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Chapter

Advances in Maintenance of Ports and Waterways: Water Injection Dredging

Alex Kirichek, Katherine Cronin, Lynyrd de Wit
and Thijs van Kessel

Abstract

The main objective of this chapter is to demonstrate developments in port maintenance techniques that have been intensively tested in major European ports. As regular port maintenance is highly expensive, port authorities are considering alternative strategies. Water Injection Dredging (WID) can be one of the most efficient alternatives. Using this dredging method, density currents near the bed are created by fluidizing fine-grained sediments. The fluidized sediment can leave the port channels and be transported away from the waterways via the natural force of gravity. WID actions can be successfully coupled with the tidal cycle for extra effectiveness. In addition, WID is combined with another strategy to reduce maintenance dredging: the nautical bottom approach, which enables the vessel to navigate through the WID-induced fluid mud layer. The nautical bottom approach uses the density or the yield stress of sediment to indicate the navigability after WID rather than the absolute depth to the sediment bed. Testing WID-based port maintenance requires thorough preparation. Over the years modeling and monitoring tools have been developed in order to test and optimize WID operations. In this chapter, the application of the recently developed tools is discussed.

Keywords: fluid mud, dredging, sailing through mud, WID, nautical depth, cohesive sediment

1. Introduction

Navigation in ports, canals and waterways must be safeguarded by maintenance dredging to remove sediments deposited by tide, river flows and currents. In order to keep ports and waterways accessible, this non-contaminated sediment is typically dredged by a trailing suction hopper dredger (TSHD) and reallocated at sea [1].

Maintenance dredging of sediment deposits can be highly expensive and inefficient as it must be done on a regular basis. Therefore, port authorities seek tailor-made solutions to reduce the costs and at the same time guarantee safe navigation in ports and waterways. Over the last decades, a number of strategies for port maintenance have been tested by port and governmental authorities. Maintenance dredging can be optimized by techniques to avoid or reduce sedimentation, such as optimization of port design, current deflecting walls, see [2], or by designing a sedimentation trap to focus sediment deposition in order to make reallocation easier and to reduce sediment deposition in other port areas [3].

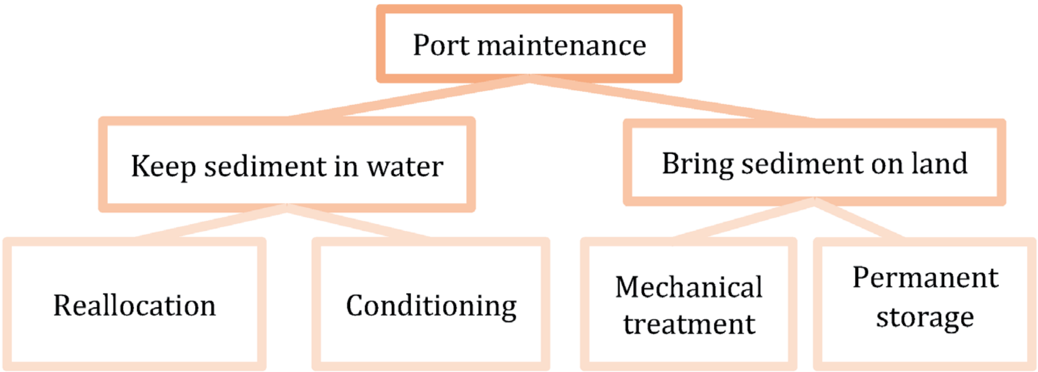

Figure 1.
Types of port maintenance methods which are based on the dredging methods keeping sediment in water or bringing dredged material on land.

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Once dredging has conducted, typical strategies for dredged sediment management are either based on the concepts of keeping sediment in the water system or bringing sediment on land (see **Figure 1**). The former is generally considered as the most cost-effective strategy. However, the latter can be utilized for beneficial re-use of dredged sediment, thus better embedded into a circular economy.

It is a well-known fact that in major sea ports fine-grained sediment deposits are routinely reallocated from the port area either further away downstream from the dredged area or directly to the sea depending on the return flow of from the reallocation locations. The choice in reallocation area often consists of finding a balance between minimizing sediment return flows back into the harbor and transport distance and costs. Often, the reallocation of dredged sediment is combined with sediment management within a building with nature concept [4]. These reallocation projects are mainly focused on the reallocation of fine-grained sediment for land creation or improvement, wild habitat restoration, shore nourishment and marsh or wetland development [5–7].

In contrast to reallocation of sediment, conditioning is used for port maintenance with the assumption that the sediment stays in the port area. The goal of conditioning the sediment is to create navigable conditions in waterways while keeping the sediment in place. In this case, the nautical bottom concept is often applied for navigation through mud [8–10]. One of the examples for applying sediment conditioning for port maintenance is in the Port of Emden. The sediment first dredged and then conditioned by reducing the strength of dredged sediment in the dredging vessel [8]. The created fluid mud is then pumped back to the port mouth creating a weak navigable fluid mud layer. If the transport of fluid mud towards the river equals the import of suspended mud by exchange flows, a dynamic equilibrium is achieved without residual import, hence dredging.

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These techniques do not apply to contaminated dredged sediment which is either stored in confined disposal facilities [1, 11] or processed in sediment treatment facilities [12, 13]. The latter technology uses mechanical treatment to prepare the sediment for further beneficial re-use options. Recently, mechanical treatment is also used for non-contaminated sediment as dredged sediment is being recognized as a resource. The treated material can be used as a constructional component for building and re-enforcement of infrastructure [14, 15].

Water injection dredging (WID) can be used as a tool for both reallocation and conditioning of the deposited sediment. The efficiency of this dredging method has been recognized over the past 30 years. However, the successful application of WID can be only achieved by combining technical approaches with knowledge of the system where WID is to be applied. Particularly, the following key questions have to be answered in order to understand better the impact of WID on reallocation and conditioning of cohesive sediment:

- What type of sediment is to be relocated or conditioned by WID?
- What are the hydrodynamic conditions and bathymetry in the WID area?
- How fluidized sediment is distributed in port basins after WID?
- How far and where is the WID-induced plume transported after WID?
- What is the impact of WID on near-surface turbidity and how is this influenced by operational parameters?
- What criteria for navigation can be used in WID-conditioned areas?

The goal of this chapter is to provide an overview of the developed knowledge and tools that can be used for addressing the abovementioned questions. In addition, recently-developed numerical modeling, field and laboratory experiments can provide the necessary information for optimizing WID and defining the boundary conditions for its application. Finally, the recent findings on navigable conditions in ports and waterways, where WID is used for conditioning the sediment and keeping fluid mud in place, are discussed.

2. Working principles behind water injection dredging (WID)

2.1 Fluidization of fine-grained sediment

The principle of the water injection process is based on fluidization of deposited sediment by a water jet (see **Figure 2**). Water injection is performed by injecting large volumes of water (approx. 12,000 m^3/h) under relatively low pressure (approx. 1-1.5 bar) from water jet nozzles, that are distributed over an equal distance on the jet [16, 17]. The injected water penetrates the cavities between the individual sediment particles weakening the forces between them and destroying the formed structure of the bed. The water-sediment mixture forms a fluid mud layer of about 0.5-3 m thickness right above the bed. Most investigations show that the sediment

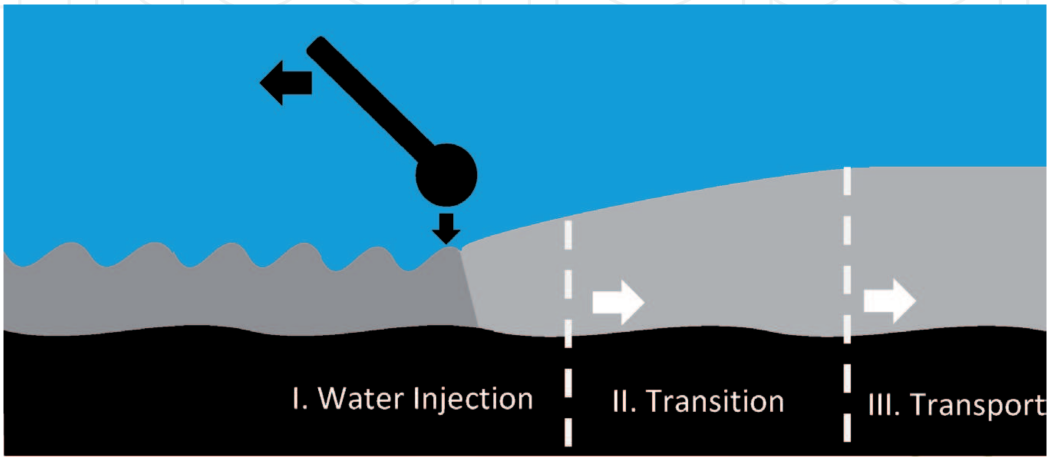

Figure 2.
Phases of WID: I. water injection and fluidization; II. Transition zone, where a density flow is created; III. Transport of the density flow. Adapted from [21, 22].

material hardly mixes into the upper water volume, and sediment transport of the fluidized mud layer remained predominantly close to the bottom [18, 19].

