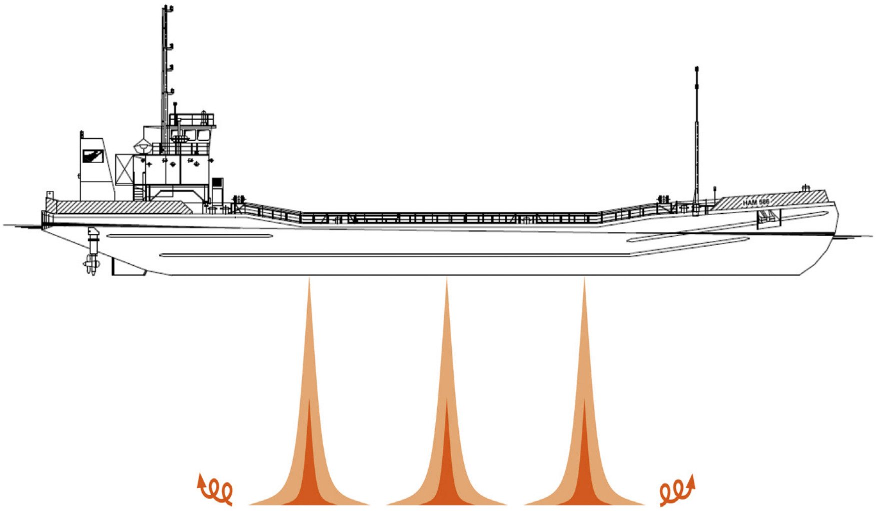

Fig. 9. Sources of a dredge plume for a Split Hopper Barge(SHB).

- It is recommended to work with the dry solids mass, as this reduces possible errors due to conversions between concentrations, densities and volumes.

3.3. *Distribute available fines over work method elements, applying source term fractions to derive far field model source terms*

Several methods are available to estimate the distribution of fines over the work method elements, depending on the project phase. In the preparation phase, hydrographic surveys and soil tests provide information on the amount and type of material to be dredged. Production calculations result in the number of hours and dredge cycles necessary to execute the works. During execution, velocity and density measurements in the suction pipe can be used to check estimates and provide adjustments if necessary. The total production of fines per cycle is calculated dividing Equation (5) by the number of cycles, or using the estimated production rate like shown in the following equation:

$$m_{t_{\text{cycle}}} = \rho_d \cdot f_{<63\ \mu\text{m}} \int_{t_0}^{t_2} P_{\text{situ}}\, \text{d}t \tag{6}$$

where $m_{t_{\text{cycle}}}$ is the total mass of fines produced per cycle and P_{situ} is the estimated situ production rate (m^3/s) during trailing (pipe on the ground).

NB: as all following equations may be applied for just one cycle or all cycles summed, we will omit the cycle subscript from here on.

When during a cycle the suction pipe is on the ground, a fraction of the fines available in the soil is brought into suspension by drag head stir-up:

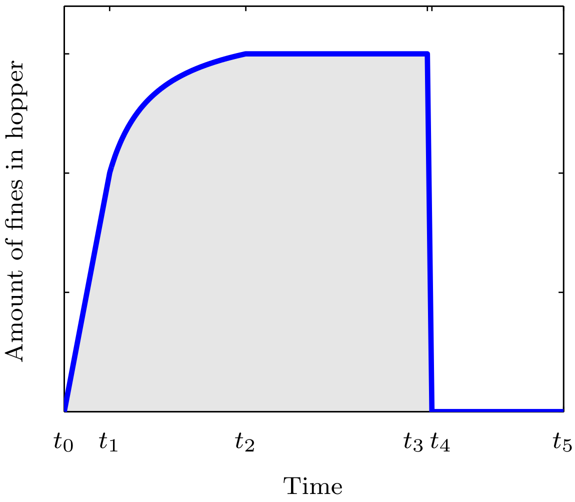

Fig. 10. TSHD cycle showing the amount of fines in the hopper.

$$m_d = \sigma_d \cdot m_t \tag{7}$$

where m_d is the total drag head related mass of fines brought into suspension during a cycle, and σ_d is an empirically derived source term fraction for stir-up (generally assumed constant). Division by cycle duration yields the drag head related sediment flux (kg/s) that can be used as a first element of the modelling source term. The remaining mass of fines (m_h) is transported into the hopper:

$$m_h = m_t - m_d \tag{8}$$

Only part of the remaining mass of fines that is transported into the hopper during one cycle will exit through the overflow:

$$m_o = \frac{t_2 - t_1}{t_2 - t_0} \cdot (1 - f_{\text{sett}}) \cdot \left(1 - f_{\text{trap}}\right) \cdot m_h \tag{9}$$

where m_o is the mass of fines per cycle leaving the overflow. It is derived from m_h by applying three consecutive reduction factors: (1) the overflow-loading ratio $(t_2 - t_1)/(t_2 - t_0)$ (the larger this ratio R_o, the more material leaves the hopper), (2) an average in-hopper settlement factor f_{sett} (the larger the in-hopper retention time, the larger the amount of fines that settles inside the hopper), and (3) the in-pore trapping factor f_{trap} (a small percentage of the fine material is trapped in the sediment matrix inside the hopper). Because Equation (9) focusses on the material that leaves the hopper via the overflow, factors $(1 - f_{sett})$ and $(1 - f_{trap})$ are used.

