CAN SURFACE TURBIDITY PLUME GENERATION NEAR A TRAILER BE PREDICTED?

Photo © Van Oord

A surface plume from overflow can stay suspended for long periods and distances. This can result in negative environmental impact through increased turbidity and sedimentation. Therefore, the question of surface plume generation is important for a proper dredging environmental impact assessment which is neither too optimistic nor too conservative.

An important environmental impact of dredging can be caused by turbidity plumes generated during dredging.

Introduction

For dredging projects, often the environmental impact needs to be assessed by model studies beforehand and monitored during execution of the work (Aarninkhof et al., 2018). An important environmental impact of dredging can be caused by turbidity plumes generated during dredging. Increased turbidity can impact ecological sensitive areas by reduced light penetration, reduced visibility, clogging and burial. When dredging with a Trailing Suction Hopper Dredger (TSHD) the main source for a turbidity plume is the overflow (Bray, 2008). The overflow is a vertical shaft ending at the keel through which excess sea water from the hopper is released. This excess water can contain fine sediment fractions which did not have sufficient time to settle in the hopper. Under the keel of the vessel the turbid water from the overflow will mix with the ambient water flowing past the keel in such manner forming a turbulent plume (see Figure 1). This overflow plume can stay near the bed like a density current and settle quickly, but it is also possible that part of the plume will mix severely and form a surface plume. The difference between these two regimes is clearly visible on a dredging project, (see Figure 2). A surface plume can stay suspended for longer periods and in this time the ambient (tidal) currents can transport the turbidity plume towards ecologically sensitive areas. For a proper assessment of the environmental impact it is required to know whether a surface plume will occur or not. This depends on the mixing of the overflow plume under the keel of the TSHD. This close to dredging equipment it is very hard to carry out reliable measurements, but with increasing computing power it has become feasible to use Computational Fluid Dynamics (CFD) to find out what is happening under the keel of a TSHD. This article presents some remarkable results from a validated CFD model incorporating all important processes.

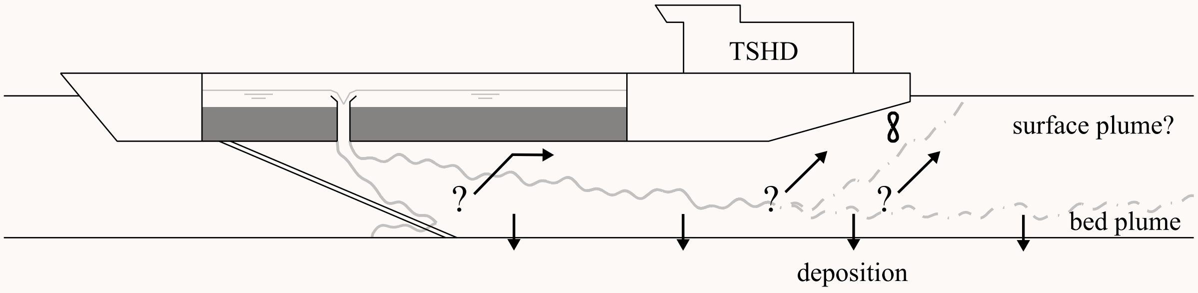

FIGURE 1

Schematic overview of the generation of an overflow plume under the keel of a TSHD.

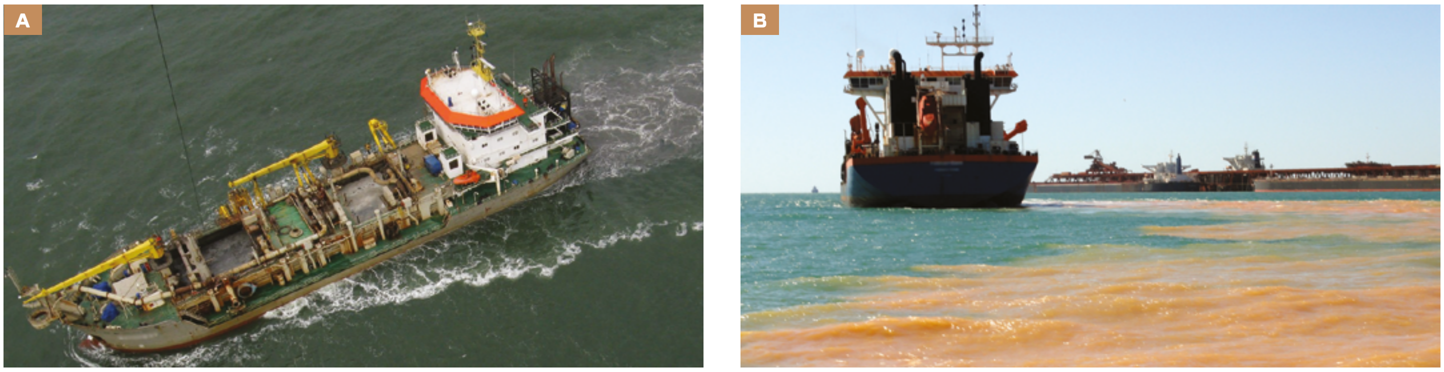

FIGURE 2

Dredging example with overflow without surface plume (A) and with surface plume from overflow (B). Photo © H. Elbers, Fotovlieger.nl