2.2 Transport of fluidized sediment

A sketch of WID performed in a navigational channel with a bed mainly consisting of fine-grained cohesive sediment is shown in **Figure 3**. The near bed fluidized sediment deposit generates a gravity driven density flow up to few meters high, transporting the sediment in a horizontal direction as a result of the density difference [17, 20–22]. This density flow can be described as a homogeneous suspension layer with a solid concentration of up to 200 g/l. Since the density between the fluid mud layer and the surrounding water body is different, fluid mud sets in motion under the action of natural hydrodynamic processes. Thus, WID is different from agitation dredging in which sediment is deliberately mixed over the full water column and then transported in horizontal direction as a passive plume by the ambient currents resulting in a less environmental-friendly outcomes.

The velocity of fluidized sediment is reported in the range between 0.3 m/s and 1 m/s [16, 21, 22]. Based on the hydrodynamic conditions in a port basin, WID-conditioned sediment can either settle over time in a low-energy area or be transported by means of gravity currents to deeper areas such as sediment traps [3].

Different transport distances from a few hundred meters to a few kilometers are reported for fluidized sediment [19, 21–23]. Natural transport of coarse-grained sandy sediment is substantially shorter. Therefore, the sediment composition of the bottom can be altered by WID operations. Fine-grained sediment can be generally more easily fluidized than coarse-grained material and has better transport properties. Since the fine grain fraction is transported away sooner and further than the coarse grain fraction, over time the particle size distribution of the sediment bed can be segregated as a result of dredging. Therefore, the coarse-grained component increases as a result of WID operations.

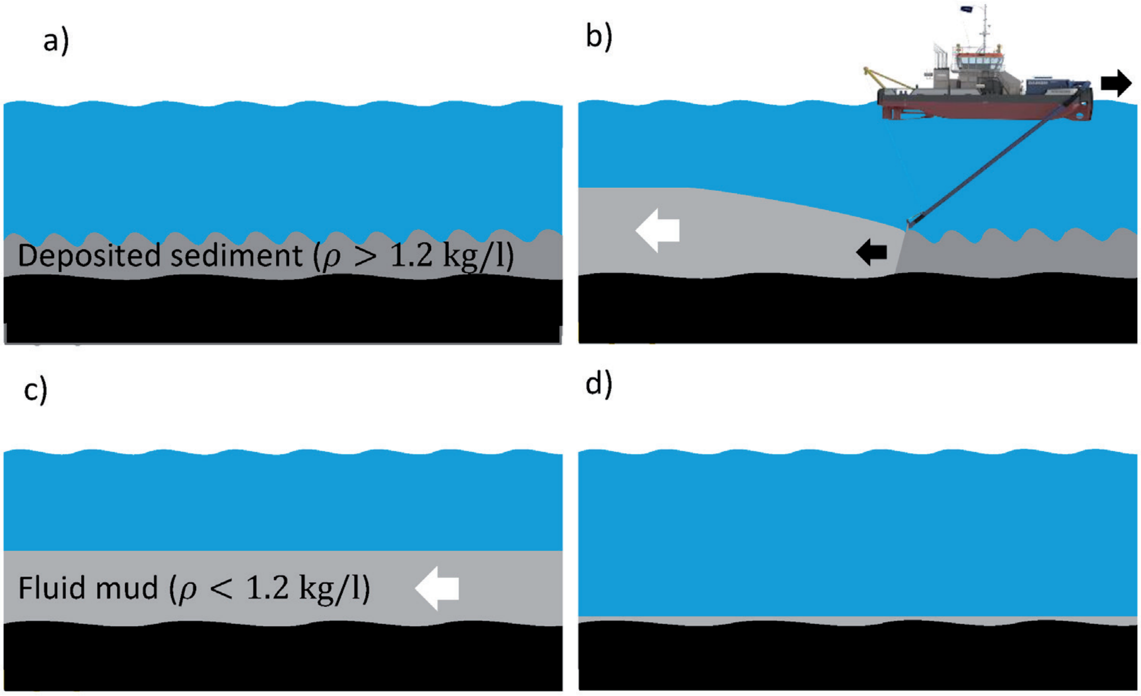

Figure 3.
Illustration of WID performed in a navigational channel during the ebb tide. a) Initial conditions for WID. b) Fluidization of deposited sediment during WID. c) WID-induced fluid mud layer. d) Final result after WID in case WID is conducted for sediment reallocation purposes.

2.3 Efficiency of WID

The effectiveness of the WID process can be influenced by various factors. The direction, velocity and achieved transport distances of the fluidized layer depend on the interaction of different physical forces. The important influencing factors are sediment composition and characteristics, WID operation characteristics, resulting density of the fluidized layer, bathymetry and natural currents and bed shear stresses in the WID area. The efficiency of the process is also influenced by the bathymetry of the dredging area and the prevailing natural currents. Productivity is generally increased when WID can be carried out so that fluid mud can flow with a natural gradient from higher to lower-lying bathymetry.

The composition and strength of the sediment are also essential for fluidization process. Although it is reported that WID has been also performed for removing coarse-grained sandy sediment and even consolidated soils [16, 21, 22], the best efficiency of WID has been achieved by fluidizing fine-grained sediment deposits. In [20] WID productions are reported in the order of a few thousand m^3/h for very fine-grained sediments and in the order of a few hundred m^3/h for coarser sediments.

The operational parameters for execution of WID are playing an important role for WID. The determining factors are the nozzles diameter, the flow velocity of the water from the jet, jet penetration, the forward movement of the jet pipe, and the distance between the jet nozzle and the surface of the sediment [24]. A WID operator can find the optimal combination of the aforementioned factors to achieve the maximum production of loosened material. However, not only the mass flux of loosened material should be optimized, but also the initial density, layer height and velocity. A thin but dense layer with little initial momentum will hardly spread, whereas a thick, diluted layer with high velocity will quickly mix with ambient water, with negative consequences for turbidity and focus of sedimentation footprint.

WID is generally considered as a relatively low-cost process [3, 25]. As the fluidized sediment is transported in the form of a density flow on the bed and is not distributed throughout the entire water column, WID is also characterized by a high level of environmental compatibility competing to traditional port maintenance dredging [3, 18]. Recently, it was also shown that WID is more CO_2 efficient than the regular TSHD maintenance because WID requires less fuel consumption than TSHD. All these aspects suggest that WID can be more attractive tool for port maintenance.

3. Modeling of WID

In recent years, different tools have been developed for optimizing WID processes and better prediction of sediment plume movement during WID. Numerical modeling tools can be used for estimating sediment dynamics in ports and waterways after WID.

Mid-field modeling is often used for calculating the sediment footprint on the areas up to about 1 km away from WID. The obtained knowledge on sedimentation can help to better design WID operations including real bathymetry of a navigational channel. Existing and hypothetical infrastructure can be included in mid-field modeling allowing for testing of WID in combination with sediment transport steering management solutions such as sediment traps, sills and current-deflection walls.

Far-field modeling evaluates the impact of WID on the scale of the entire port or estuary area. This kind of modeling is used for estimating WID reallocation strategies of sediment from the port basins to the sea and for assessing return flows. Simulations can demonstrate the transport of the WID plume during different phases of the tide and the impact of river and sea conditions. Based on the obtained information, the authorities can decide if conducting WID for reallocation purposes is effective in the port.

3.1 Mid-field modeling of WID

Mid-field modeling is carried out by two distinct models: a Lagrangian 1DV model and a 3D CFD model (TUDflow3D). The Lagrangian 1DV model is a rapid assessment tool which can be used for rather uniform bathymetry and slowly varying flows while neglecting lateral spreading. When these assumptions are not valid the more sophisticated 3D CFD model TUDflow3D can be used which includes lateral spreading and simulates a WID density current in three dimensions. TUDflow3D needs much more simulation time as the Lagrangian 1DV model.