As indicated earlier in this paper the majority of the fine material that leaves the hopper through the overflow (m_o) descends to the bed as a dynamic plume or density current (m_{od}). An empirical fraction σ_o of m_o, ends up in a passive plume at a certain distance from the vessel (m_{op}):

$$m_{op} = \sigma_o \cdot m_o \tag{10}$$

$$m_{od} = (1 - \sigma_o) \cdot m_o \tag{11}$$

Division of m_{op} by the overflow duration yields the overflow related sediment flux (kg/s) that can be used as a second element of the modelling source term.

The mass of fines retained in the hopper (m_r):

$$m_r = m_h - m_o \tag{12}$$

is transported to the placement location and in this example released through the bottom doors. There the majority of the fine material descends to the bed as a dynamic plume or density current (m_{pd}). An empirical fraction σ_p of m_r, ends up in a passive plume at a certain distance from the placement location (m_{pp}):

$$m_{pp} = \sigma_p \cdot m_r \tag{13}$$

$$m_{pd} = (1 - \sigma_p) \cdot m_r \tag{14}$$

Division of m_{pp} by the placement duration $(t_4 - t_3)$ yields the placement related sediment flux (kg/s) that can be used as the third element of the modelling source term.

The passive plume source terms for draghead stir-up (F_{dp}), overflow (F_{op}) and dredge material placement (F_{pp}) for this cycle are, respectively (in kg/s):

$$F_{dp} = \frac{m_d}{t_2 - t_0} \tag{15}$$

$$F_{op} = \frac{m_{op}}{t_1 - t_0} \tag{16}$$

$$F_{pp} = \frac{m_{pp}}{t_4 - t_3} \tag{17}$$

The empirical source term fractions for draghead stir-up (σ_d), overflow (σ_o) and dredge material placement (σ_p) are of crucial importance to arrive at the appropriate fluxes. Deriving these fractions with some confidence relies on the execution of (extensive) field monitoring campaigns. Significant contributions to the available datasets have come from the Check Lap Kok airport land reclamation project in Hong Kong (Whiteside et al., 1995), the Øresund Fixed Link project in Denmark (Jansen, 1999), various dedicated field monitoring campaigns initiated by the SSB P15 Turbidity Assessment project (TASS) (VBKO, 2003; Land et al., 2004; Burt and Land, 2007; Aarninkhof, 2008; Spearman et al., 2011) and the Building with Nature innovation programme (De Vriend et al., 2014a).

Practical considerations:

- There are inherent uncertainties involved in the estimation of source terms. The use of empirically derived source term fractions leads to estimates that are likely of an order of magnitude found in subsequent compliance monitoring. Provided circumstances are sufficiently similar of course.
- For circumstances that are fundamentally different, advanced models exist to derive more appropriate values for aspects like the in-hopper settlement factor (f_{sett}), the overflow related passive plume fraction (σ_o), etc. (cf. Van Rhee, 2002; De Wit, 2010; De Wit et al., 2014a).
- Good practice nowadays is to plan for a so-called characterisation campaign to verify assumptions and subsequent predictions. Properly executed, each characterisation campaign adds to the overall database of empirical source term fractions.
- In line with the earlier recommendation to select an appropriate level of prediction detail, it is suggested that the overflow related source term is first modelled as an average rather than a time varying value. Considering all other uncertainties, the additional information provided by a time varying overflow value rarely justifies the effort and introduces fake accuracy at best.
- Great care should be taken with suggestions for the various empirical fractions that are not based on extensive field experience and/or measurements. Especially for projects with great

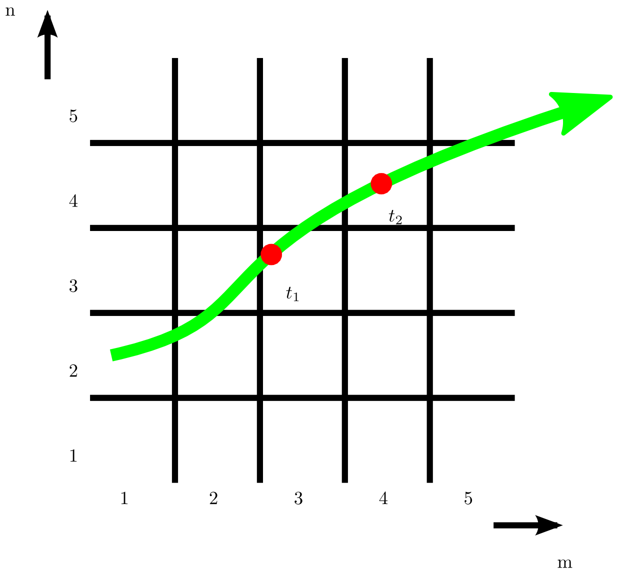

Fig. 11. Vessel moving over the computational grid.

environmental sensitivities, there is a tendency to stack worst case assumptions inspired by the precautionary principle (Sunstein, 2003). In the long run deriving realistic values that can be scientifically defended (beforehand) and verified by dedicated characterisation monitoring (during and after) provides the most productive approach.