Near field – far field

Close to a dredging vessel the behaviour of the dredging plume is governed by: interaction between plume, flow past the hull and propellers of the vessel; by the significant density difference between the plume and the ambient water; and by air bubbles entrained in the overflow. This zone where all these influences are important is called the near field. Further away from a dredging vessel the density difference is not significant anymore, air bubbles have disappeared and there is no interaction between the plume and the vessel. In this zone, called the far field, a dredging plume is turned into a passive plume being transported by ambient (tidal) currents and sediment settling velocity. Far field mixing of a dredging plume can be simulated by well-known large scale hydrodynamic and sediment flow models like Delft3d, FINEL, MIKE, or TELEMAC. Far field models cover the area of dozens of kilometres round a dredging work, often complete estuaries or coastal seas. The specific near field processes cannot be simulated by a far field model due to lack of grid resolution and lack of representation of all important near field physical processes. For accurate simulation of the near field a specific detailed near field model is required with sufficient resolution and incorporating all important physical processes. The plume results from near field then can be applied as source term in a far field model. See Becker et al. (2015) and Aarninkhof et al. (2018) for more information to go from the in-situ sediment to be dredged to the determination of a sound source flux in a far field model. The near field CFD model of present article can be used to determine the initial mixing in the near field, vertical and horizontal distribution of the overflow plume at the end of near field. Coarser sediment particles tend to settle already in the near field and will never reach far field and the near field CFD model can give information on what particle sizes and what amount of sediment will deposit in the near field.

> **Far field models cover the area of dozens of kilometres round a dredging work, often complete estuaries or coastal seas.**

Near field dredging plume

The plume flowing out of the overflow mixes with the ambient water flowing past the keel. The overflow mixture flows with 0.5-5 m/s vertically downward in the overflow shaft and typically contains 25-250 kg/m^3 of mud and fine sand (mixture density 1040-1200 kg/m^3) with maxima of even 500 kg/m^3 (mixture density 1330 kg/m^3) which have been measured at the end of the overflowing phase when the hopper is nearly full (Nichols et al., 1990, Whiteside et al., 1995, Spearman, 2011, De Wit, 2014b). The time evolution, amount and composition of sediment flowing out of the overflow (overflow losses) depends on processes inside the hopper which have been simulated in detail by Van Rhee (2002), Saremi (2014), and due to recent advancements also the CFD model presented in this paper can simulate hopper sedimentation accurately in 3D (De Wit, 2019). Hence, the overflow losses can either be estimated, simulated by simplified hopper sedimentation models or determined in more detail by process based models. But knowing the overflow losses is not sufficient to determine far field source terms of a TSHD in environmental impact assessments, because also the near field processes have influence. Dependent on the velocity ratio between the flow velocity in the overflow and the effective flow velocity of the moving TSHD and the densimetric Froude (or Richardson) number of the overflow mixture, the plume follows a certain path. If the plume stays close enough to the TSHD keel, the expanding flow at the aft of the TSHD hull and propellers can lift the plume upward and increase mixing.

Air bubbles in the overflow plume can give the plume a higher path caused by a reduced mixture density and sediment particles from the plume can follow the rising air bubbles towards the surface. Air can be entrained in the overflow when the excess water from the hopper drops into the pipe in a free falling manner. When the inflow into the overflow is gentle, the amount of entrained air is less or even absent. An environmental valve can be applied in order to force a gentle inflow into the overflow in order to reduce air entrainment, see Decrop (2015) and Saremi (2014) for how

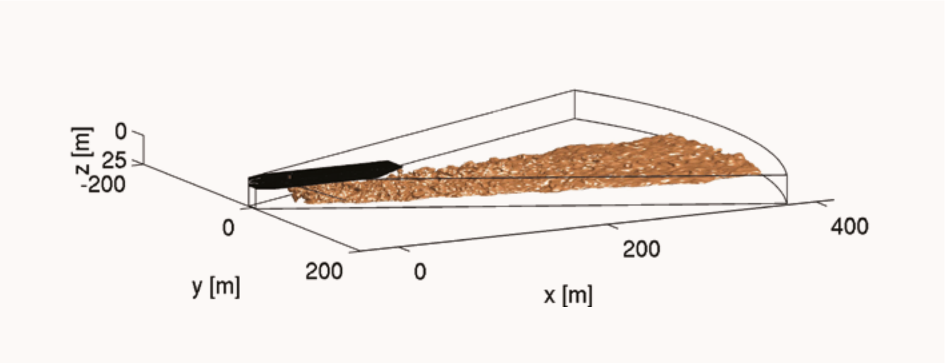

FIGURE 3

Near field CFD model area with TSHD hull and 3D contour of the overflow dredge plume.

efficient an environmental valve can be and for dredge plume simulations in the near field round a TSHD.