The Lagrangian 1DV approach allows us to follow the development of the fluidized layer flow along a user-defined trajectory using a moving frame of reference. The 1DV model determines the thickness and the density (or the sediment concentration) of the fluidized mud layer and correlates these properties to the hydrodynamics in the water column and the slope of the bed. Additionally, it determines the sedimentation flux on the bed. For an equal initial momentum of the fluidized mud layer, the layer will flow further along a downward slope than along a flat bed. In general, the results of 1DV modeling can be used for a better planning of WID.

Figures 4 and **5** illustrate an example of utility of the 1DV model for water injection dredging. In both figures, the left panel shows the distribution of the sediment concentration and the height of the fluidized mud layer along the slope. The right panel shows the flow velocity of the fluidized mud layer. **Figure 4** shows the simulation of WID for an initial WID plume height of 2 m and **Figure 5** shows the results of WID for an initial WID plume height of 3 m. Both cases start with an initial sediment concentration of 170 kg/m^3 and 0.7 m/s flow velocity. It can be seen that a higher fluidized mud layer travels faster and reaches a higher internal velocity.

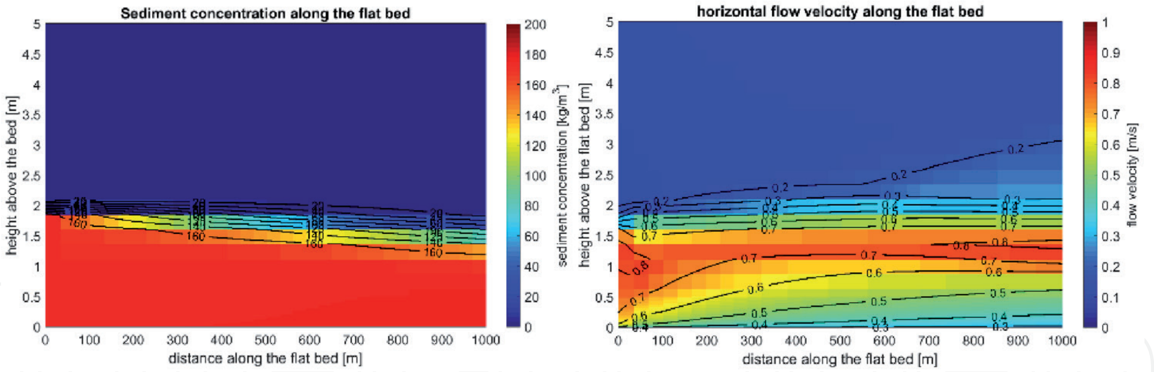

Figure 4.
1DV results for initial WID plume height of 2 m.

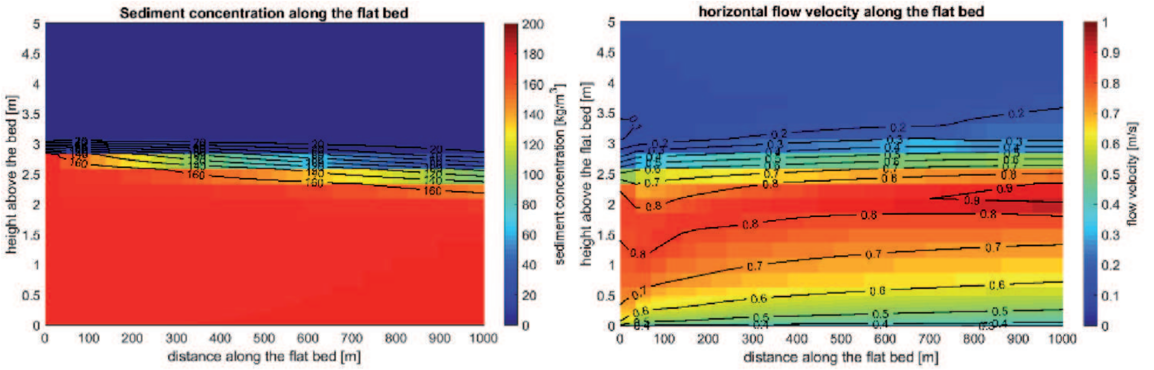

Figure 5.
1DV result for initial WID plume height of 3 m.

WID density-driven plumes can be also simulated in 3D by the CFD model TUDflow3D [26, 27]. Originally, TUDflow3D has been developed for accurate near field simulations of Trailing Suction Hopper Dredger overflow plumes on real scale. It has also been used for MFE (Mass Flow Excavation) plumes, deep sea mining tailing plumes and salinity driven density flows. TUDflow3D can supplement the 1DV model for complex situations in which the simplifications of the 1DV model make application impossible. TUDflow3D is fully 3D with variable density taken into account in all three dimensions (not just in the vertical), non-hydrostatic pressure and turbulence captured by either the accurate LES (Large Eddy Simulation) approach or by a faster RANS (Reynolds Averaged Navier Stokes) approach.

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An instantaneous snapshot of the modeled density current is shown in **Figure 6**. The individual turbulent eddies and whirls resolved on the grid in LES are clearly visible. Comparison for time averaged velocity and Suspended Sediment Concentration (SSC) profiles with measured ones is given in **Figure 7**. Here, different manners of capturing turbulence are compared. In addition to LES with the WALE sub-grid-scale model, the RANS with Realizable K-Epsilon model and Realizable K-Epsilon model with reduced eddy viscosity near the bed are tested. In the latter the eddy viscosity near the bed is adjusted, effectively reduced, to correspond to the correct amount of bed shear stress. The results show that this adjustment improves the Realizable K-Epsilon results for this flow. The vertical SSC profile and layer thickness of the density current is captured very well in the CFD LES model and the velocity profiles are captured reasonably well with a small overprediction of the near bed velocity. The Realizable K-Epsilon results with adjusted near bed viscosity are considerably better as the default Realizable K-Epsilon results.

An example a of application of TUDflow3D for WID is given in **Figure 8**. In this CFD run a WID works along a 300 m track which it has done 6 times in a row.

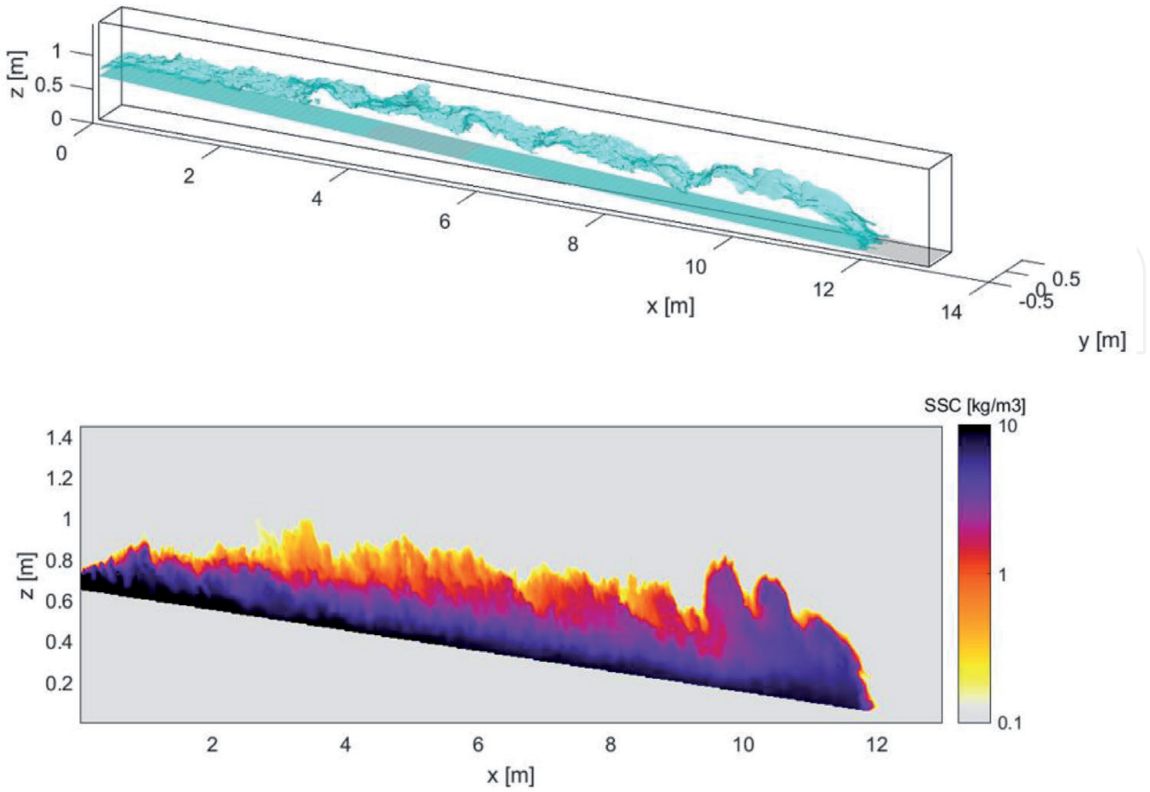

Figure 6.
Instantaneous LES snapshot of 3D contour (top) of a turbidity current and SSC at a vertical slice through the center of the turbidity current (bottom).