3.4. Ensure appropriate application of source terms on the computational grid

The fourth step is the application of the source term to the far field model, where the calculated fines flux needs to be specified in time and in space. There are several aspects a modeller should be aware of.

First, the computational time step may affect concentration levels as they are represented in the model. The amount of material released to a computational grid cell during a time step is equal to the calculated flux to that cell (in kg/s) integrated over that timestep. The timestep has to be selected carefully to avoid the introduction of an unrealistically high Suspended Sediment Concentration(SSC) at certain times and locations in the model grid. Dynamic timestepping increases the simulation accuracy and reduces the simulation time by varying timestep size, based on numerical stability criteria. As most far field models nowadays work with dynamic timestep algorithms this issue is generally addressed automatically.

Second, the grid cell dimensions of the computational grid have to be chosen in such a way that they properly reflect the diffusion characteristics of an actual plume created by the dredger. Cells that are too large will introduce artificial diffusion, whereas cell that are too small could introduce artificially high concentrations locally (in particular for stationary sources).

Third, the degree of movement during operation affects the way the source is represented on the computational grid. A stationary source is modelled straightforwardly: the rate of release is specified on one particular location and generally attributed to one computational cell for a given timestep. Moving sources are more complex to model: the correct amount of suspended sediment should be allocated to each grid cell given the time spent there by the source during that time step. The correct amount depends on the movement of the source in question and the sediment flux at that point in time. When (part of) a sediment flux is attributed to a cell for given time step, the parameter that is influenced is the average sediment concentration for that cell.

Fig. 11 provides a graphical representation of a moving spill source. As an extremely simplified example, consider that the vessel travels through grid cells $(m,n) = (3,3)$, $(3,4)$ and $(4,4)$ during the interval between start overflow t_1 and stop overflow t_2. Should this interval happen to fall in one computational timestep, the suspended sediment flux should be divided over these cells proportionally to the time spent in each cell. The flux in this time interval consist of two components:

$$F_{t_1 \rightarrow t_2} = F_{dp} + F_{op} \tag{18}$$

Obviously in practice the time from start to stop overflow would not normally coincide with one computational timestep only. A source that travels through one to four gridcells during one timestep, however, is quite realistic. This paper primarily addresses the estimation of source terms. Further detail on their numerical implementation is considered to be outside the scope of this paper.

Practical considerations:

- While applying carefully derived source terms on the computational grid there is the potential to introduce significant uncertainty, such as undesirable numerical diffusion. Boundary conditions imposed by the far-field model at hand (e.g. minimum gridcell sizes at the source locations), may influence what level of detail is still relevant in the previous step (large gridcells cause instant numerical diffusion obscuring higher levels of detail from the previous step).
- The interpretation of the model results should include a relative comparison against the ambient background concentrations. Also one may consider to use a certain threshold value for the lowest concentrations. It is important to strike a balance between the detail of predictions and the potential for verification through field monitoring.

4. Estimating source terms for other equipment types

Comparable with the TSHD example outlined in the previous section the same steps are followed for other equipment types:

1. Analyse the work method for plume sources
2. Assess the total amount of available fines
3. Distribute available fines over work method elements, applying source term fractions to derive far field model source terms
4. Ensure appropriate application of source terms on the computational grid

The technical aspects of Steps 1, 2 and 4 are quite similar to the TSHD example and the reader is referred to Section 2 for a qualitative description of plume sources for various equipment types. The main differences are found for Step 3.

The starting point for each type of equipment is the total mass of fines (dry solids) available in the soil, calculated according to Equation (5), reiterated here for convenience:

$$m_t = \rho_d \cdot V_{\text{situ}} \cdot f_{<63\ \mu\text{m}}$$

A quick estimate of a source term associated with cutter head spill can be derived as follows:

$$m_c = \sigma_c \cdot m_t \tag{19}$$

where m_c is the total cutter head related mass of fines (dry solids) brought into suspension and σ_c is an empirical source term fraction related to cutter head stir-up. Division by operational hours yields the cutter head related sediment flux (kg/s) that can be used as a first element of the modelling source term.

In fact Equation (20) provides a general equation for source terms that are effectively directly proportional to the total available mass of fines (dry solids):

$$m_{\mathrm{eq}} = \sigma_{\mathrm{eq}} \cdot m_t \tag{20}$$

where m_{eq} is the total dry solids mass brought into suspension by an arbitrary piece of equipment and σ_{eq} is an empirical source term fraction associated with that piece of equipment. Division by operational hours yields the sediment flux (kg/s) that can be used as the modelling source term.