In this work results from a dedicated TSHD near field CFD model (De Wit, 2015) are presented which has been developed during an Ecoshape Building with Nature PhD project at the section of dredging engineering of TU Delft. In this model the influence of TSHD hull, propellers, entrained air bubbles in the overflow, multiple sediment fractions, density differences are represented accurately. It solves the Navier Stokes equation including variable density. The Large Eddy Simulation approach is used to account for the influence of turbulence by simulating the larger turbulent eddies directly on the grid. This requires very fine grids. The CFD model in this study employs grids of 10-30 million cells to cover the near field zone up to 350 metres with a resolution up to decimetres. Figure 3 shows a typical near field CFD model area with a TSHD and overflow dredging plume. The model has been validated by laboratory plume results (De Wit, 2014a) and field measurements of TSHD dredging plumes (De Wit, 2014b). The CFD model has also been used to assess the effectiveness of silt screens (Radermacher, 2013).

Results

The influence of the effective flow velocity, depth and amount of entrained air on the overflow plume mixing and generation of a surface plume is shown by comparing different runs with the CFD model. The base case consists of a 150-metre-long jumbo TSHD with a draught of 8 metres in a depth of 25 metres dredging with 0.75 m/s against an ambient current of 0.75 m/s leading to an effective flow velocity of 1.5 m/s. The round overflow pipe has a diameter of 2.25 metres and the overflow discharge is 7 m^3/s with a mixture density of 1200 kg/m^3. In the base case there is no air entrainment in the overflow. Starting from the base case other runs are defined with a different depth, effective flow velocity or amount of air entrainment. In each run only one parameter has been changed compared to the base case in order to assess only the influence of the condition under consideration.

Influence of effective flow velocity TSHD on surface plume generation

The magnitude of the effective flow is an important factor whether a surface plume will be generated or not. When dredging at a slow speed in stagnant water or when dredging with the current, the effective flow velocity remains low and the overflow plume descends towards the seabed quickly with hardly any surface plume being generated (see Figure 4A). With a strong effective flow, e.g. when dredging at high speed against an ambient current, a big surface plume with sediment concentrations of more than 100 mg/l is generated because the overflow plume gets into the influence zone of the propellers and expanding flow past the aft of the TSHD hull (see Figure 4C). These results are obtained without air entrainment, so purely the higher effective flow velocity is responsible for the

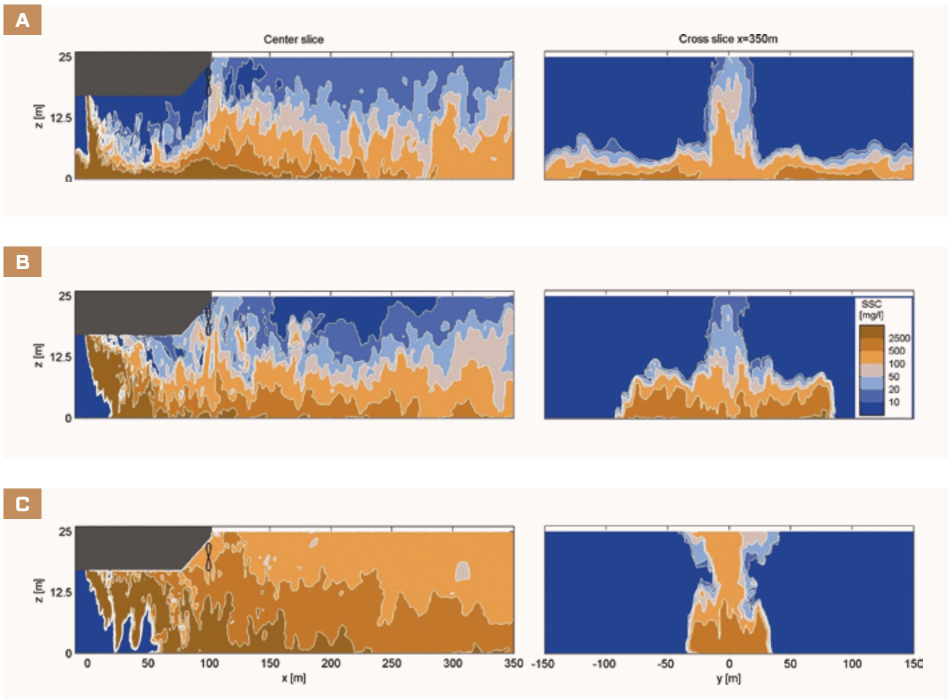

FIGURE 4

Influence of u_{ef} = trailing speed + ambient velocity: (A) u_{ef}=0.5 m/s; (B) u_{ef}=1.5 m/s; (C) u_{ef}=3 m/s on cross view plume.