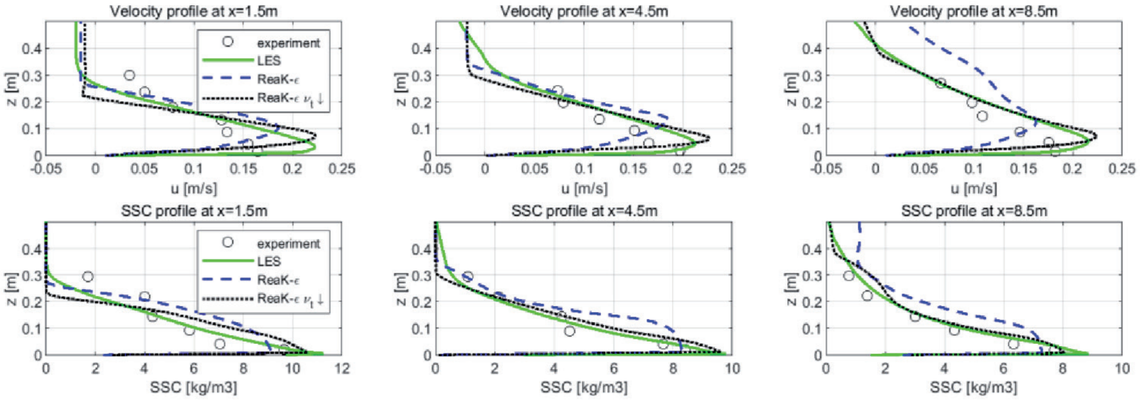

Figure 7.
Comparison modeled time averaged velocity and SSC profiles with 3 different turbulence settings (LES; realizable K-epsilon and realizable K-epsilon with reduced near bed viscosity) and measurements from [28].

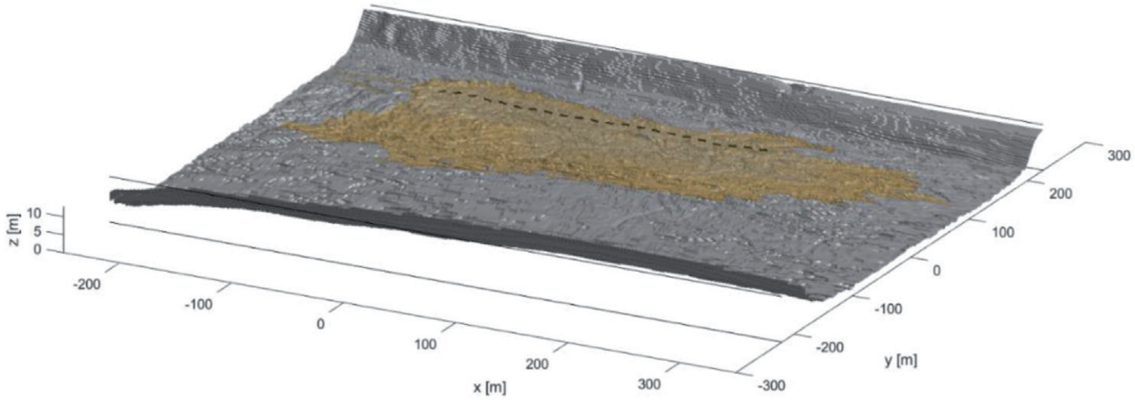

Figure 8.
Example of TUDflow3d simulation: Plume distribution from WID action along black dashed line.

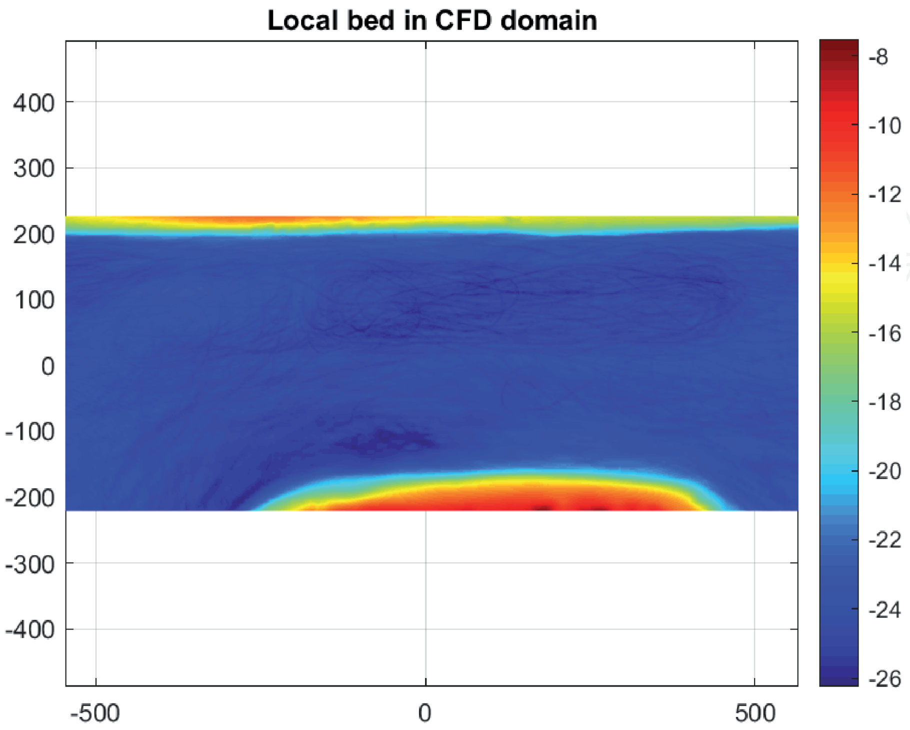

Figure 9.
Example of TUDflow3D simulation: Implementing bathymetry in a CFD domain.

The CFD model uses the real bathymetry of the port. The resulting WID plume is shown in brown and the bathymetry is illustrated as a gray surface. At the moment of this image the WID has just finished the 6th time along the black dashed track of 300 m long. In this example the WID plume flows down the sloping bed in lateral direction under influence of gravity. A top view of the bathymetry is shown in **Figure 9**.

A comparison of TUDflow3D and the Lagrangian 1DV model for WID in a lateral confined situation without bed-slope is shown in **Figure 10**. For this simulation, the following initial conditions were applied: initial WID layer thickens of 2 m, 170 kg/m^3 and 0.7 m/s inflow (resulting in an influx of 238 kg/s). The example shows the simulated vertical velocity profiles and density profiles at different distances from the WID. The model also calculates the sedimentation flux out of the WID density current. The results of the 1DV model and full 3D CFD are close to each other for this case. For cases where the assumptions of the Lagrangian 1DV model (neglecting lateral spreading and slowly varying flow conditions) hold it is much faster as the more sophisticated TUDflow3D model and in other cases it is advised to use a 3D near field model like TUDflow3D.

