On the Effects of Fine Sediments in Mud Disposal Basins

Towards a better understanding of basin design by means of a numerical modeling study

Nils van der Ent

ON THE EFFECTS OF FINE SEDIMENTS IN MUD DISPOSAL BASINS

TOWARDS A BETTER UNDERSTANDING OF BASIN DESIGN BY MEANS OF A NUMERICAL MODELING STUDY

Master's Thesis

by

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PREFACE

This thesis is a result of my graduation project which concludes the Master of Science program Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences at Delft University of Technology. This study was initiated by Royal Boskalis Westminster N.V.

I would like to express my gratitude towards my graduation committee. Mark Klein as my daily supervisor at Boskalis, Bram van Prooijen as the committee chair, Jill Hanssen, and Alex Kirichek. All have provided me with feedback and ideas which were imperative to this research. I would also like to thank my colleagues from various departments for the help with my model, enjoyable walks and coffee moments. Finally, I would like to thank my family, friends and especially Rosa for their interest and support along the way.

Delft, 16 September 2022

Nils van der Ent

ABSTRACT

Nowadays, the process of dredging has become extremely important in society. It keeps ports accessible, offers opportunities for new infrastructure connections and even gives the opportunity to create new land. During the dredging process, sediment comes into suspension. Also when the sediments are deposited at the deposit location, there is increased turbidity. Increased turbidity can cause damage to the surrounding environment. Light is blocked in the water column, causing primary producers in the food chain to suffer, which in turn affects the overall ecological structure. Among other things, corals can be buried under the sediment once it settles, negatively affecting entire coral reefs.

With the recent paradigm shift towards a more sustainable future, turbidity thresholds are imposed for most dredging projects. Dredging plumes must be managed, but also the effluent of disposal areas. To manage the effluent of disposal areas, the behavior of sediments in the disposal areas must be predictable. At Boskalis, sediment disposal sites are designed with help of a tool 'SetBas'. This tool provides the expected filling behavior of the basin and the associated sediment outflow concentration over time. However, the mathematical models behind SetBas appear to be oversimplified. This leads to the following research question which is answered in this thesis:

The aim of this study is to provide a better understanding on the potential improvements on the current design tool 'SetBas' used to evaluate settling/siltation basins at Boskalis.

A numerical modeling study is done to answer the question. In the numerical model, the turbulent quantity and the sediment outflow concentration is analysed for various processes and parameters. Moreover, a comparison is made between the numerical model and SetBas. The processes tested are density effects, wind effects and density effects. Parameter sensitivity is tested for discharge, settling velocity, wind velocity, wind direction, and sediment influx.

From the analysis for the turbulence quantity it follows that wind shear stress and wind waves are both very important parameters for basin design. The turbulent quantity appears to have by far the greatest sensitivity to wind speed.

The analysis for sediment outflow concentration shows that the processes of density effects and wind effects dominate a basin. The sensitivity analysis shows that sediment fall speed, wind speed, and sediment influx cause the greatest sensitivity to the outflow concentration.

The comparison with SetBas shows large differences in sediment outflow concentration. Due to the difference in mathematical models used in both, there is no clear conclusion to be drawn from the differences, and which of the models performs better. However, the conclusions made about dominant sediment transporting processes in the numerical model for basin design seem largely in agreement with the literature. This shows that there is room for improvement for SetBas. The most important conclusion from this thesis is that SetBas must be redesigned to be multidimensional so that density effects and wind effects can be added.

CONTENTS

LIST OF SYMBOLS

Symbol	Definition	SI Unit
Latin symbols		
c	Sediment concentration	$[kg/m^3]$
c_a	Reference concentration	$[kg/m^3]$
$c_{\text{in floc}}$	Flocculating inflow concentration	$[kg/m^3]$
$c_{\text{in nonfloc}}$	Non flocculating inflow concentration	$[kg/m^3]$
c_{out}	Outflow concentration	$[kg/m^3]$
$c_{\text{out floc}}$	Flocculating outflow concentration	$[kg/m^3]$
$c_{\text{out nonfloc}}$	Non flocculating outflow concentration	$[kg/m^3]$
d	Sediment diameter	$[m]$
h	Water depth	$[m]$
h_{end}	Final water depth	$[m]$
p	Probability of deposition	$[-]$
t	Time	$[s]$
t_{50}	Time needed for a 50% concentration decrease	$[s]$
t_r	Retention time	$[s]$
t_s	Setting time	$[s]$
u_*	Shear velocity	$[m/s]$
v	Wind velocity	$[m/s]$
w	Settling velocity	$[m/s]$
z	Distance from the bed	$[m]$
C	Chézy coefficient	$[m^{\frac{1}{2}}/s]$
CFL	Courant number	$[-]$
H	Water depth	$[m]$
I	Theoretical water slope	$[-]$
M	Grid cell number in y direction	$[-]$
M_k	Mass of sediment	$[kg]$
M_w	Mass of water	$[kg]$
N	Grid cell number in x direction	$[-]$
MORFAC	Morphological scale factor	$[-]$
Q	Discharge	$[m^3/s]$
Ri	Richardson number	$[-]$
Ri_{cr}	Critical Richardson number	$[-]$
Tr	Trapping efficiency	$[\%]$
V_k	Volume of sediment	$[m^3]$
V_w	Volume of water	$[m^3]$
Greek symbols		
β	Prandtl Schmidt number	$[-]$
ϵ_f	Fluid mixing coefficient	$[m^2/s]$

$\epsilon_{s,i}$	Sediment mixing coefficient	$[m^2/s]$
κ	Von Karman constant	$[-]$
ρ_k	Sediment density	$[kg/m^3]$
ρ_w	Water density	$[kg/m^3]$
τ_b	Bed shear stress	$[N/m^2]$
$\tau_{b,cr}$	Critical bed shear stress	$[N/m^2]$
τ_w	Wind shear stress	$[N/m^2]$

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

Dredging projects in essence is the removal of sediments in one location and disposing of the sediment in another location. The goal may either be the removal of sediments (e.g. dredging harbor silt) or the disposal of sediment (e.g. land reclamation). Dredging unavoidably comes with nuisance to the surroundings, in the form of noise, but also through turbidity.

Turbidity is the result of sediment rich water being released into the ambient waters of the environment. The impact of fine sediments on ecological life is significant (Erftemeijer et al., 2012). Turbidity has a negative impact on the environment, as it blocks light out of the water column, impacting the primary producers in the food chain, such as phyto plankton and other vegetation,(Armengol et al., 2019). This has a repercussion on the entire food chain, eventually impacting local fishing communities, as fish populations reduce. Furthermore, corals are especially vulnerable to turbidity, as they get buried under a small layer of sediment and in a later stage die because of this. In the end, turbidity decreases ecosystem resilience and stability (Bejarano and Appeldoorn, 2013).

With the recent paradigm shift towards a more sustainable future, turbidity thresholds are imposed for most dredging projects. Dredging plumes must be managed, but also the effluent of disposal areas. To manage the effluent of disposal areas, the behavior of sediments in the disposal areas must be predictable.