> **The magnitude of the effective flow is an important factor whether a surface plume will be generated or not.**

generation of a surface plume in this case. When dredging at an intermediate effective flow velocity (Figure 4B), no surface plume is generated. The top view in Figure 5 shows a surface plume growing to a width of 75 metres at x=350 metres for the case of a strong effective flow, and hardly any visible surface plume with low or intermediate effective flow velocity.

Influence of depth on surface plume generation

The depth is also an important factor for the generation of a surface plume. Figure 6 shows the cross view overflow plume results for three different depths: a normal deep water case of 25 metres, a shallow case of 12 metres and an intermediate case of 17 metres deep. When dredging in deep water of 25 metres no surface plume is generated, at intermediate depth of 17 metres a significant surface plume with sediment concentrations of more than 100 mg/l is generated and at a shallow depth of 12 metres, the overflow plume is fully mixed over the water column with concentrations of more than 500 mg/l to be found near bed and at the free surface. The lower keel clearance for dredging at shallower depth leaves the plume in the influence zone of the propellers of the TSHD and expanding flow past the aft of the TSHD hull which then generates a surface plume. Again these surface plumes are generated without air entrainment; it is purely the small keel clearance which is responsible for the surface plume being generated. Figure 7A shows a surface plume growing in width from equal to the TSHD width right behind the dredger to about 100 metres wide at x=350m for the 17 metres depth and 12 metres depth cases and no surface plume for the 25 metre case.

Influence of entrained air on surface plume generation

The different overflow plumes resulting from three different amounts of air entrainment in the overflow shaft are shown in Figure 8. Without air entrainment in the overflow, for example by using an environmental valve, no surface plume is present for this set of conditions (see Figure 8A). Strong air entrainment can occur in the overflow when the water drops meters deep into the overflow and 12% air entrainment (in volume) is possible (De Wit, 2015). With 12% air entrained in the overflow shaft a large surface plume is generated with concentrations of more than 100 mg/l (see Figure 8C). The air decreases the overflow mixture density which leads to a higher plume path and when the air bubbles rise towards the free surface they lift water with sediment particles towards the free

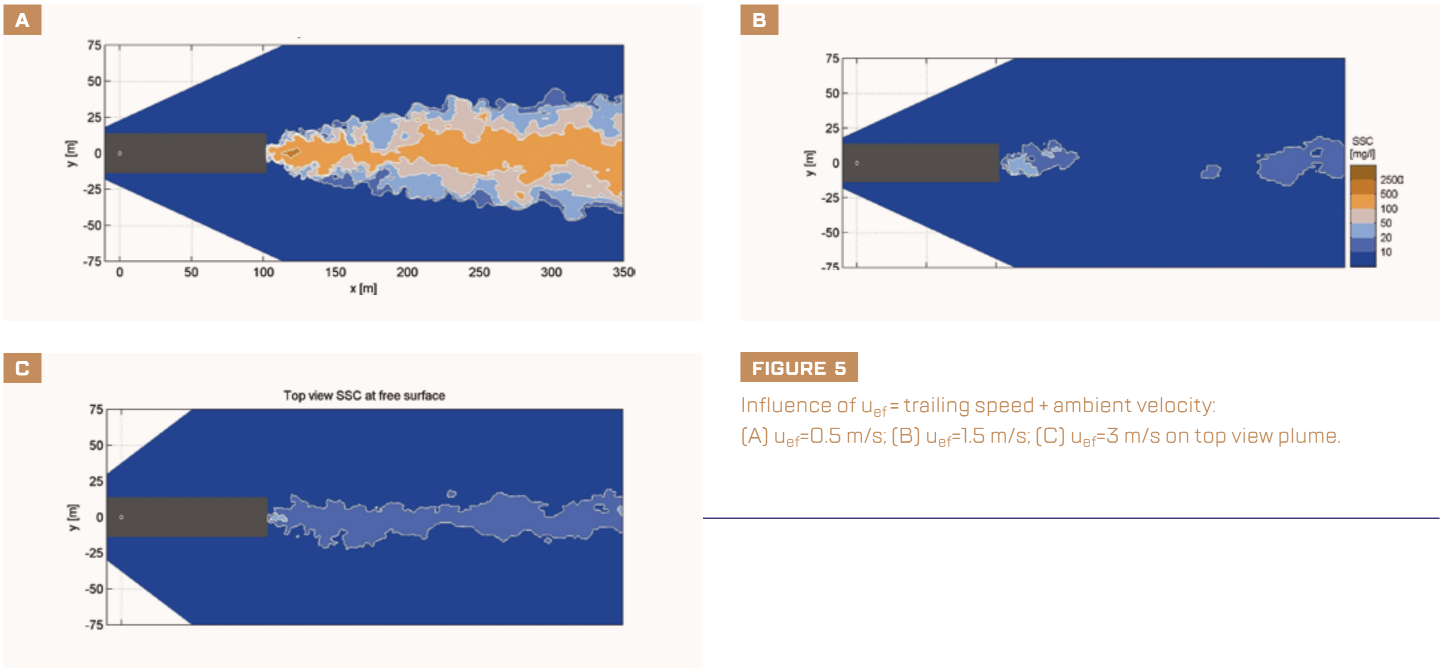

FIGURE 5

Influence of u_{ef} = trailing speed + ambient velocity: (A) u_{ef}=0.5 m/s; (B) u_{ef}=1.5 m/s; (C) u_{ef}=3 m/s on top view plume.