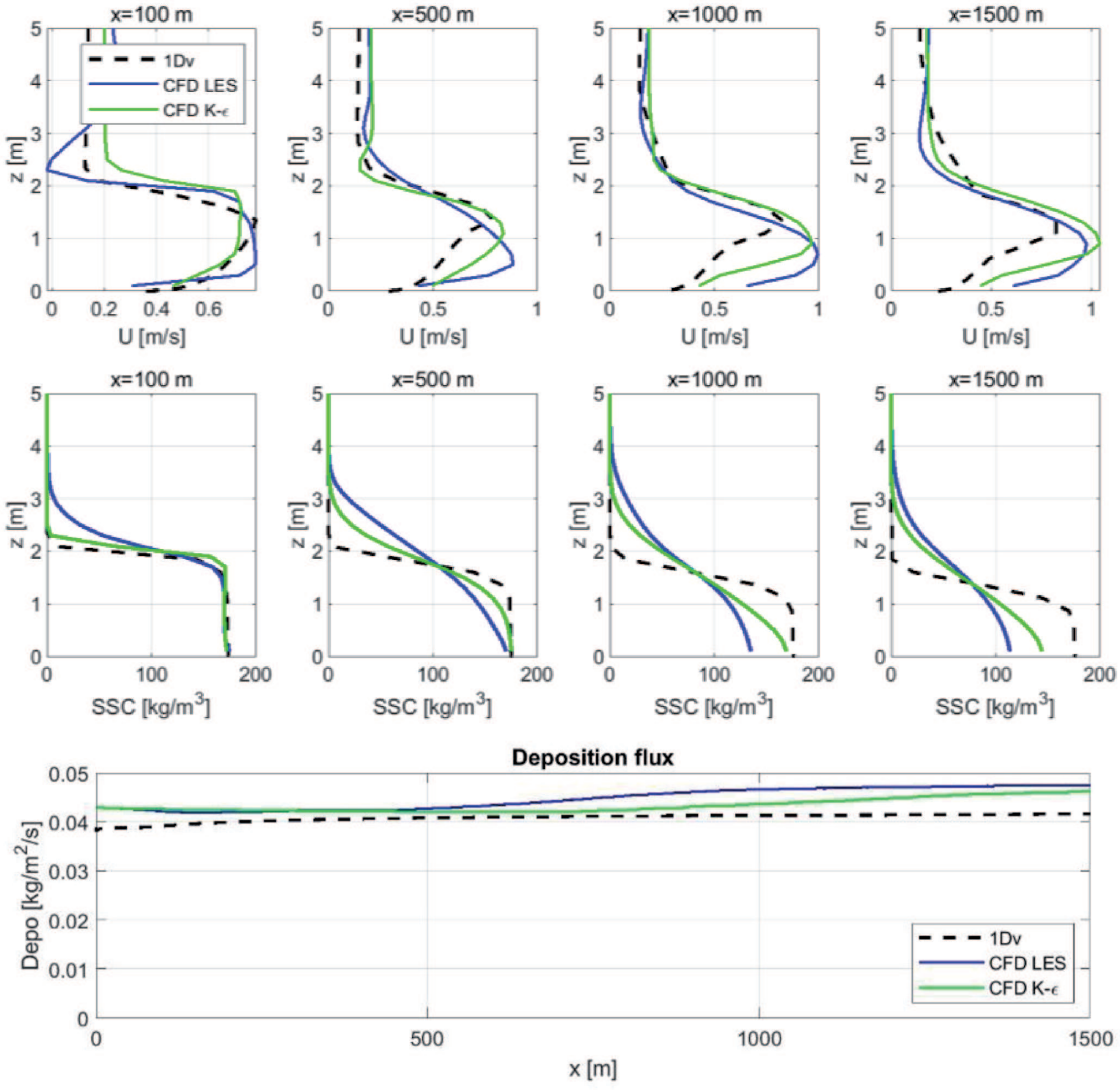

Figure 10.
Comparison of CFD model TUDflow3D and 1Dv simulations for WID in a lateral confined situation. TUDflow3D is compared for two different turbulence settings (LES; realizable K-epsilon).

3.2 Far-field modeling of WID

Sediment dynamics and specifically, the siltation of mud, in ports is of great interest to those responsible for the maintenance of ports, harbors and access channels around the world. The amount of siltation determines the frequency and volume of maintenance dredging needed to maintain navigable depth. In order to understand sediment dynamics in the system, in particular the processes responsible for suspended mud and fluid mud transport, a range of spatial and temporal scales must be analyzed. A numerical model is an ideal tool with which to investigate both the transport, deposition, and potential resuspension of a WID plume. Such a model was developed, using Delft3D, for the Rhine Meuse Delta in the Netherlands, in order to calculate both background fine sediment dynamics in the Port of Rotterdam and the transportation of a fluid mud layer after a WID operation.

Deltares' open source software Delft3D is a flexible, integrated modeling framework which simulates two and three-dimensional flow, waves, sediment transport and morphology (as well as dredging and dumping) on a time-scale of days to decades. The sediment transport module includes both suspended and bed/total load transport processes for an arbitrary number of cohesive and non-cohesive sediment fractions. It can keep track of the bed composition to build up a stratigraphic record. The suspended load solver is connected to the 2D or 3D advection–diffusion solver of the hydrodynamic module and importantly for fluid-mud simulations, density feedback can also occur.

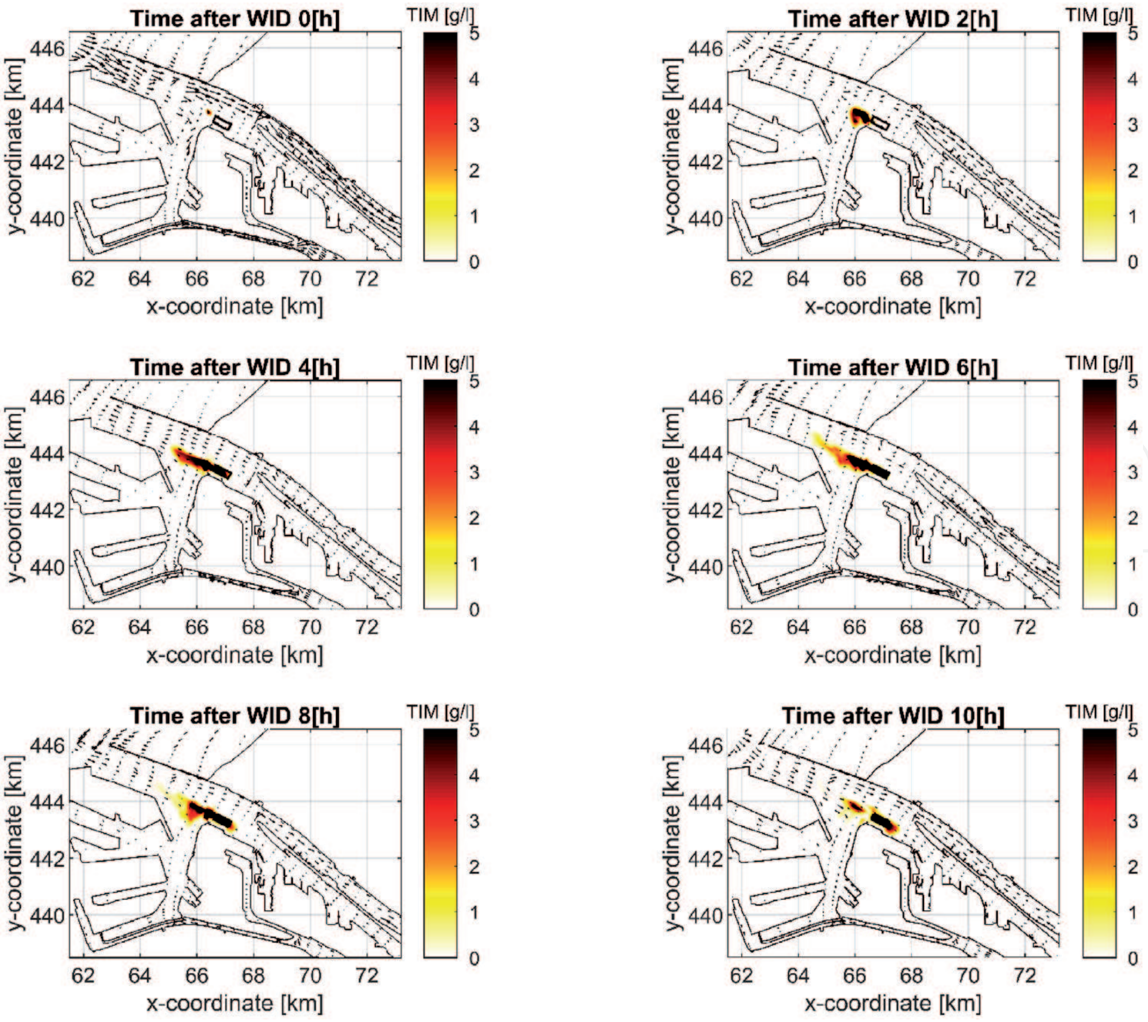

Figure 11.
Horizontal near bed plume spreading, WID starts 1 h before HW with a production rate of 500 kg/s.

For this work, a Delft3D model of the entire Rhine Meuse Estuary was setup. Hydrodynamic conditions were simulated for a full month, including wave effects. This hydrodynamic model is then used to force the sediment transport model. Background sediment concentrations are included in the model using three sediment fractions to represent the appropriate range of coarser and finer fractions. Once natural dynamics regarding sediment transport and sediment deposition in the different ports was captured, a range of WID tests could be undertaken. The parameters derived for different WID production rates in the mid-field modeling (described in Section 3.1) are used to define the initial conditions for the WID plume in the far-field model. Numerical experiments could then be performed such as simulating where the WID plume is transported to, the amount of return flow into different parts of the port and the amount of mixing that occurs throughout the water column. Vertical mixing may result in elevated turbidity levels near the surface, which should remain within the environmental limits. The model is also used to investigate the optimum location for sediment traps to capture the WID high density plume.