Table 1 lists reasonable ranges for a number of the source term fractions discussed in this paper. The ranges are derived from the earlier mentioned field monitoring campaigns in combination with practical experience.

5. Example: comparison of work methods

To understand its implications, we apply the method described in Section 3 and Section 4 to the following fictitious (yet realistic) example: A greenfield port is being developed in a coastal area. The dredging works involve an approach channel, turning circle and two jetty pockets. The material is placed 10.8 nautical miles offshore at a designated area. The total *in situ* volume to be dredged is 2.0 million m^3 and consists of silty sand (30% fines). After a number of soil tests, the dry density of the material is assumed to be homogeneous throughout the area and equal to $\rho_d = 1590\ kg/m^3$.

5.1. Analyse the work method for plume sources

Two work methods are considered to be equally feasible for this project: (1) a TSHD or (2) a BHD loading two Split Hopper Barge(SHB)s. The work methods and their respective environmental impact due to dredge plumes have to be estimated. The outcome will play a role in the selection of the equipment. Important aspects in the evaluation of work methods are the duration and intensity of the impact and the total amount of material released into the environment.

The TSHD is expected to dredge 100,000 m^3 of *in situ* material per week, leading to an execution period of 20 weeks. The cycle time is estimated to be 4 h, which leads to 42 cycles per week.

The BHD is expected to dredge 50,000 m^3 of *in situ* material per week, leading to an execution period of 40 weeks. The cycle time for the SHBs is estimated to be 12 h. This would lead to 28 cycles per week (i.e., a loading time per barge of 6 h).

In reality, the operational hours per week and efficiency of the equipment will limit the amount of cycles per week. However, these aspects are not included in the calculation. As long as the total *in situ* volume is correct, the cycle duration and the volume dredged per cycle are not critical in this stage of the decision process.

Table 1
Reasonable ranges for (empirical) source term fractions.

Plume source	Symbol	Fraction
Draghead	σ_d	0–0.03
Overflow ratio	R_o	0–1
In-hopper settlement	f_{sett}	0–1
In-matrix fixation	f_{trap}	0.01–0.05
Overflow	σ_o	0–0.2
Cutterhead	σ_c	0.01–0.05
Bucket drip	σ_b	0–0.04
Bottom door (hydraulic)	σ_p	0–0.1
Bottom door (mechanic)	σ_p	0.0–0.05

5.2. Assess the total amount of available fines

The total amount of fines available in the dredge volume can be calculated with the information given above, using Equation (5):

$$m_t = \rho_d \cdot V_{\mathrm{situ}} \cdot f_{<63\ \mu\mathrm{m}}$$

which results in a total mass of fines of 954 million kg (dry solids). Generation of additional fines due to the work method is not considered in this example.

5.3. Distribute available fines over work method elements, applying source term fractions to derive far field model source terms

5.3.1. TSHD

Table 2 indicates the cycle components for dredging with a TSHD.

As indicated in Subsection 5.1 and Table 2 the cycle time is estimated to be 4 h. The loading time $t_2 - t_0$ is 75 min of which 60 min including overflow. The resulting *in situ* production rate is:

$$P_{\mathrm{situ}} = \frac{V_{\mathrm{situ}}}{T \cdot n_c \cdot (t_2 - t_0)} \tag{21}$$

where $T = 20$ weeks is the execution period and $n_c = 42$ is the amount of cycles per week. The 2 h loading time is given in seconds, resulting in an estimated production rate of 0.53 m^3/s. The production of fines per cycle is calculated according to Equation (6) and equals $m_t = 1.1$ million kg. This quantity is the basis for further calculations. As mentioned in Section 3, the subscript 'cycle' is dropped and mass of fines refers to the dry solid weight.

The amount of fines per cycle that is stirred up by the drag head is calculated using Equation (7), where σ_d is estimated to be 0.03. This leads to a mass of fines of 34 thousand kg that is available in the passive plume due to drag head stir-up. The remaining fines will be transported into the hopper. The fraction that leaves via the overflow is calculated according to Equation (9). In the cycle as shown in Table 2 the ratio of overflow to total loading time per cycle $R_o = 4/5$. To estimate the values of the factors f_{sett} and f_{trap} a hopper settlement model can be used (e.g., Van Rhee, 2002; Spearman et al., 2011). For this example $f_{sett} = 0.25$ and $f_{trap} = 0.05$ are used, leading to a mass of fines leaving the overflow equal to $m_o = 0.63$ million kg. Equation (10) states that only part of these fines, represented by $\sigma_o = 0.2$, is transported to the passive plume. This is an additional mass of fines available in the passive plume of $m_{op} = 0.13$ million kg as a result of the overflow.

A significant part of the fines is retained in the hopper and carried to the placement area. Equation (13) describes the amount of fines that ends up in the passive plume after the dredge material has been placed. The empirical fraction σ_p is estimated to be 0.1. The input for the passive plume as a result of placement consists of $m_{pp} = 47$ thousand kg. The suspended sediment fluxes F_{dp}, F_{op} and

Table 2
Dredge cycle.