The depth is also an important factor for the generation of a surface plume.

surface. With an intermediate amount of air in the overflow shaft (4% in volume) a small surface plume is generated with about 20 mg/l, see Figure 8B. With much air the surface plume in the top view in Figure 9 is 50-100 metres wide and with some air the width is limited to 50 metres, without air there is hardly any plume visible at the free surface. So air entrainment can be responsible for the generation of a significant surface plume from overflow, even with a large depth of 25 metres and an intermediate effective flow velocity of 1.5 m/s.

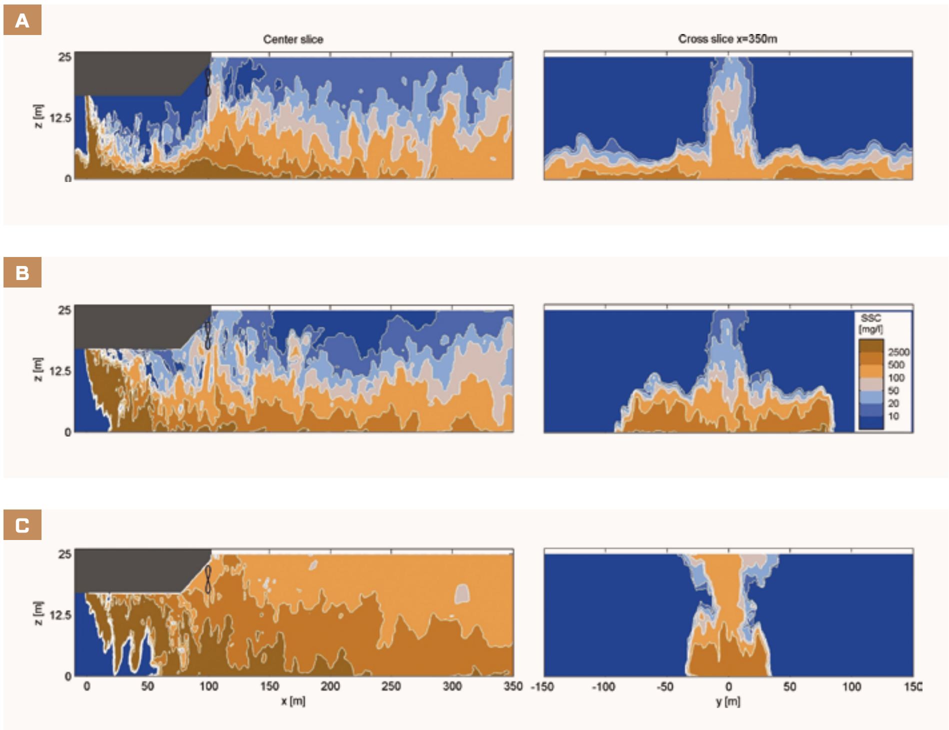

FIGURE 6

Influence of depth: (A) d=25m; (B) d=17m; (C) d=12m on cross view plume.