Figures 11 and **12** show an example of how the far-field modeling was used to investigate the impact of carrying out WID at different stages of the tidal cycle. WID was carried out in the area of a black rectangle. The colourbar indicates the distribution of suspended sediment concentration (SSC) in the port area. The duration of WID was 8 hours with a production rate of 500 kg/s. During 2 simulations, WID was initiated 1 h before high water (HW) and 1 h before low water (LW). The results of both simulations are shown in **Figures 11** and **12**, respectively.

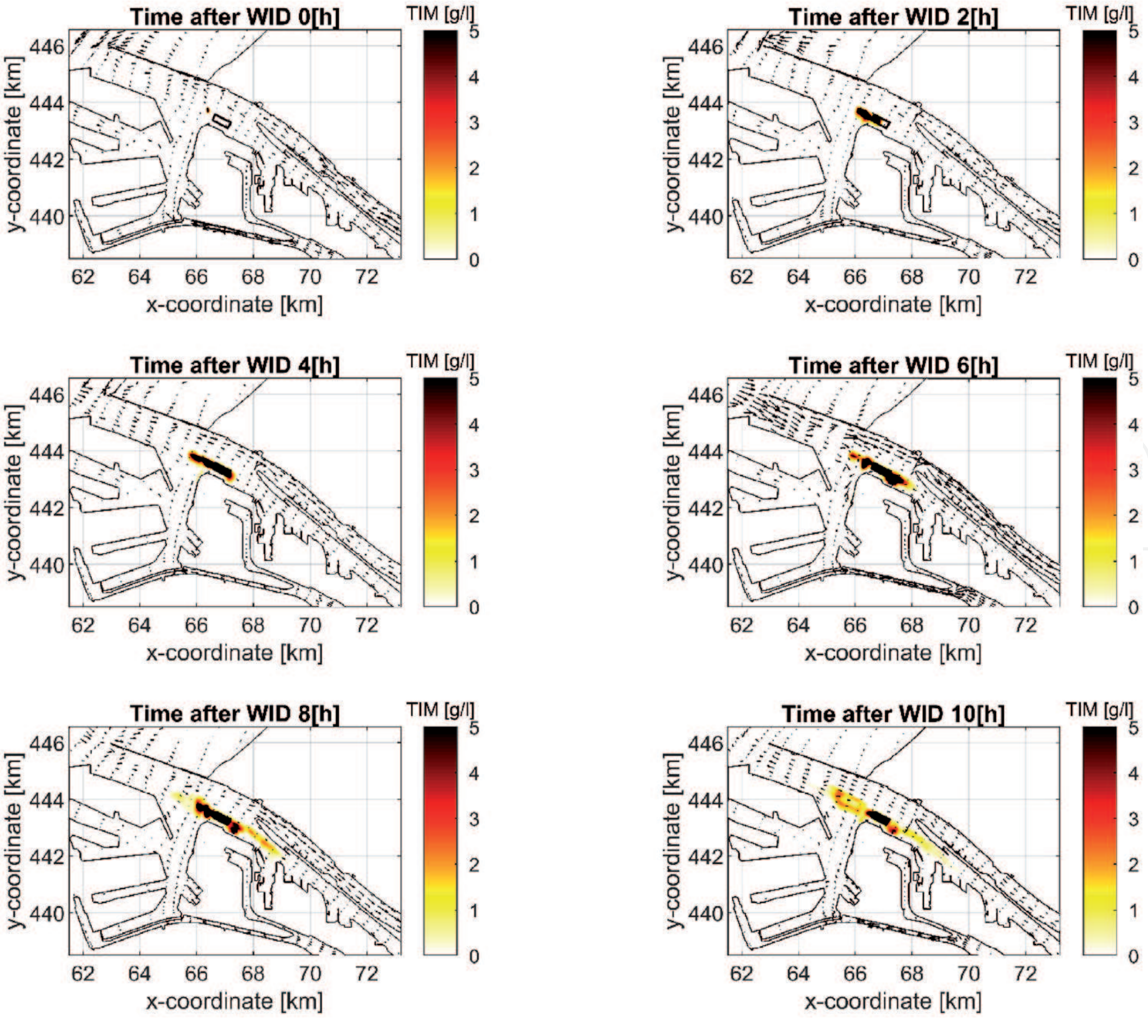

Figure 12.
Horizontal near bed plume spreading, WID starts 1 h before LW with a production rate of 500 kg/s.

The plume disperses in a distinct way between the simulation starting before high water (HW) compared to a start at low water (LW). **Figure 11** shows that the plume is predominantly dispersed in the seaward direction with the outgoing tide. For WID, this would be the most preferable conditions because in this way the suspended sediment will be relocated from the area where WID is conducted offshore. However, after approximately six hours the flow is reversed, and the plume is pushed in the landward direction.

Figure 12 show the initial plume dispersion for the simulations in which sediment is released just before LW. The dispersion of the plume in the first 2 hours of the simulations is similar to the experiment with WID release just before HW. However, between four and eight hours a predominant landward plume dispersion is observed. After the flow reversal, it is observed that the plume starts to disperse in the seaward direction. A continuation of the landward spreading is observed in the channel because of the predominant landward flood directed current.

The far-field modeling illustrates the importance of the hydrodynamic conditions during WID. This knowledge can help to choose the most-efficient strategy for WID in ports and waterways with mud layers. The most efficient strategy is not only related to optimizing the sedimentation footprint, but also to minimizing vertical mixing and the contribution of WID to turbidity higher up in the water column. By choosing operational parameters wisely and executing WID operations only during favorable hydrodynamic conditions demands on sedimentation footprint and turbidity are more easily met.

4. WID and navigation through mud

In low-energy regions or in a tidal area of the port, WID-induced sediment can form a fluid mud layer that remains in the port area. The thickness of WID-induced fluid mud layer is often larger than the thickness of original mud layer resulting in a reduced draft for the incoming vessels. In this case, WID is often combined with the nautical bottom approach defined by PIANC for navigation. According to PIANC, 'The nautical bottom is the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability' [10, 29]. The nautical bottom allows to use the fluid mud in estimates of under keel clearance (UKC) that the vessels can navigate in the port areas with no unacceptable effects on controllability and maneuvering of the vessels. If accepted by the port authorities, the nautical bottom approach is used for navigation through mud in ports and waterways with fluid mud layers.

Generally, the density of the top sediment layer is used for defining the nautical bottom (see **Figure 13**). The level, where the density of sediment is lower than 1.2 t/m^3, is widely accepted for navigation in ports. Ports in Rotterdam, Zeebrugge, Bordeaux, Saint-Nazaire, Bristol, Bangkok, Tianjin have successfully adapted the density criterium for navigation [29, 30]. However, the Port of Emden relies on the rheological properties rather than density of the sediment for defining the nautical bottom. The yield stress of the top sediment layer gives an indication if the sediment is navigable or not. The sediment with yield stress lower than 100 Pa is considered navigable. The choice of the nautical bottom criterium is related to the conditioning of sediment, that the Port of Emden has been conducting for port maintenance.

The knowledge on in-situ density or rheological properties of the top sediment layer are necessary for implementing the nautical bottom approach. There are in-situ tools that can provide an information about vertical profiles of density and strength in water-mud column. The in-situ devices Rheotune, Graviprobe and DensX have been intensively tested for the nautical bottom approach over last years [3, 29, 31].

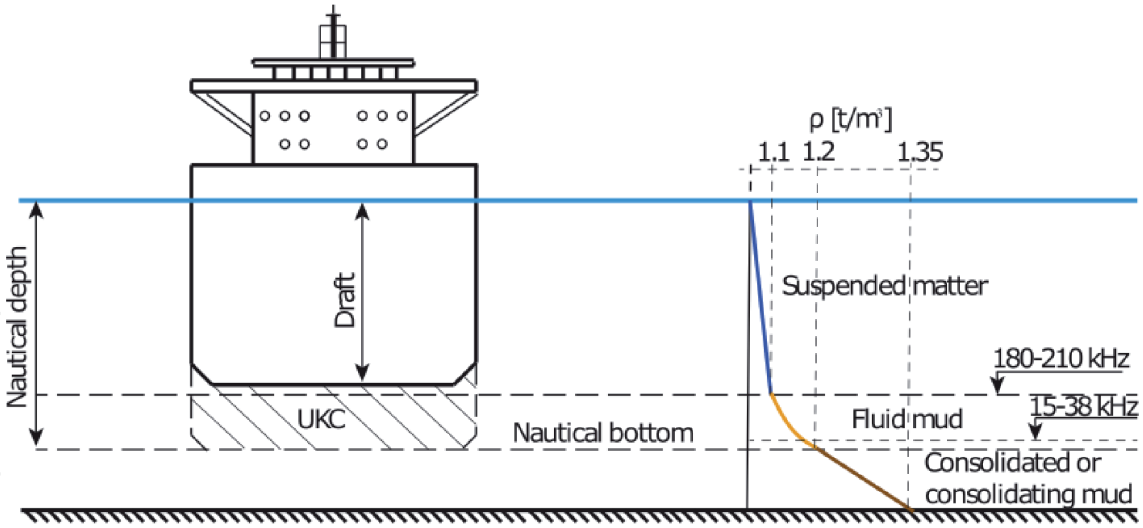

Figure 13.
Illustration of the nautical bottom concept with the density of 1.2 t/m³.