Activity	Duration (*min*)
Loading without overflow	15
Loading with overflow	60
Sailing full	85
Placement	10
Sailing empty	70

F_{pp}, that form the source terms, can be calculated taking into account the loading, overflow and placement durations respectively. The required formulas are given in Subsection 3.3. An overview of the calculation results is presented in Table 3.

5.3.2. BHD and two SHBs

The BHD is assumed to dredge continuously and fill two barges alternately. The cycle time (loading time per barge) is 360 min and the placement time is 10 min. Since the weekly *in situ* production is lower than for the TSHD, the execution period is 40 weeks. The number of barges per week that can be filled is 28, assuming full-time operation. This assumption, though not realistic, is suitable for this calculation, as mentioned earlier. The *in situ* volume per barge is 1786 m^3.

The *in situ* production rate of the BHD is $P_{situ} = 0.083\ m^3/s$ resulting in a fines production of 39 kg/s. To calculate the amount of fines that is dispersed into the far-field plume due to bucket drip, this value is multiplied by the empirical fraction $\sigma_b = 0.04$. This leads to a suspended sediment flux of $F_{bp} = 1.6\ kg/s$ and a total mass of fines $m_b = 34.1$ thousand kg per SHB load.

The amount of fines that is transported to the placement area is $m_h = 0.82$ million kg per barge load. As for the TSHD, a certain fraction $\sigma_p = 0.05$ will be available for the passive plume. The rest will be transported to the sea bed in the form of a density current. An amount of fines of $m_{pp} = 41$ thousand kg will end up in the far-field plume. Assuming a 10 min placement duration, the flux $F_{pp} = 68\ kg/s$. An overview of the calculation results is presented in Table 4.

5.4. Application of source terms on the computational grid

The source term is the suspended sediment input for the hydrodynamic and sediment transport model (the so-called far field model). To be able to apply the source term in the model, information is required regarding the rate of release, duration of release and location of release. The calculated fluxes F_{dp}, F_{op} and F_{pp} for the TSHD (Table 3) and F_{bp} and F_{pp} for the BHD (Table 4) describe the rates of release as estimated for this example.

Table 3
Calculation results for a TSHD.

Parameter	Symbol	Unit	Value
Total *in situ* volume	V_{situ}	m^3	2,000,000
Dry density	ρ_d	kg/m^3	1590
Fines percentage	$f_{<63\mu}$	%	30
In situ production		m^3/wk	100,000
Execution period	T	wk	20
Cycle time		min	240
Loading time		min/cycle	75
Overflow time		min/cycle	60
Placement time		min/cycle	10
No. of cycles	n_c	wk^{-1}	42
Total amount of fines		kg	$9.5 \cdot 10^8$
In situ production	P_{situ}	m^3/s	0.53
Fines per cycle	m_t	kg/cycle	$1.1 \cdot 10^6$
Drag head fraction	σ_d	%	3
Fines to far-field	m_d	kg/cycle	$3.4 \cdot 10^4$
Fines into hopper	m_h	kg/cycle	$1.1 \cdot 10^6$
Settlement factor	f_{sett}	%	25
Entrapment factor	f_{trap}	%	5
Fines via overflow	m_o	kg/cycle	$6.3 \cdot 10^5$
Fines retained	m_r	kg/cycle	$4.7 \cdot 10^5$
Overflow fraction	σ_o	%	20
Fines to far-field	m_{op}	kg/cycle	$1.3 \cdot 10^5$
Fines density current	m_{od}	kg/cycle	$5.0 \cdot 10^5$
Placement fraction	σ_p	%	10
Fines to far-field	m_{pp}	kg/cycle	$4.7 \cdot 10^4$
Fines density current	m_{pd}	kg/cycle	$4.3 \cdot 10^5$
Flux drag head	F_{dp}	kg/s	7.6
Flux overflow	F_{op}	kg/s	35
Flux placement	F_{pp}	kg/s	79

Table 4
Calculation results for a BHD and two SHBs.

Parameter	Symbol	Unit	Value
Total *in situ* volume	V_{situ}	m^3	2,000,000
Dry density	ρ_d	kg/m^3	1590
Fines percentage	$f_{<63\mu}$	%	30
In situ production		m^3/wk	50,000
Execution period	T	wk	40
Number of barges			2
Loading time		min/barge	360
Placement time		min/barge	10
No. of barge loads	n_c	wk^{-1}	28
Total amount of fines		kg	$9.5 \cdot 10^8$
In situ volume		$m^3/barge$	$1.8 \cdot 10^3$
In situ production	P_{situ}	m^3/s	0.083
Fines production		kg/s	39
Fines per barge load	m_t	kg/barge	$8.5 \cdot 10^5$
Bucket drip fraction	σ_b	%	4
Fines to far-field	m_b	kg/barge	$3.4 \cdot 10^4$
Fines into barge	m_h	kg/barge	$8.2 \cdot 10^5$
Placement fraction	σ_p	%	5
Fines to far-field	m_{pp}	kg/barge	$4.1 \cdot 10^4$
Fines density current	m_{pd}	kg/barge	$7.8 \cdot 10^5$
Flux bucket drip	F_{bp}	kg/s	1.6
Flux placement	F_{pp}	kg/s	68