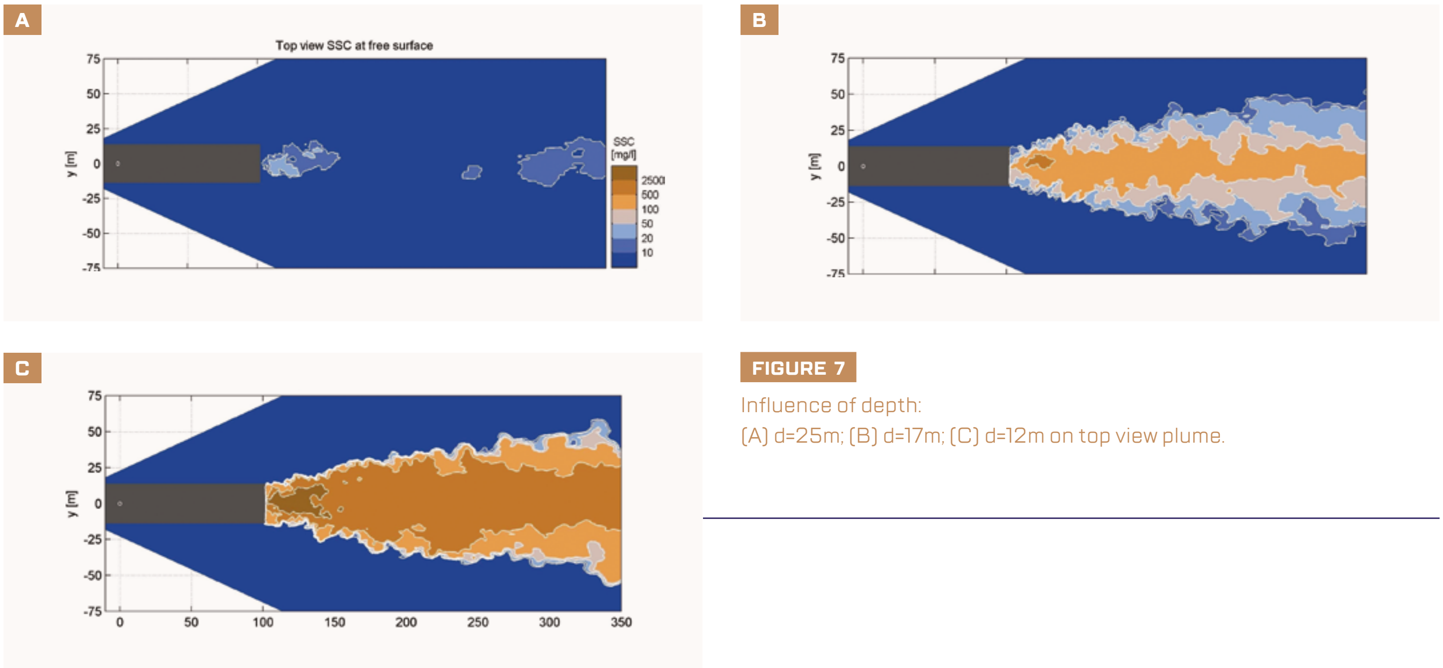

FIGURE 7

Influence of depth:
(A) d=25m; (B) d=17m; (C) d=12m on top view plume.

Translation to practice

The CFD results have made it clear that effective flow velocity, depth and amount of entrained air in the overflow are important factors for the question whether a surface plume is generated or not. The potential environmental impact depends on the answer to this question: a surface plume gives increased turbidity high in the water column which can have adverse effects on flora and fauna and a surface plume can stay suspended for longer periods thus being able to have influence on sensitive areas at larger distances from the dredging site. Therefore, when one wants to assess the environmental impact from overflow dredging plumes, then it is wise to conduct CFD simulations for some characteristic conditions of that specific project in order to see how the plume is mixing and whether a surface plume can be expected. Given the recent increase in computer power this does not have to take much time or money.

A typical CFD simulation as presented in this article takes about a day or two on a cluster computer. In past years several detailed sediment plume mixing simulations have been carried out with this CFD model in the preparation for actual dredging projects. Especially in non-standard situations like sediment released at very deep water, next to a platform or a trench, CFD has proven

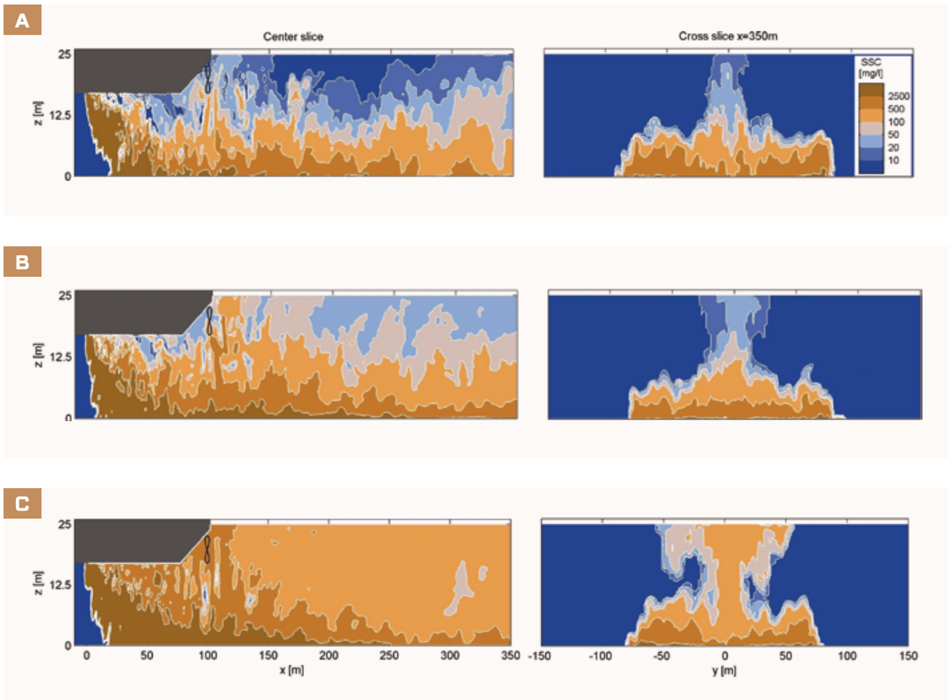

FIGURE 8

Influence of entrained air in overflow:
(A) no air; (B) some air (4% volume); (C) much air (12% volume) on cross view plume.