An example of in-situ measurement of density and yield stress provided by Rheotune is shown in **Figure 14**. The measurements are conducted in a sediment trap that was filled with WID-induced fluid mud during day 1. The development of density and yield stress of WID-induced sediment has been observed for the period of 3 months. The in-situ devices can naturally provide only 1D vertical profiles. However, the thickness of mud layer can be defined from the profiles if the critical value for physical parameters is defined.

In the example given in **Figure 15**, the critical value for the density is chosen as 1.2 t/m^3 providing the density-based nautical bottom shown in red line. In this case, the SILAS software is used for matching the density given by Rheotune (shown by vertical blue line in **Figure 15**) to the seismic data of 38 kHz. The measurements are conducted 7, 21 and 42 days after WID.

The development of WID-induced mud layer be also estimated with the numerical code solving the Gibson Eq. [33]. For instance, settling and consolidation of fluid mud can be predicted by matching the measured data to the model output. **Figure 16** shows the comparison of 1DV model and measured data during consolidation of WID-induced fluid mud layer. The model's output is the density of mud and the water mud interface as a function of time, that can be correlated to measured densities and multibeam data, respectively. The latter can typically provide a reliable water-mud interface for WID operations. For instance, **Figure 17** shows the development of water-mud interface before, during and after WID in the Calandkanaal.

Vertical density profiles are shown in the right panel of **Figure 16**. The density measurements can be done by different penetrometers [3, 31, 32], in this case the densities are measured by DensX. It can be observed that the measured density profiles show a good resemblance with the results of numerical modeling [31, 32]. Thus, the combination of the model with the in-situ measurements can potentially be used for predicting the development of the nautical bottom in time.

An example of the application of PIANC's nautical bottom approach after WID in the Port of Rotterdam is shown in **Figure 18**. The standard multibeam echosounder survey indicated the bathymetry that corresponds to the water-mud level. However, the WID-induced fluid mud has relatively low densities (<1200 kg/m^3) and weak strength (<100 Pa). Therefore, the nautical bottom approach can be applied. Adapting either a density-based (1200 kg/m^3) or yield stress-based (100 Pa) criterium for the nautical bottom results in an additional 1.5 and 2 m of navigable depth, respectively.

20 days after WID, these differences are reduced. However, the yield stress-based nautical bottom still shows an advantage of about 0.5 m of extra navigable depth.

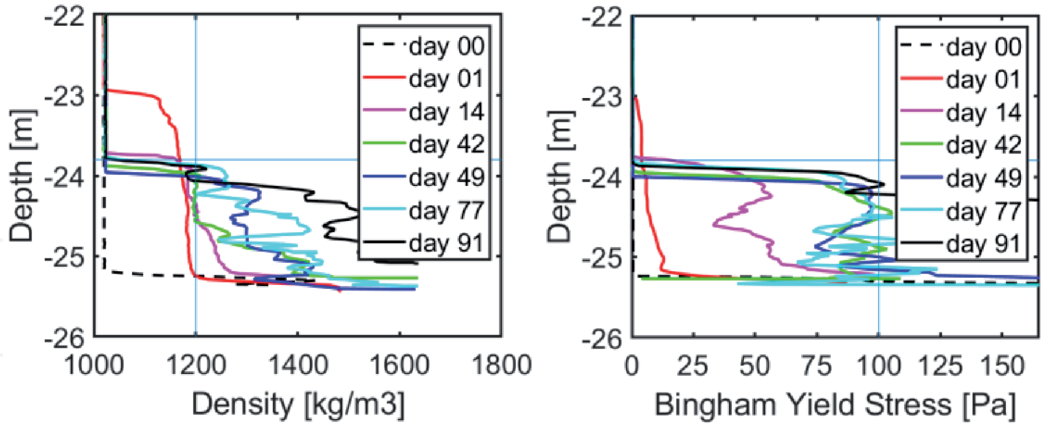

Figure 14.
Density and yield stress profiles measured by Rheotune.

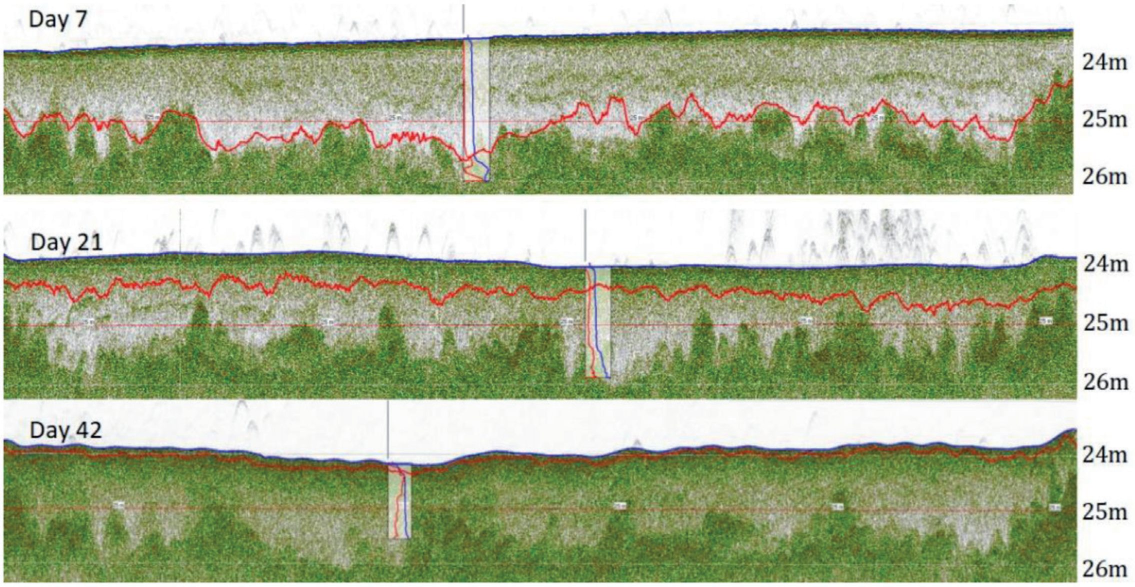

Figure 15.
Development of the density-based nautical bottom after WID. Red line shows the level, where the density of sediment is equal to 1.2 t/m^3.

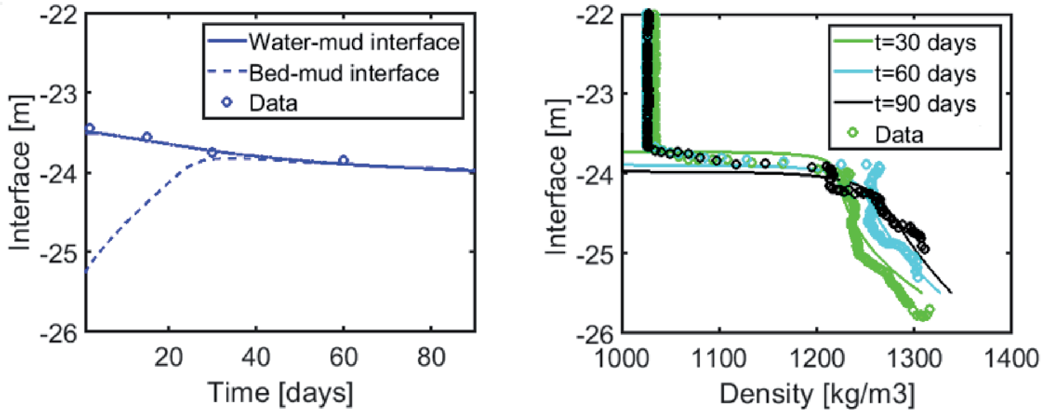

Figure 16.
Estimating consolidation of fluidized mud layer after WID. Left panel shows development of water - fluidized mud interface as well as fluidized mud – Consolidated bed interface. Right panel show model predictions (solid lines) and in-situ measurements (symbols) of densities in water-mud vertical column.