To design a sediment disposal areas, Boskalis now uses the Setbas tool (Monge, 2018). This tool calculates the outflow concentration (of sediments) of a settling basin given an inflow concentration. The model is a 1D flow model, which limits its applicability and accuracy. Furthermore, only limited sediment transport processes are considered. Because of this, there is a demand for a better design tool. This means improving on the physical correctness of the current tool and defining the key processes which influence design of a settling basin.

1.1. DISPOSAL BASINS

This section gives insight into the types of basins and gives a conceptual description of the processes in a basin. Disposal basins can have different applications, see Figure 1.1. These are explained below. For the **land reclamation**, a range on sediment sizes is input into the basins. Often, a maximum percentage of fines which can stay behind in the basin is given by the client due to soil quality purposes. The rest of the fine sediment proceeds as outflow. For a **mud disposal** the goal is to store as much fines as possible. The only inflow into this basin is fine material, in high concentrations. As a result, outflow concentrations are relatively high as well. The final case, the **Land reclamation with disposal area** is a two component system. First, the land reclamation is filled with influx of fines and sand. The outflow of the land reclamation flows into a disposal area. This basin has the goal to retain as much fines as possible. The influx into this basin is significantly lower than the fines disposal, even though sediment type is the same.

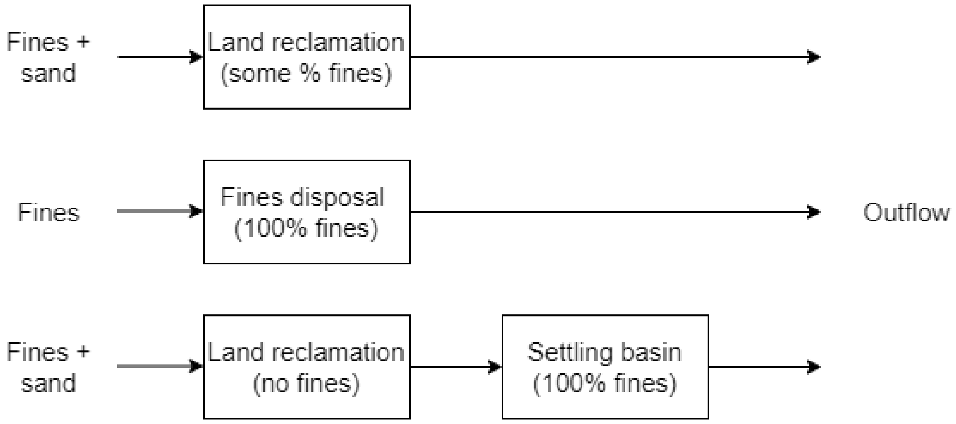


Figure 1.1: Three types of disposal basin applications

Generally, the goal of a disposal area is to capture sediment from the sediment rich influent, so that the outflow water contains as little fines as possible. In the dredging industry, the consequence of this is that these basins become quite large ($\mathcal{O}$ km^2), as volumes to be dredged are usually quite large as well. Figure 1.2 shows an example of a disposal area.

Figure 1.2: A mud disposal basin at the project location of the Fehmarnbelt, Denmark

In a disposal area, the entire perimeter is closed. The only (significant) fluxes into or out of the basin are the inflow and the outflow. The inflow usually is a pipe, through which a slurry mixture is fed at several meters per second into the basin. An example of an inflow can be seen in Figure 1.3. The outflow of a disposal area is normally in the form of a weir box. In essence, this is an overflow. The benefit of an overflow in a disposal area is that near the water surface the sediment concentration is lowest, and thus, the sediment outflow concentration is lowest from this point (van Rijn, 1984). An example of a weir box can be seen in Figure 1.4.

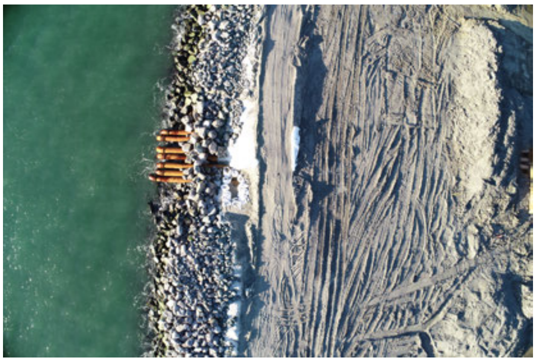


Figure 1.3: Example of an inflow at the Fehmarnbelt project, Denmark

Figure 1.4: Example of an outflow at the Fehmarnbelt project, Denmark

The principle on which as disposal area works is retaining water long enough so that the fine sediment particles can settle out of suspension. This is achieved by having a long time between the inflow and outflow. This is why inflow and outflow are always on opposing sides in disposal areas. Depending on particle settling velocity and flow velocity in the basin, a particle path is described in which either the particle settles or does not before reaching the other side. Figure 1.5 shows a schematic disposal area, where potential particle paths are depicted. As larger particles have a greater settling velocity, this creates a distribution of particle sizes over the basin, as larger particles will settle closer to the inflow. The effect of turbulence can result in an upward sediment velocity as shown in the same figure.

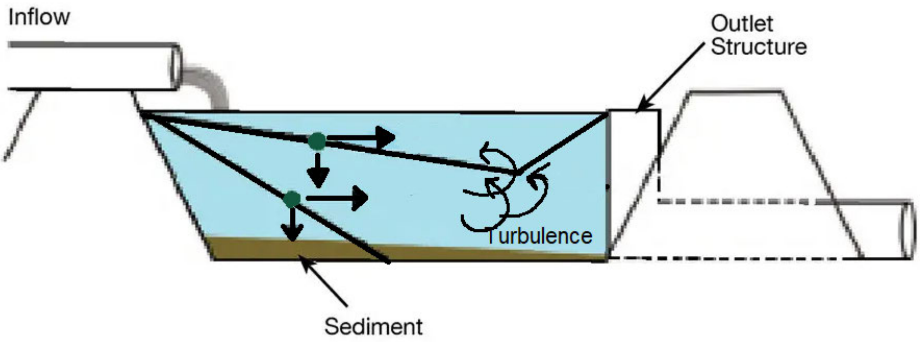


Figure 1.5: Potential particle paths of sediment particles in a schematic disposal area. Without turbulence, the particle path looks like that on the left of the basin. When turbulence is introduced, mixing occurs, and particle paths can head up.

For relatively small basins, these basic processes dominate disposal areas. In other industries (e.g. aquaculture, mining and hydro power), disposal areas have been designed based solely on these two sediment transport parameters for decades (Raju et al., 1999) where outflow concentration is a function of settling velocity and turbulence. Recent literature however, suggests that especially for larger basins (basins designed for the dredging industry) other processes dominate the sediment outflow concentration. De Lange et al. (2011) suggests wind plays a crucial role in sediment outflow concentration. Veenman (2020) confirms this and adds that density currents significantly affect sediment outflow concentrations and sediment behavior in the basin.

1.2. RESEARCH GOALS

The aim of this study is to provide a better understanding on the potential improvements on the current design tool 'SetBas' used to evaluate settling/siltation basins at Boskalis.