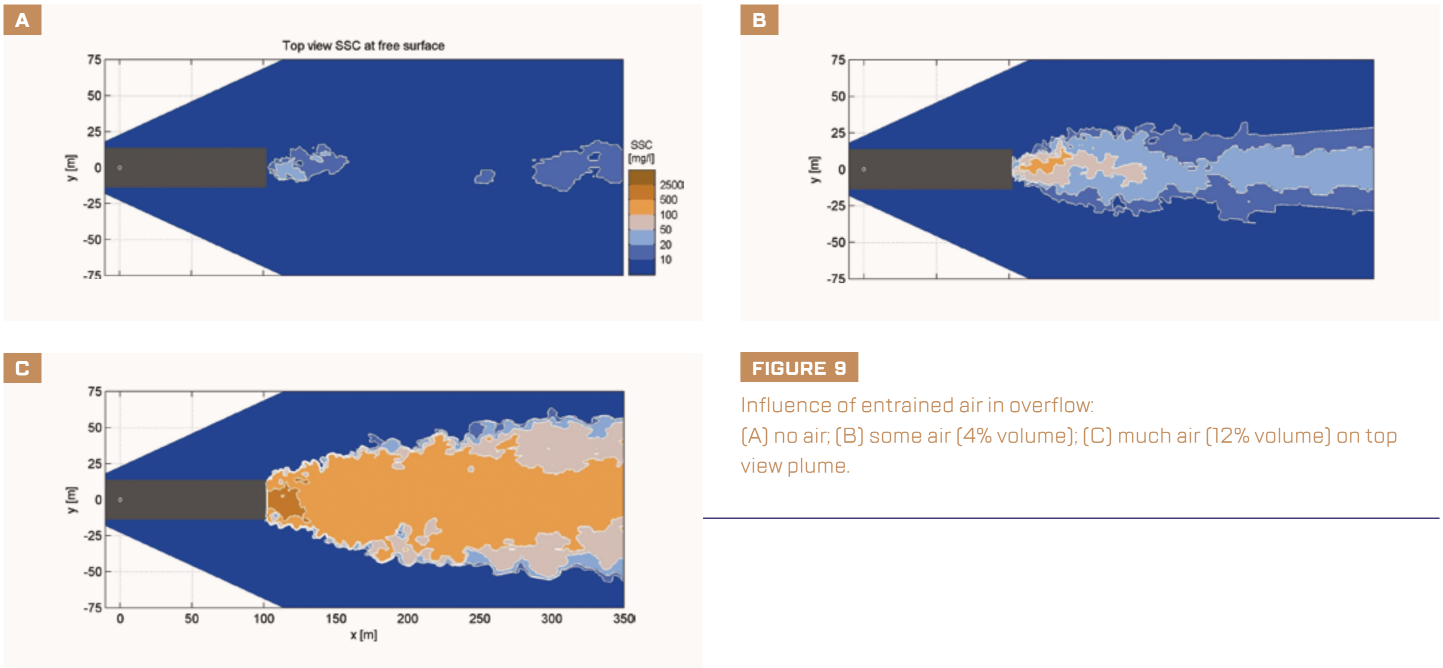

FIGURE 9

Influence of entrained air in overflow:
(A) no air; (B) some air (4% volume); (C) much air (12% volume) on top view plume.

to provide valuable insight in expected (surface) plume behaviour and the influence of operational changes on this.

However, in practice it is not always feasible to conduct heavy CFD simulations for a project at hand. Therefore, a large parameter study of 136 CFD runs for a wide range of possible conditions can be found in De Wit (2014c) and a translation of the results into mathematical formula is given. These mathematical formulas provide a prediction of the vertical distribution of the plume and how much of each sediment fraction within the plume has deposited after some minutes mixing in the near field. They give a reasonable result within a second on a laptop instead of days of calculation time on a cluster computer for a more accurate CFD run. This makes them very suitable for (extensive) parameter studies covering all possible conditions and also for live forecasting simulations.

The influence of other factors than effective flow velocity, depth and entrained air on the near field overflow plume mixing and surface plume generation can be found in De Wit (2014a) and De Wit (2014c). These other factors include: the overflow mixture density; what happens when a TSHD sails at an angle with the current; what is the influence of having the overflow in the front or back of the vessel; a pulsing flow in the overflow. A complete recipe to go from the in-situ sediment characteristics via dredging method to the determination of a sound source flux in a far field model is given in Becker et al. (2015) and Aarninkhof et al. (2018). The results from the CFD model presented in this article or from the predictive mathematical formula in De Wit (2014c) can be used to determine the amount of deposition of the coarser fractions from an overflow plume in the near field and the (vertical) distribution and remaining particle size composition of the overflow plume at the end of near field which is input in this recipe.

Monitoring of turbidity levels round a dredging site or near an environmental sensitive area might be needed during the execution of a dredging project (CEDA, 2015a). Through adaptive management strategy dredging can be adjusted in order to assure that the impact remains within acceptable limits (CEDA, 2015b). Detailed plume modelling might be helpful to optimise the dredging project beforehand and thus minimise the need for adaptation while executing the project and it can be used to place the monitoring stations at the best possible vertical and horizontal positions.