As indicated previously in Subsection 3.4, details of the numerical implementation of source terms on the computational grid are considered to be outside the scope of this paper. Nonetheless some qualitative notions to consider when modelling are worth mentioning here:

- Settling velocity is an important parameter with respect to the potential for dispersion in a suspended sediment plume. It is generally good practice to specify a limited number of fractions to account for the different settling velocities that depend on grain size. It is furthermore good to realize that in a 2DH model settling velocity is in fact a calibration parameter. Compared to a 3D model, settling velocities in a 2DH model should be adjusted upward to arrive at similar suspended sediment concentrations in the far field.
- Regarding the time interval each of the sources should be applied, it is important to realise that the drag head source has to be applied during the entire loading process (from t_0 to t_2). In the current example, this is 75 min per 4-h cycle. The overflow source should be applied during the period of overflow (from t_1 to t_2). In the current example, this is 1 h per 4-h cycle.
- To obtain reliable results, the source has to be applied when the hydrodynamic model is stable (after spin-up). When statistical operations are performed on the computational results, the full project duration has to be modelled or a subset of the results has to be used where the SSC is in a steady state. A common approach is to calculate a full spring-neap cycle with representative dredging activity. This way at least variations associated with the normal tidal cycle can be investigated. Additionally scenario investigations to study the effect of different hydro-meteo conditions are recommended.
- The location of release, especially for a moving source, depends on the spatial characteristics of the source itself. For a TSHD the trailing velocity and direction are important for the eventual dispersion and extent of the dredge plume. Generally a TSHD's trailing speed does not exceed 2 *knots* or approximately 1 m/s. Furthermore a TSHD generally trails either with or against the ambient current. Main reason for this is to prevent the suction pipes from being trapped and damaged underneath the vessel.

5.5. Reflection on the calculation results

Two work methods were compared for a fictitious and simplified (yet realistic) project. The resulting source terms, and subsequent dredge plumes, vary in many respects.

The TSHD alternative leads to an execution period of 20 weeks. The total amount of fines in the passive plumes is 210 thousand *kg* per cycle, 8.7 million *kg* per week and 170 million *kg* over the entire project duration. This is approximately 18% of the total amount of fines available in the *in situ* dredged material.

The BHD with SHBs alternative leads to an execution period of 40 weeks. The total amount of fines in the passive plumes is 75 thousand *kg* per barge load, 2.1 million *kg* per week and 84 million *kg* over the entire project duration. This is approximately 9% of the total amount of fines available in the *in situ* dredged material.

The four-step method and the example, objectively illustrating the difference in sediment fluxes by different work methods, contribute to the primary and hopefully the secondary objective of this paper. As indicated in Section 1 the unambiguous translation of the estimated sediment fluxes to environmental impact is much more difficult. The effect, if any, of each of the estimated fluxes, depends entirely on the characteristics of the environment wherein the sediment is released. These environmental characteristics also determine whether a higher shorter term load (such as by the TSHD) or a smaller longer term load (such as by the BHD with SHBs) is most or least harmful to the local environment. Duration-concentration aspects can play a crucial role in the assessment of environmental risk. It is important to realise, however, that other factors may be decisive in the ultimate selection of work methods. Such factors could include: acceptable length of impact on marine traffic, cost associated with delaying the primary economic objective of the project, issues of concern to local stakeholders, etc.

6. Conclusions

- This paper describes a generic method to calculate source terms for far field dredge plume modelling as it is used in practice in the dredging industry.
  - The method is based on soil characteristics and dredge production figures, combined with empirically derived, equipment and condition specific 'source term fractions'.
  - A source term fraction relates the suspended fine sediment that is available for dispersion, to the amount of fine sediment that is present in the soil and the way it is dredged.
  - The empirical source term fractions are based on and verified by extensive field measurements. As such they are a way to circumvent modelling of the complicated near field processes, at least initially, enabling quick assessments.
  - When further detail is required and extra information is available, the applicability of the empirical source term fractions can/should be assessed by characterisation monitoring and/or near field modelling.
  - A number of practical considerations from application in practice are listed for the various steps of the method.
- The method is illustrated by applying it to a fictitious yet realistic dredging project. The example demonstrates that the total available mass of fines is distributed over dredging and placement depending on the selected equipment and work method.
  - Two different work methods are shown to trigger two distinctly different types of stress to the environmental system in terms of sediment concentration and duration.
  - The importance of striking a practical balance between the detail of the source predictions, the potential for verification through field monitoring and the degree of certainty that is required for the decision making process has been emphasized.
  - It pays off to spend significant effort on the selection of work methods. Innovative ways to operate and combine various types of equipment can have a large influence on potential stresses on the environment.
- The method fills a gap in current literature as it enables professionals to assess the effect of different work methods despite the large complexities involved.
  - The ranges for the empirical fractions presented in this paper can be used to make a first assessment of dredging source terms. The full details of a source term analysis depend on equipment specifications and the work methods used. Timely consulting of dredging companies is crucial if these are to be incorporated.
  - The method as it is outlined in this paper should help professionals in the field to produce realistic impact studies. In the long run realistic impact studies that can be scientifically defended (beforehand) and verified by dedicated characterisation monitoring (during and after) are in the best interest of society at large.