Objectives are set to measurably work towards the aim.

1. *Review* the SetBas tool
2. *Identify* processes and parameters which potentially effect basin flow fields and sediment transport
3. *Set up* a model which can model the processes and parameters which are found from research question 2.
4. *Quantify* the dominating processes and parameters for the turbulent quantity of a basin
5. *Quantify* the dominating processes and parameters for sediment outflow concentration of a basin
6. *Compare* the SetBas tool and the model and show the practical implication the conclusions of research goals 4 and 5.

1.3. SCOPE

To understand how to improve SetBas, an understanding of how the tool works is needed. This is done in Chapter 2. Reports on SetBas are reviewed, and the tool is compared to current literature on disposal areas. Next to that, processes which affect sediment outflow concentration of disposal areas are identified in the same chapter. This gives a basis for the modeling study.

To quantify the processes that influence sediment outflow concentration, a model is set up on a basin case from the industry. This case is the [redacted] basin study. Comparing this basin to other basins in the industry (Table 1.1), it stands out that this basin is average in its dimensions to make applicability as large as possible. The goal is to find dominating factors for the turbulence quantity in a disposal area and quantify the processes which effect sediment outflow concentration. The set up of the model and analytical verification of this model is done in Chapter 3.

Referring to Figure 1.1, the SetBas tool works with all cases. For the modeling study, the second application is chosen, the fines disposal. The reason for this is that fines are the critical components of such basins, and computation costs. Introducing a high inflow concentration gives a lower total simulation time before the basin is full.

Basin	**Volume** $[m^3]$	**Area** $[m^2]$	**Length** $[m]$	**Depth** $[m]$
Limerick	160 000	80 000	693	2
Debicks	1 027 000	422 800	780	2.40
[redacted]	1 535 783	875 242	2106	1.75
[redacted]	11 960 000	2 990 000	7480	4
[redacted]	62 128 000	7 060 000	2657	8.8

Table 1.1: Dimensional overview of designed disposal areas in the industry

With the model set up in Chapter 3, the turbulent quantity is determined for the basin case chosen for several processes and parameters. The parameters which are be tested for basin hydrodynamics are inflow, varying wind effects. This is done by analyzing the turbulent profile over depth in the middle of the basin and comparing scenarios. This is done in Chapter 4.

To quantify the effects of processes and parameters on sediment outflow concentration, the model is used once more in Chapter 5. Here, the sediment outflow concentration over time is compared for runs with varying parameters. In this way, the net effect of a parameter or process is quantified. These results should give insight in which parameters to include in a SetBas improvement step.

With the conclusions on parameters and their effect on sediment outflow concentrations the same model is used to compare various scenarios with the SetBas tool. This is done in Chapter 6. This is a basic scenario, one where the model resembles the SetBas processes, a storm event, a case where there are bunts in the basin, and a case with multiple sediment fractions. This gives insight into the differences between the model and SetBas. Furthermore, the practical implication of the insights are shown in a simulation where real world situations are simulated.

2

THEORETICAL FRAMEWORK

This chapter addresses the first and second research goal: *Review the SetBas tool* and *Identify processes and parameters which potentially effect settling basin flow fields and sediment transport*, respectively.

2.1. A REVIEW OF SETBAS

SetBas is a Boskalis design tool for settling basins, land reclamation areas and mud disposal areas. The tool outputs the sedimentation levels and sediment outflow concentration of a basin over time (Monge, 2018). To determine the outflow concentration of the basin, a mass balance is used. SetBas has two versions. With these two versions, each disposal basin type (see Figure 1.1) can be designed. There is a so called *'1 component version'* and a *'2 component version'*. The 1 component version can design a land reclamation and a fines disposal (the first two basin applications of Figure 1.1. The 2 component version can design a land reclamation with a settling basin behind it. It must be noted that SetBas has been validated for a settling basin case only, where inflow concentrations are low. A fines disposal, although theoretically possible to design, has not been validated in SetBas. The theory for the model makes a distinction between the two versions as well. Both are described in this section. The difference between both versions is the fill area before the settling basin. To visualize this, a flow chart for both versions is shown in Figure 2.1 and Figure 2.2. The parameters in these figures are given in Table 2.1.

As the one component version only considers a settling basin and not a fill in front of it, the value for M_k and V_w is assumed to be equal for the input and the output of the fill area. By doing this, in essence, the fill area is skipped.

For the two component version, the fill area is considered. In this case, it is assumed that all coarse fractions are trapped in the fill area. Furthermore, the user defined 'p_{fines}' parameter defines the percentage of fines which stays behind in the fill area. The rest of the sediments proceed to the settling basin, in the form of M_k and V_w. The computations in the settling basin are the same for both versions of the design tool.

To determine an outflow concentration and how much sediment is trapped in the settling basin, a turbulence model and a flocculation model are used. Figure 2.3 shows a flow chart for the settling basin. To determine the distribution of sediments between both models, the user must define the 'p_{floc}' parameter. This gives the percentage of fines which are used in the flocculation model. The coarse sediment fractions and the rest of the fine sediment fractions go to the turbulence model. Sediments which are subject to flocculation do not take place in the turbulence model and vice versa.

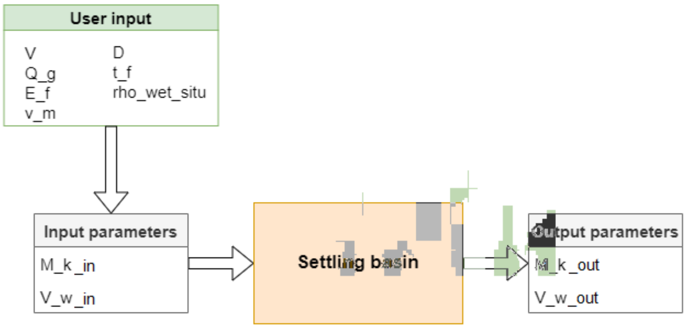


Figure 2.1: Parameter flow chart describing the single component version of SetBas

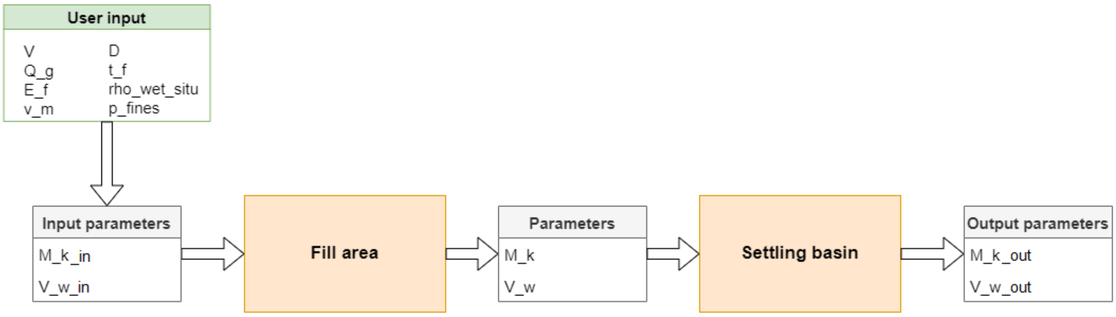


Figure 2.2: Parameter flow chart describing the duo component version of SetBas

Parameter	**Unit**	**Symbol**
Mass of sediment	kg	M_k
Volume of water	m^3	V_w
Volume to be dredged	in-situ m^3	V
Production	in-situ m^3/h	Q_d
Production efficiency	%	E_f
Velocity of mixture in pipeline	m/s	v_m
Diameter of transport pipeline	m	D
Transport factor	-	t_f
Wet density of in-situ matrial	kg/m^3	$\rho_{\text{wet situ}}$
Percentage of fines in the dredged material	%	p_{fines}