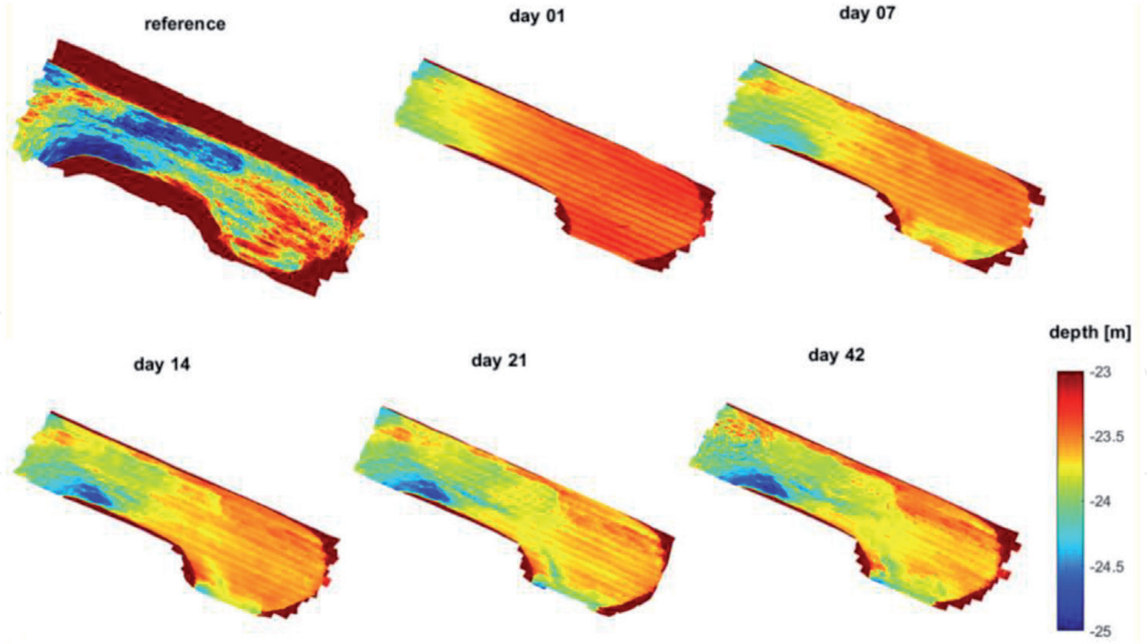

Figure 17.
Multibeam measurements indicating water-mud interface before WID (reference), during WID (day 1) and after WID (day 7 - day 42) in the Calandkanaal.

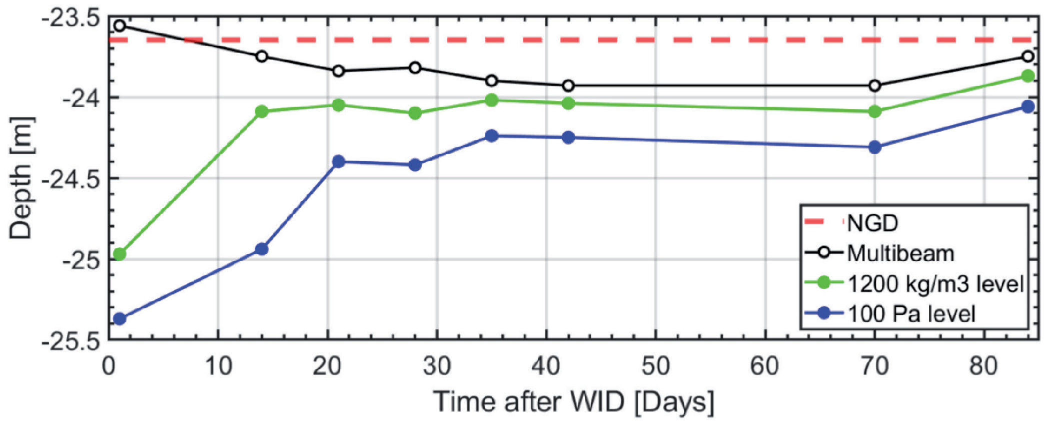

Figure 18.
An example of applying the nautical bottom approach after WID [3]. The density-based (1200 kg/m^3) or yield stress-based (100 Pa) criteria brings additional 2 m for nautical depth comparing to the standard multibeam-based navigational criterium.

5. Discussion

Water injection dredging is a widely applicable dredging method. The efficiency of the method for maintaining ports and waterways is generally high. WID operational parameters, knowledge of sediment properties, boundary and hydrodynamic conditions of the maintained area can greatly increase the efficacy of the water injection process. The most important parameters and factors influencing the performance of WID are the following: WID operational parameters (diameter of nozzles, flow velocity from the nozzle, stand-off distance of the jet, trailing speed of the WID vessel), sediment properties (grain size distribution, shear strength, density, oxygen consumption potential and sediment quality), boundary conditions of the maintained area (bathymetry, slope angle, embankments), hydrodynamics conditions (direction and velocity of tidal currents, existing density currents and salinity gradients).

Apart from the operational parameters, other factors and conditions that can increase the performance of WID are site-specific. Currently, the literature on research investigations into WID operational parameters is scarce. Therefore, there is a need for further systematic laboratory investigations for exploring the most-efficient WID operational parameters, which can further maximize the WID production rates in the field.

Sediment properties in the proposed area for WID can be studied before conducting WID. Typically, sediment samples are collected for laboratory analysis. The shear strength and density of sediment are linked to WID operational parameters (such as flow velocity) during the WID fluidization processes. The literature on investigations of sediment properties while testing varying WID operational parameters is very limited. Predominantly, WID is applied in the area with no-contaminated sediment. Therefore, the knowledge of the quality of sediment in the WID area is important.

The geometry of the WID area should be taken into account for planning and execution of WID operations in port and waterways. Bathymetric charts, which, will provide the information about deeper areas in the WID location, which are typically filled in with fluid mud after WID. Furthermore, bathymetric charts will indicate the slopes in the WID area, which can be also used for transporting the fluidized mud more efficiently.

Hydrodynamic conditions in the WID area should be taken into account when determining the final fate of fluid mud generated by WID, whether WID is used for the transport or conditioning of mud. For the transport of mud, the knowledge of the direction of the natural current and current velocities can help to minimize the spread of the WID-induced fluid mud deeper into the port area and maximize the transport of the sediment from the port area. For the conditioning of mud, the hydrodynamic conditions can potentially provide an indication whether fluid mud starts to settle in the allocated area or is transported to other locations of the port. Salinity gradients and local density currents can influence the density currents by damping the velocity of WID-induced fluid mud, thus decreasing production rates in the WID-area.

6. Conclusions

This chapter focusses on presenting an overview of developed knowledge for WID. In particular, new insights gained using a combination of in-situ monitoring and numerical modeling. The research focusea on fluid mud behavior and transport, but also the resulting sediment plume. Both mechanisms are important and depend on the surrounding hydrodynamic conditions. Mid-field modeling was used to investigate the WID plume flow and deposition behavior up to 1 km away from the WID dredger. The WID-induced fluid mud layer thickness and WID production estimates were used as input in to the far-field model. The far-field model was used to determine where the WID-induced plume traveled under different tidal and discharge conditions, how much deposited back in the harbors and how much was flushed out to sea with the ebb tide. The model was also used to test different disposal locations to reduce return flow.

Key factors and parameters influencing the efficiency of WID have been identified from the available literature and discussed further. The modeling tools presented in the chapter can potentially help to analyze the sediment properties, boundary conditions and hydrodynamic conditions in the WID area and in the entire port area. However, more experimental research is needed for defining the most-efficient set of operational parameters. Particularly, the knowledge on linking WID operational parameters with sediment properties for maximizing production rates is very scarce.

By combining measurements from the field, laboratory experiments on fluid mud properties, with a state-of-the-art modeling approach, new insights were gained on the best approach for implementing WID as a maintenance dredging strategy. In addition due to more efficient maintenance, reduction of costs, CO_2 emissions and additional environmental impacts is achieved during the application of these techniques.

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Conflict of interest

The authors declare no conflict of interest.

Nomenclature

WID	water injection dredging
TSHD	trailing suction hopper dredger
RANS	Reynolds averaged Navier Stokes
SSC	suspended sediment concentration
LES	Large Eddy Simulation
MFE	Mass Flow Excavation
HW	high water
LW	low water
PIANC	World Association for Waterborne Transport Infrastructure
UKC	under keel clearance

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