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References

Aarninkhof, S.G.J., 2008. The day after we stop dredging: a world without sediment plumes? Terra Aqua 110, 15–25.

Aarninkhof, S.G.J., Rosenbrand, W.F., Van Rhee, C., Burt, T.N., 2007. The day after we stop dredging: a world without sediment plumes?. In: Proceedings CEDA Dredging Days.

Becker, J.H., 2011. Dredge Plumes: Ecological Risk Assessment. Delft University of Technology. Master's thesis. http://repository.tudelft.nl/view/ir/uuid:98e64038-86f4-4588-92ae-40b09783f251/.

Blokland, T., 1988. Determination of dredging-induced turbidity. Terra Aqua 38, 3–12.

Bray, R.N. (Ed.), 2008. Environmental Aspects of Dredging. Taylor & Francis, Balkema. http://books.google.nl/books?id=7x-YzciM42YC.

Bray, R.N., Bates, A.D., Land, J.M., 1997. Dredging, a Handbook for Engineers, 2nd revised edition. Butterworth-Heinemann Ltd. http://books.google.nl/books?id=lhkfAQAAIAAJ.

Burt, N., Land, J.H.O., 2007. Measurement of sediment release for calibration of turbidity prediction software. In: Proceedings of WODCON XVIII, Orlando, USA.

Dankers, P.J.T., 2002. The Behaviour of Fines Released Due to Dredging - a Literature Review. Technical Report. Hydraulic Engineering Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology.

De Lange, W., 2011. Probabilistic Design of Settling Basins for Environmental Compliance. Development and Evaluation of a Risk-based Approach. Delft University of Technology. Master's thesis. http://repository.tudelft.nl/view/ir/uuid:0fe4643f-d868-4849-90af-579fb543a8b2/.

De Vriend, H.J., Van Koningsveld, M., 2012. Building with Nature: Thinking, Acting and Interacting Differently. EcoShape, Building with Nature, Dordrecht, the Netherlands. http://ecoshape.nl/files/paginas/ECOSHAPE_BwN_WEB.pdf.

De Vriend, H.J., Van Koningsveld, M., Aarninkhof, S.G.J., 2014a. 'Building with Nature': the new Dutch approach to coastal and river works. Proc. ICE - Civ. Eng. 167 (1), 18–24. http://dx.doi.org/10.1680/cien.13.00003.

De Vriend, H.J., Van Koningsveld, M., Aarninkhof, S.G.J., De Vries, M.B., Baptist, M.J., 2014b. Sustainable hydraulic engineering through building with nature. J. Hydro-environment Res. http://dx.doi.org/10.1016/j.jher.2014.06.004. <http://authors.elsevier.com/TrackPaper.html?trk_article=JHER289&trk_surname=van%20Koningsveld>.

De Wit, L., 2010. Near field 3D CFD modelling of overflow plumes. In: Proceedings of WODCON XIX, Beijing, China, p. 12. http://www.svasek.com/news/WODCON_paper_LdeWit.pdf.

De Wit, L., Talmon, A.M., Van Rhee, C., 2014a. 3D CFD simulation of trailing suction hopper dredge plume mixing: a parameter study of near field conditions influencing the suspended sediment source flux. Mar. Pollut. Bull. 88 (1–2), 47–61. http://dx.doi.org/10.1016/j.marpolbul.2014.08.042.

De Wit, L., Van Rhee, C., Talmon, A., 2014b. Influence of important near field processes on the source term of suspended sediments from a dredging plume caused by a Trailing Suction Hopper Dredger: the effect of dredging speed, propeller, overflow location and pulsing. Environ. Fluid Mech. 1–26. http://dx.doi.org/10.1007/s10652-014-9357-0.

Doorn-Groen, S.M., 2007. Environmental monitoring and management of reclamations works close to sensitive habitats. Terra Aqua 108 (1), 3–18. http://www.iadc-dredging.com/ul/cms/terraetaqua/document/1/7/6/176/176/1/nr108-1.pdf.

Dupuits, E.J.C., 2012. Stochastic Effects of Dredge Plumes. Development and Application of a Risk-based Approach to Assess Ecological Effects of Dredge Plumes on Sensitive Receivers. Delft University of Technology. Master's thesis. http://repository.tudelft.nl/view/ir/uuid:0fef7506-3bfe-4ec1-8f35-a00d4eb24246/.