Table 2.1: Dredger parameters used to determine the inflow concentration and volume of SetBas

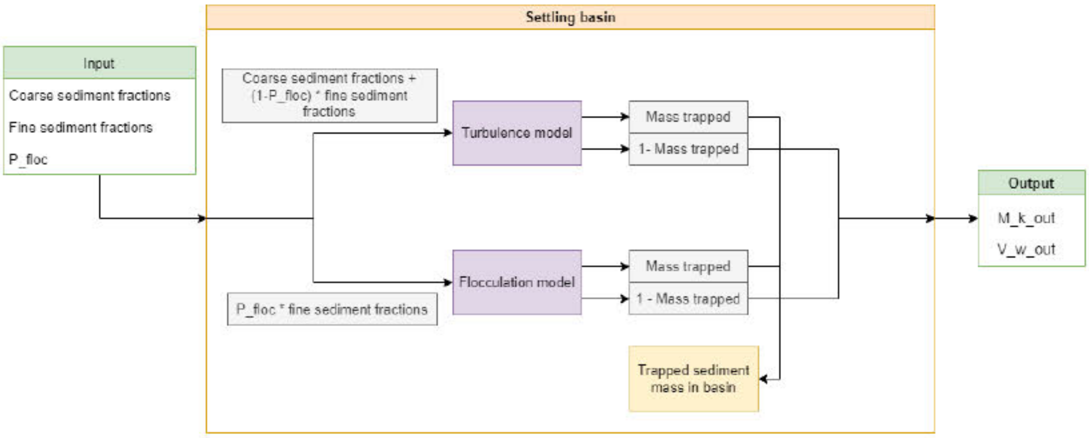


Figure 2.3: Parameter flow chart showing the two mathematical models, the turbulence model and flocculation model, for the SetBas design tool

2.1.1. TURBULENCE MODEL

[redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

2.1.2. Flocculation model

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted]

[redacted]

2.1.3. DISCUSSION

This discussion aims to discuss the design choices of SetBas. In this, points of improvement are given as a basis for this study.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

2.2. DISPOSAL AREA STUDIES

SetBas utilizes flocculation, settling and turbulence processes to determine sediment outflow concentration. De Lange et al. (2011) and Veenman (2020) both studied disposal areas considering different parameters. Both found these can affect sediment outflow concentrations.

De Lange et al. (2011) performed a probabilistic analysis on a disposal area. For this case, a 1D flow model and a 2DV sediment transport model is considered. Parameters considered are turbulent mixing, flocculation, hindered settling and secondary flow. The output of the model was the outflow concentration. Conclusions are that discharge and inflow concentration strongly affected outflow concentration. Wind velocity and direction can also impact outflow concentration, especially when the direction is opposite to flow direction. Flocculation proved to be of influence on the outflow concentration, as this effectively increases the settling velocity. Increasing the effective settling velocity has the same effect as increasing sediment size.

Veenman (2020) does a comparative study with a 2DV tool and a Delft3D modeling study. A goal of this study is to find the factors dominating sediment outflow concentrations in disposal areas. On a relatively small basin of 200 [m] x 100 [m] it is found that density driven currents are the main process influencing sediment transport within the disposal area. Next, it was found when combining wind and density effects effects influence one another. For wind speeds higher than 10 m/s, turbulence caused by wind overcomes stratification and becomes dominant. Finally, it is concluded that the RWQ 2DV flow model shows significantly different results compared to the 3D flow model. It is suggested that a 3D model is needed to correctly solve flow patterns for outflow concentrations in a disposal area. This however requires more input which is not always available during a tender phase.

disposal areas used in other industries (e.g. hydro power, agriculture or aquaculture) have been around for decades. A lot of literature exists on the design of these basins. Raju et al. (1999) analyses many methods used for disposal area design. The flows and dimensions in these cases however is very small compared to disposal areas used in the dredging industry ($\mathcal{O}(10-100)$). Because of this, the effect of turbulence is enhanced, and other effects become less important. The methods thus used for years in these basins designs therefore is justified.

For example, Chemeda and Dinka (2020) analyses an agricultural basin. This is a basin where retention times are 5 hours and its volume is 450 m^3. Such a small scale makes turbulence and settling velocities much more significant. Winterwerp et al. (2002) shows that the process of flocculation can take days to reach steady state. In the same study it is shown that flocculation is a function of salinity. For agricultural purposes, water is fresh, and with a small retention time, flocculation becomes negligible. Wind effects over a small basin also become negligible when comparing to the turbulence of the flow. As the scales of dredging projects are much larger, the processes which De Lange et al. (2011) and Veenman (2020) describe and research become important.

2.3. CONCLUSION

[redacted]

[redacted]

In the dredging industry, disposal areas are something which have not extensively been studied yet. There are only a few numerical models on disposal areas. Most are 1D or 2DV models. A majority of the models do not consider all processes which can affect sediment outflow concentrations. For models of lower dimensionality not all physical processes are considered. This is a simplification of the reality. The result is a model of which it is unsure whether it represents the reality. The drawback of a model considering more dimensions is the increasing number of parameters and information required for the setup, something which is not always present in a tender phase.

Overall, it is unknown which processes are most critical regarding sediment outflow concentrations. This may be due to the different parameters under which these processes are considered. Wind effects tend to be seen as potentially significant depending on velocity and direction. In all studies however, only wind shear is considered. This excludes the formation of wind waves. Wind waves result in greater turbulence and elevated bed shear stress. This effect may enhance the effect of wind on outflow concentrations. No study was found which considers the possibility of resuspension in these basins. This is something which wind waves may potentially overcome.

A large uncertainty lies within the flocculation process. The chemistry behind the concept is understood. The specific behavior of varying sediment compositions, of sediment and mud (which is almost always the case in the field) is not yet understood. Until now, in modeling, simple equations where effective settling velocity is a function of concentration are used.

Most processes interact with one another. Stratification caused by density effects tend to counteract wind effects. Turbulence effects floc formation. These dependencies complicate the quantification of individual effects of the processes.

For this research, the following processes are considered:

- Turbulence
- Density effects
- Discharge
- Wind shear stress
- Wind waves
- Resuspension

Next to that, the following parameters are considered

- Discharge
- Settling velocity
- Wind velocity
- Wind direction
- Sediment flux

3

MODEL SETUP AND VERIFICATION

This chapter aims to complete the third research goal: *'Set up a model which can model the processes and parameters which are found from research question 2'*.