Conclusions

Whether a surface plume near a TSHD will occur can be predicted by process-based detailed CFD simulations of the near field zone. CFD results presented in this paper lead to the following main conclusions:

- **Quick descent overflow dredging plume towards seabed for base case**
  Without entrained air bubbles e.g. because of the use of an environmental valve, with a large depth and with a small effective flow velocity an overflow dredging plume descends quickly to the seabed under the keel of the TSHD without generation of a surface plume. In dredging practice this is often the case and it is caused by the significant excess density of the slurry flowing out of the overflow and the initial downward velocity.
- **Generation surface plume with large effective flow velocity**
  A large effective flow velocity can cause the generation of a large surface plume, even without entrained air bubbles. The reason for generation of a surface plume lies in the fact that a large effective flow velocity makes that the plume cannot descend enough to get out of the influence zone of the TSHD propellers and expanding flow past the aft of the TSHD hull.
- **Generation surface plume with small depth**
  Also a small depth can cause the generation of a large surface plume, even without entrained air bubbles. A small depth makes that the plume cannot descend enough to get out of the influence zone of the TSHD propellers and expanding flow past the aft of the TSHD hull; this leads to the generation of a surface plume.
- **Generation surface plume with entrained air**
  Entrained air can generate a significant surface plume as well, even with a large depth and small effective flow velocity. The reason now lies in the reduced mixture density caused by the entrained air and by sediment particles being brought to the free surface by the rising air bubbles.

The numerical results and photos in the paper show that significant surface plumes of >100 mg/l over areas of hundreds of meters from the dredger can occur behind a TSHD in ordinary dredging operations, but under slightly different conditions they are absent. Whether a surface plume is generated or not has big implications on the assessment of environmental impact of a TSHD. Increased turbidity high in the water column can have adverse effects on flora and fauna and a surface plume can stay suspended for long periods thus being able to have influence on sensitive areas away from the dredging site.

The presented CFD model can be applied to investigate surface plume generation under the conditions of a specific dredging project and characteristic plume results for a range of relevant conditions have been presented. For cases that CFD simulations require too much effort, predictive mathematical formulas are available which can predict the vertical distribution and amount of deposition of the coarser fractions of the overflow plume at the end of near field within a second on a laptop. The insight from this article can be used for a better assessment of the environmental impact of dredging projects and help with setting up appropriate monitoring campaigns and adaptive management strategies.

> **When dredging with a TSHD, the main source for a turbidity plume is the overflow which is a vertical shaft ending at the keel through which excess sea water from the hopper is released.**

Summary

A surface plume from overflow can stay suspended for long periods and distances potentially resulting in negative environmental impact through increased turbidity and sedimentation. Surface plume generation is an important factor for a proper dredging environmental impact assessment which is accurate.

When dredging with a TSHD, the main source for a turbidity plume is the overflow which is a vertical shaft ending at the keel through which excess sea water from the hopper is released. This excess water can contain fine sediment fractions which did not have sufficient time to settle in the hopper. Increased turbidity can impact ecological sensitive areas by reduced light penetration, reduced visibility, clogging and burial. For dredging projects, often the environmental impact needs to be assessed by model studies beforehand and monitored during execution of the work.

Generation of a surface turbidity plume from the overflow of a TSHD is investigated by a process-based, detailed Computational Fluid Dynamics model. The influence of effective flow velocity (sum of dredging speed and ambient current), depth, and entrained air bubbles in the overflow pipe is visualised with appealing results. A selection of results from a validated CFD model incorporating all important processes is presented.

Lynyrd de Wit
Lynyrd is a dredge plume expert. He has been involved in projects regarding TSHD/WID/MFE/offshore mining plumes, outfall mixing, salt intrusion from a sea lock, land reclamation Khalifa Port, hopper/caisson sedimentation, siltation in harbor basins and approach channels. The combination of developing and applying models and monitoring in the field makes him aware of limitations of numerical models, but also of their possibilities. Between 2008 and 2014 he finished a PhD study on near-field mixing of overflow TSHD dredge plumes.

Bram Bliek
Bram (1955) is the General Manager at Svašek Hydraulics since 1984. He joined the company in 1977 upon completion of his MSc. work at Delft University of Technology. He is a recognized expert in coastal engineering and hydraulic modelling. His expertise is based on a sound and practical understanding of the physical processes in surface waters and includes themes like tidal and river currents, wind wave and swell characteristics, seabed morphology, hydraulic structures and their environmental impacts, and the interactions between all of this.

Cees van Rhee
Since 1985, Cees has been engaged with research for the dredging industry. The first five years were at WL|Delft Hydraulics (presently Deltares) and then at Van Oord, a dredging contractor where he was employed at the various departments and projects, from 1990 to 2011. At the end of 2002, the author obtained his PhD degree. Since October 2007, he is professor Dredging Engineering at Delft University of Technology. His main scientific achievements are modelling of highly concentrated sediment water flows and high velocity erosion of granular sediments.

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