Erftemeijer, P.L.A., Lewis III, R.R., 2006. Environmental impacts of dredging on seagrasses: a review. Mar. Pollut. Bull. 52 (12), 1553–1572. http://dx.doi.org/10.1016/j.marpolbul.2006.09.006.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A., 2012. Environmental impacts of dredging and other sediment disturbances on corals: a review. Mar. Pollut. Bull. 64 (9), 1737–1765. http://dx.doi.org/10.1016/j.marpolbul.2012.05.008.

Hayes, D.F., Crockett, T.R., Ward, T.J., Averett, D., 2000. Sediment resuspension during cutterhead dredging operations. J. Waterw. Port. C.-ASCE 126, 153–161. doi:10.1061/(ASCE)0733-950X(2000)126:3(153).

Henriksen, J., Randall, R., Socolofsky, S., 2012. Near-field resuspension model for a cutter suction dredge. J. Waterw. Port. C.-ASCE 138, 181–191. http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000122.

Jansen, E.F.P., 1999. Introduction to spill, spill monitoring and spill management. In: Proceedings Oresund Link Dredging & Reclamation Conference, pp. 175–184.

John, S.A., Challinor, S.L., Simpson, M., Burt, T.N., Spearman, J., 2000. Scoping the Assessment of Sediment Plumes Arising from Dredging. Technical Report. Construction Industry Research and Information Association. http://www.asce.org/Product.aspx?id=25769805960&productid=5941.

Land, J., Burt, N., Otten, H., 2004. Application of a new international protocol to measurement of sediment release from dredgers. In: Proceedings of WODCON XVII, Hamburg, Germany. Paper B5–1.

Ngan-Tillard, D., Haan, J., Laughton, D., Mulder, A., Nooy van der Kolff, A., 2009. Index test for the degradation potential of carbonate sands during hydraulic transportation. Eng. Geol. 108 (1–2), 54–64. http://dx.doi.org/10.1016/j.enggeo.2009.06.005.

Pennekamp, J.G.S., Epskamp, R.J.C., Rosenbrand, W.F., Mullié, A., Wessel, G.L., Deibel, I.K., 1996. Turbidity caused by dredging; viewed in perspective. Terra Aqua 64, 10–17.

Spearman, J.R., De Heer, A., Aarninkhof, S.G.J., Van Koningsveld, M., 2011. Validation of the TASS system for predicting the environmental effects of Trailing Suction Hopper Dredgers. Terra Aqua 125 (3), 14–22. https://www.iadc-dredging.com/ul/cms/terraetaqua/document/3/0/4/304/304/1/terra125-3.pdf.

Sunstein, C.R., 2003. Beyond the precautionary principle. U. Penn. Law Rev. 151, 1003–1058.

Van Eekelen, E.M.M., 2007. Experimental Research on Dynamic Dredge Overflow Plumes. Delft University of Technology. Master's thesis. http://repository.tudelft.nl/view/ir/uuid:54829c36-b70d-48e1-a47f-cd8be008ca6c/.

Van Koningsveld, M., Damsma, T., Van der Hout, R., Van Wiechen, J., De Boer, G.J., 2013. Openearth: a knowledge management workflow for dredging projects. Terra Aqua 131 (1), 3–14. https://www.iadc-dredging.com/ul/cms/terraetaqua/document/3/7/3/373/373/1/terra131-1.pdf.

Van Koningsveld, M., De Boer, G.J., Baart, F., Damsma, T., Den Heijer, C., Van Geer, P., De Sonneville, B., 2010. OpenEarth - inter-company management of: data, models, tools & knowledge. In: Proceedings of WODCON XIX, Beijing, China, p. 14.

Van Rhee, C., 2002. On the Sedimentation Process in a Trailing Suction Hopper Dredger. Delft University of Technology. Ph.D. thesis. http://repository.tudelft.nl/view/ir/uuid:c16d25e7-7b02-43ff-8ec8-e6069f8a1ce2/.

VBKO, 2003. Protocol for the Field Measurements of Sediment Release from Dredgers, 1, pp. 1–83. VBKO report.

Whiteside, P.G.D., Ooms, K., Postma, G.M., 1995. Generation and decay of sediment plumes from sand dredging overflow. In: Proceedings of WODCON XIV, Amsterdam, Netherlands, pp. 877–892.

Winterwerp, J.C., 2002. Near-field behavior of dredging spill in shallow water. J. Waterw. Port. C.-ASCE 128 (2), 96–98. http://dx.doi.org/10.1061/(ASCE)0733-950X(2002)128:2(96).

Acronyms

BHD: Backhoe Dredger
BLD: Bucket Ladder Dredger
CSD: Cutter Suction Dredger
EIA: Environmental Impact Assessment
GD: Grab Dredger
SHB: Split Hopper Barge
SSC: Suspended Sediment Concentration
TSHD: Trailing Suction Hopper Dredger