3.1. MODEL SETUP

This section describes the model set up for the Delft3D model used in this study. The model will be set up as a mud disposal area. This means a high influx of fine sediments only.

3.1.1. DOMAIN

Basins in the industry can vary greatly in dimensions. To ensure a representative case is chosen as a case study, some projects are compared in their dimensions. Table 1.1 shows an overview of some basins from the industry, with their accompanying dimensions. The [redacted] basin is an average basin, and its dimensions are used in the modeling study.

The horizontal grid of the model consists of 125 × 25 [-] grid cells, which can be seen in Figure 3.1. Individual grid cells are square, with $dx = dy = 16.7m$. The coordinate system is Cartesian and the basin is located at the equator, to not account for Coriolis force (latitude and orientation is 0 deg). Next to the fact that Coriolis is quite small over short distances (Persson, 2005), Coriolis adds extra unnecessary complexity.

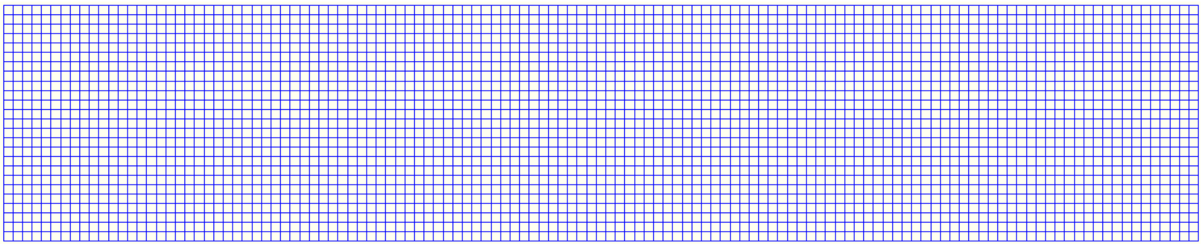


Figure 3.1: A top view of the horizontal grid used for Delft3D model

The σ model is used for the vertical grid. This is a dynamic grid type where a fixed number of layers move between the bottom and the water surface. The number of layers is 15. This is due to the accuracy restrictions for the horizontal logarithmic velocity profile. Both at the bottom and the surface, the initial layer may not be larger than 2% of the total water depth. Next, the layer thickness change may not be too large (Deltares, 2021). The layer thickness as a consequence of this restriction is given in Table 3.1. Finally, the depth is set to uniform, with a value of 1.75 m.

	Layer number	**Layer thickness as a fraction of the water depth**
Surface layer	1	2%
	2	3%
	3	4%
	4	6%
	5	8%
	6	10%
	7	11%
	8	12%
	9	11%
	10	10%
	11	8%
	12	6%
	13	4%
	14	3%
Bottom layer	15	2%

Table 3.1: Layer thickness as percentage of the total water depth for the Delft3D hydrodynamic and sedimentary model

3.1.2. TIME FRAME

The simulation time step is a critical value, as it determines the accuracy of the model, given by the Courant number.

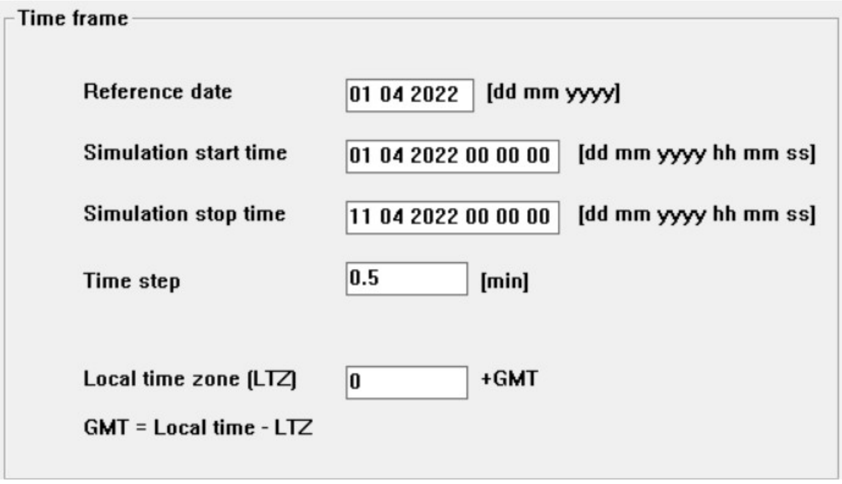
$$CFL = \frac{\Delta t \sqrt{gH}}{\{\Delta x, \Delta y\}} \tag{3.1}$$

in which:

Δ t : time step $[s]$
g : gravitational acceleration $[m/s^2]$
H : total water depth $[m]$
$\{\Delta x, \Delta y\}$: minimal value of grid spacing in either direction $[m]$

As the Courant value should not exceed a value of 10 (Deltares, 2021), the time step for the simulation must be smaller than 40 s or 0.667 min. During a number of test rests it turned out to be better to use a time step of 0.5 min for accuracy. Ultimately, a time step of 0.5 min was chosen.

The duration of the simulation time is chosen differently per run. For the results of Chapter 4 this means a developed flow field, where spin-up effects are no longer visible. For all runs, this turned out to be 24 hours. For the results of Chapter 5, the simulation duration is chosen until the basin is physically filled with sediment. A first indication was obtained with a mass balance, where after fine tuning with testing gave a simulation time of 10 $days$ for the given setup. An overview of the time frame parameters can be found in Figure 3.2.



Time frame

Reference date 01 04 2022 [dd mm yyyy]

Simulation start time 01 04 2022 00 00 00 [dd mm yyyy hh mm ss]

Simulation stop time 11 04 2022 00 00 00 [dd mm yyyy hh mm ss]

Time step 0.5 [min]

Local time zone (LTZ) 0 +GMT

GMT = Local time - LTZ

Figure 3.2: Time frame values chosen for the sedimentary case in the Delft3D model

3.1.3. PROCESSES

The only constituent included is cohesive sediment. Temperature and salinity are assumed to be constant. The effects of these constituents on the fluid density is negligible compared to density effects caused by sediment. As this case study considers a fines disposal, only a cohesive sediment fraction is chosen.

In runs where wind shear stress is considered, the wind process is utilized. In runs where wind waves are considered as well, the wave and online Delft3D-WAVE processes are used. The bathymetry of the basin changes significantly over time as the basin fills. This effects the wave field in the basin as well. This is why it is important to update the wave field during the simulation, to minimize effects of a too large wave field. The interval at which this online coupling happens is discussed in the output section of this chapter.

3.1.4. INITIAL CONDITIONS

In practice, a mud disposal basin starts as a basin of clear water, or even an entirely empty basin. It is assumed that the sediments in the basin have had time to sink out of suspension before the filling starts. To simulate this, an initial water level of 0 m is chosen. Furthermore, the initial concentration of sediment in the basin is chosen at 0 kg/m^3 as well. The sensitivity of initial conditions is shown in Section 3.2.

3.1.5. BOUNDARIES

All mud disposal basins' outflows is regulated via a weir box. The inflow of the basin is treated in Subsection 3.1.8. In essence, the weir box is an overflow of the system at a certain water level. Normally, in the field, the basin is dammed up. The water level then becomes higher and higher by continuing to physically increase the overflow level with planks. This is done so that only the upper part of the basin discharges, where sediment concentrations are the smallest. For this study however, a constant water level over time is chosen.

Delft3D allows the option for 2D boundary conditions, meaning a water level boundary extracts water over the whole vertical profile. As this is not physically correct, a 3D gate is added close to the location of the boundary condition. In essence, a 3D gate imposes a zero velocity boundary in the grid, which can be given per vertical grid cell. By placing gates around the 2D boundary condition, a weir box is created, as only the top layers can now flow into the boundary. The 3D gate is placed at the lower 10 cells of the vertical grid. A top view of this can be seen in Figure 3.3. A perspective view (to scale) can be seen in Figure 3.4. This figure shows the spatial representation of the 3D gate in an empty basin.

The 3D gate can be given at certain layers. As the grid type is a σ-grid, the overflow depth is always given as a percentage of the total water depth. For most of the filling this is correct, as the bed layer stays constant near the over flow. However, in the final stages of filling, the bed level starts rising, and the overflow depth becomes smaller as a result. This is physically incorrect, and the effects are explored in Section 3.2.

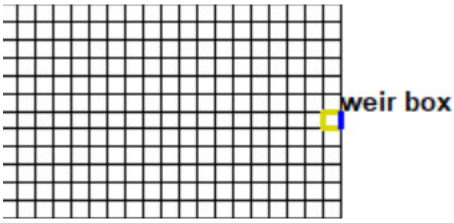


Figure 3.3: Top view visualization of the weir box setup in the Delft3D model. The location of the 3D gates are shown in yellow, the water level boundary condition is shown in blue.

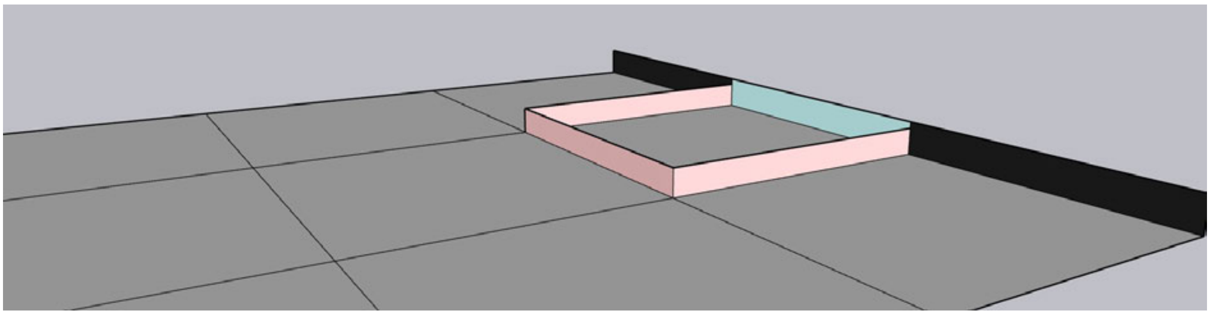


Figure 3.4: Perspective view visualization of the weir box setup in the Delft3D model. The 3D gates are shown in pink, the water level boundary condition is shown in blue, closed boundaries are shown in black. The grid cells can be seen as well.

3.1.6. PHYSICAL PARAMETERS

ROUGHNESS

For the bottom roughness the Chézy formula is used. The Chézy coefficient C $[m^{1/2}/s]$ is a measure for the roughness of the bed. As basins are constructed, it is assumed there are no plants or friction increasing objects. In combination with the fine sediments, a relatively smooth bed is assumed. Uniform values for C are chosen at 65 $m^{1/2}/s$. The wall roughness slip condition is chosen to be zero. The effects of this are shown in Section 3.2.

VISCOSITY

Delft3D has four turbulence closure models to determine the vertical eddy viscosity coefficient ν_V and the vertical eddy diffusivity coefficient D_V, both of which are correlated by the Prandtl-Schmidt number. These models are the following: a constant coefficient model, an algebraic eddy viscosity closure model, the $k-L$ closure model, and the $k-\epsilon$ turbulence closure model. Each model has a different description of the kinetic energy k, the energy dissipation rate of kinetic energy ϵ and the mixing length L. Of these four models, the $k-\epsilon$ model is chosen. The main benefit of the $k-\epsilon$ model over other models is that no damping functions are needed in case of stratification, as mixing length is a property of the flow. This turbulence model is widely used in hydraulic CFDs (Bradshaw, 1980), due to its superior accuracy compared to other models (van Rijn and Walstra, 2004).

The option for subgrid scale HLES is not chosen for the model. Not using HLES does not solve sub grid turbulence. This especially underestimates turbulence intensity at the discharge. The sub grid turbulence is not solved, which makes the near field effects inaccurate compared to the real world situation. However, turning the sub grid scale HLES option on gave so many stability issues it was chosen not to work with this option. The background eddy viscosity and diffusivity is a means of correcting for the lack of sub grid turbulence intensity. The option for locally increasing these background values has been tested. However, due to the filling of the basin, these values must change over time as well, something which is not possible. Therefore a background value for the eddy viscosity is chosen at 1 $[m^2/s]$ and the diffusivity at 10 $[m^2/s]$.

SEDIMENT

For most of the runs, a single sediment fraction is chosen. This is a cohesive sediment fraction with a specific density of 2650 kg/m^3. The dry bed density is chosen at 500 kg/m^3. Mud takes a long time to consolidate, and this value is the density after a long period of consolidation (van Rijn and Barth, 2018). However, this value is chosen so that the settled density is greater than the inflow density of the discharge. If this is not the case, numerical effects give inaccurate results. The settling velocity is a parameter which is tested for sensitivity. For the base case, a settling velocity of $0.25 mm/s$ is chosen. Using stokes velocity, this gives a grain diameter of 17 μm.

For the critical bed shear stress for erosion, a value of 0.5 N/m^2 is chosen. This is a value confirmed by Chen et al. (2021). The critical bed shear stress for sedimentation is 1000 N/m^2, meaning sedimentation can always take place. Finally, the erosion parameter used for the amount of erosion which takes place, varies widely depending on the sand-mud mixture. The value used in the model of 1e-5 $kg/m^2/s$ falls within the accepted range according to Perkey (2020).

MORPHOLOGY

In siltation basins, the bed changes over time, as the basin fills with sediment. Thus, for the morphology, the option to update the bathymetry during the FLOW simulation is chosen. During the runs, the effect of sediment on the fluid density is considered as well. The morphological scale factor is kept at 1 [-]. The consideration for this is that the bathymetry changes quite significantly compared to the flow field each time step, so that increasing that further leads to significant margins of error. Next, the computation time currently remains below the one hour mark, which is sufficient. The spin-up interval is chosen to be 0 [min]. When spin-up is considered, the concentration in the water builds up, however, sedimentation and erosion does not take place. This ensures a build up of a concentration higher than the bed concentration, which leads to inaccuracies in the simulation. The effects of spin-up possibilities is shown in Subsection 3.2.8. As the depth of the basin is relatively shallow compared to normal Delft3D simulations, the minimum depth for sediment calculations is set at the minimal value Delft3D accepts; 0.05 m.

WIND

In most cases, wind velocity and wind direction is assumed to be constant over the simulation time. The base case is 7.5 m/s from 270 deg (wind in the same direction as the flow direction). The flow simulation considers the wind shear stress only. The wind waves as a result of the wind are calculated by the coupled WAVE module. The setup of the wave module is found in Subsection 3.1.10.

3.1.7. NUMERICAL PARAMETERS

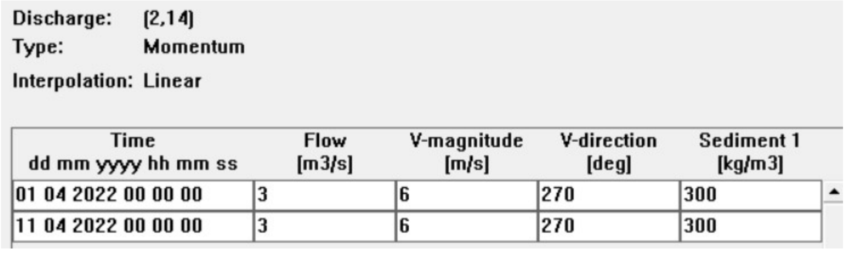
This section explores the numerical parameters used in the model. Drying and flooding checks are performed at both the cell centers and faces, to ensure this is always done correctly. It also does not need much extra calculation time. The determination of the depth at grid cell faces is set to 'Mor', the default value. This means that the depth at the cell face is the minimum value of the water level points around it.

The smoothing time is the time interval used at the start of a simulation for a smooth transition between initial and boundary conditions. By default it is set to 0 min. However, here it is set to 60 min. The effects of this are shown in Subsection 3.2.8. For the advection schemes for momentum and transport the Cyclic scheme is chosen. This scheme has high accuracy. However, in some cases the scheme can give negative concentrations. Because of this case, a Forester filter is applied, which adds numerical diffusion to solve this problem.

3.1.8. OPERATIONS

The inflow is modeled as a discharge. As mentioned in Subsection 3.1.6, the near field effects are not solved due to the sub grid turbulence not being solved. To partially solve this, the type 'momentum' is chosen. This adds the momentum of the discharge to the momentum balance. The discharge is located at the west side of the basin, opposing the overflow boundary condition. An overview of this is seen in Figure 3.5. The discharge pipe in practice flows out a small distance above the water. To simulate this, the discharge is released in the top layer. This is an area 2 % of the water depth by 16.6 m. When releasing 3 m^3/s into this area, a different momentum is created in the water column than theoretically happens with flow from a pipe where velocity is higher. Therefore the V-magnitude is given as well.

An overview of the parameters chosen is seen in Figure 3.5. Notice a constant discharge is assumed in time. The sediment concentration is chosen at 300 kg/m^3. [redacted] The V-magnitude is the velocity used to calculate the momentum of the discharge.



Discharge: (2,14)
Type: Momentum
Interpolation: Linear

Time dd mm yyyy hh mm ss	Flow [m3/s]	V-magnitude [m/s]	V-direction [deg]	Sediment 1 [kg/m3]
01 04 2022 00 00 00	3	6	270	300
11 04 2022 00 00 00	3	6	270	300

Figure 3.5: Values used for the discharge input in the Delft3D model

3.1.9. MONITORING

For monitoring, three observation points are created. The locations of these are in the West of the basin (150 m from the discharge location), in the middle, and in the East (150 m from the outflow) of the basin, see Figure 3.6. All points are located in the center line connecting the discharge and the outflow. In these points, parameters can be tracked with high accuracy over depth and over time. A cross section is placed over the outflow boundary condition. This gives the fluxes of water and sediment over the boundary condition.

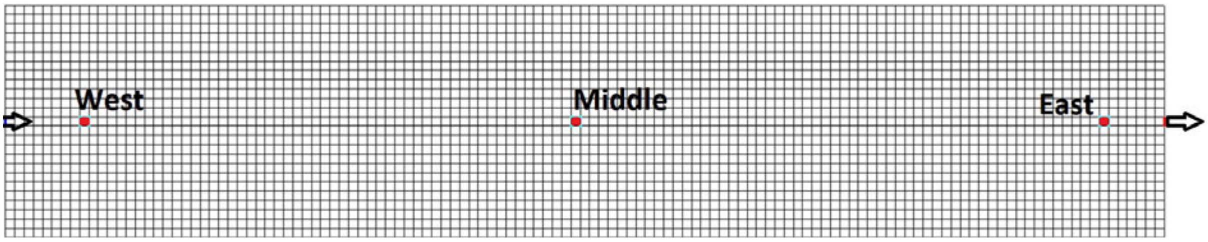


Figure 3.6: An overview of the Delft3D model horizontal grid, observation points and location of in- and outflow.

3.1.10. WAVE MODULE

To model waves, Delft3D-WAVE is used. The wave model behind this is the SWAN wave model as presented by Holthuijsen et al. (1999). In the case where current and waves exist together, both will affect one another (e.g. set-up, enhanced turbulence, enhanced bed shear stress) (Soulsby and Clarke, 2005). When modeling these interactions, three possible choices can be made.

1. A stand alone wave computation

In this computation, users can define the flow properties them self. This way the effect of flow on the waves is accounted for. Adding no flow field is also possible of course, by which a wave only computation is carried out.

2. An offline coupling of WAVE with FLOW

In this case, Delft3D uses the flow characteristics from a completed Delft3D-FLOW computation, to account for the effect of flow on the waves.

3. An online coupling of WAVE with FLOW

In an online coupling, the WAVE and FLOW module of Delft3D exchange information on a user defined interval. By this, the effect of flow on the waves is accounted for, but also the effect of the waves on the flow is considered.

Because of the significance of the wave flow interactions on morphology in shallow water (Soulsby and Clarke, 2005), the choice is made to model potential waves via the third method, the online wave coupling. Also, the rapid change in bed level which takes place in a siltation basin asks for a frequently updated wave field.

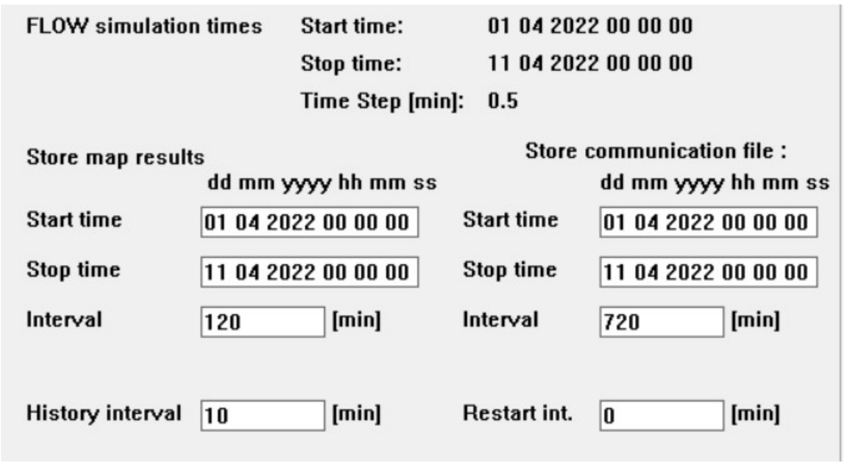
The setup of the WAVE module is not extensive, as it is run together with the flow simulation. The choices for relevant parameters are explained below. Locally generated wind waves are the only waves considered in this model, as a closed basin is modeled. The hydrodynamics, time frame, physical parameters and grids are given by Delft3D-FLOW. The frequency space is chosen from 0.1 to 4 Hz, as initially, the wind waves have quite a small wave period.

Numerically, default values are used in Delft3D WAVE. In the spectral space the stability of the directional space (CDD) and the frequency space (CSS) can be determined by choosing the numerical scheme. As gradients are somewhat strong in this case, a value of 0.5 is chosen for both. This is the default. With these values, no spurious fluctuations can be seen. A value of zero for both gives a central scheme, where accuracy is high but a chance of random fluctuations is high. On the other hand, when these values are one, an upwind scheme is used. This scheme has quite some diffusivity, and thereby is somewhat less accurate, but more stable. In case of strong gradients in current, the value of one is advised (Deltares, 2021).

The accuracy criteria for relative change in Tm01 and Hs are all chosen to be 0.02 [-] (the default). This relative change criteria must be met for 99.5 percent of all wet grid points. This is higher than the default value of 98%, as, from experience, this led to better accuracy.

3.1.11. OUTPUT

The values chosen for the output are shown in Figure 3.7. The storage interval of the communication file refers to the coupling of the WAVE module. This is set at 720 min. This means that every 720 min, the wave field is calculated according to the updated bathymetry. This is quite expensive in terms of calculation time. However, as the bathymetry changes so fast in the mud disposal basin, this is the minimum required for the calculations. For more elaborate calculations in Chapter 6, a wave coupling of 60 min is used. The effects of this wave coupling interval are shown in Subsection 3.2.9.



FLOW simulation times
Start time: 01 04 2022 00 00 00
Stop time: 11 04 2022 00 00 00
Time Step [min]: 0.5

Store map results
dd mm yyyy hh mm ss
Start time 01 04 2022 00 00 00
Stop time 11 04 2022 00 00 00
Interval 120 [min]

Store communication file :
dd mm yyyy hh mm ss
Start time 01 04 2022 00 00 00
Stop time 11 04 2022 00 00 00
Interval 720 [min]

History interval 10 [min]
Restart int. 0 [min]

Figure 3.7: Output values used in the Delft3D model

3.2. MODEL VERIFICATION

This section will verify the model functionality and tests the sensitivity of numerical parameters.

3.2.1. MASS BALANCE

To verify that the model does the mass balance correctly, the mass balance is shown below for the water in the model. It applies that the storage of water in the basin, combined with the outflow over time, must be equal to the inflow over time. For this verification, the run has a flow rate of 3 m^3/s. In Figure 3.8 you can see the influx as well as the sum of the storage and the outflux. The outflux is obtained by the flux over the water level boundary. The storage is determined by calculating the mean water level in the basin at each map file interval. From this the water volume in the basin is calculated.

It is noticeable that in the first twelve hours there is a small difference in the mass balance. After these twelve hours, both lines are exactly the same. This difference in the mass balance has two possible causes. First of all, spin up effects can play a role. The spin up period of the model is also twelve hours, so that would be correct over time. In addition, the history file data set and the map file data set were used for the mass balance. These are written at different time intervals (10 min and 120 min respectively). This can cause rounding errors due to the spin up effects that take place in the first twelve hours of the simulation. What is important is that the sum of the excess of mass (the first time step) and the deficit of mass (the successive time steps) is exactly zero. The mass is thus preserved over the total simulation duration.

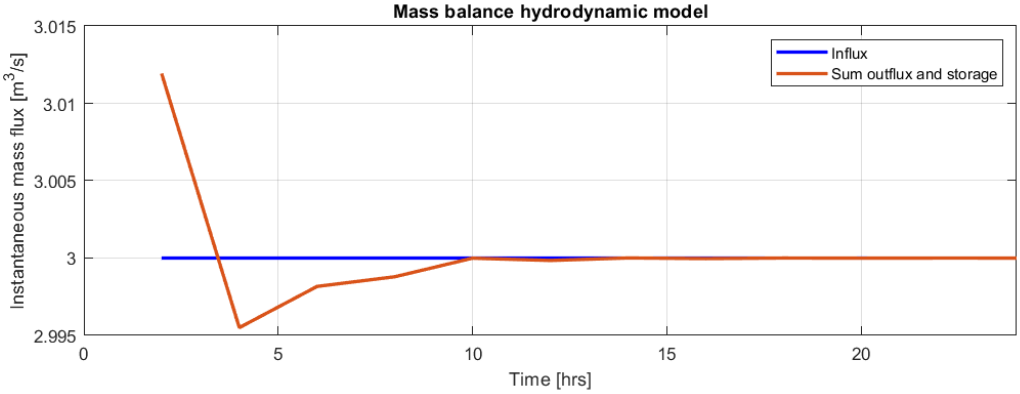


Figure 3.8: Hydrodynamic mass balance over time of the Delft3D model, considering a discharge of 3 m^3/s. The influx (constant) is shown in blue, and the sum of the storage and outflux is shown in orange.

3.2.2. WATER LEVEL

This section treats the water level in the basin. Figure 3.9 shows the water levels in the three stations over time in the first 24 hours. Initially, a spin-up period takes place in the model. After this period, the water levels become constant over time. What is striking is a difference in water levels per station. This is due to wind setup. The amount of wind set up can be verified with the literature. Myrbo et al. (2012) give a theoretical water slope I [-] as a function of wind shear, water density and water depth. This equation is seen in Equation 3.2. In the study, the lake had a depth of 8 m, and a wind speed of 7 m/s is used.

$$I = \frac{\tau}{\phi g h} \tag{3.2}$$

In which τ [N/m^2] is the shear stress by wind, ϕ [kg/m^3] is the water density, g [m/s^2] is gravitational acceleration and h [m] is the water depth. Using station East and station West (see Figure 3.6), the slope between these points can be determined, and compared to the theoretical slope given by Equation 3.2. The theoretical slope is $1.9e{-}05$ [-], and the slope between the observation points is $3.1e{-}06$ [-]. Myrbo et al. (2012) assume discharge does not play a role, and that boundaries are closed. As the model contains a discharge and the outflow, the slope should be less than the theoretical slope, which is the case. This is confirmed by a run with closed boundaries, giving a slope of $2.3e{-}5$ [-]. This value is nearly the same as the theoretical value.

Concluding, the water level slope as a result of the wind set up in the model is accurate to a degree which is satisfactory for the model.

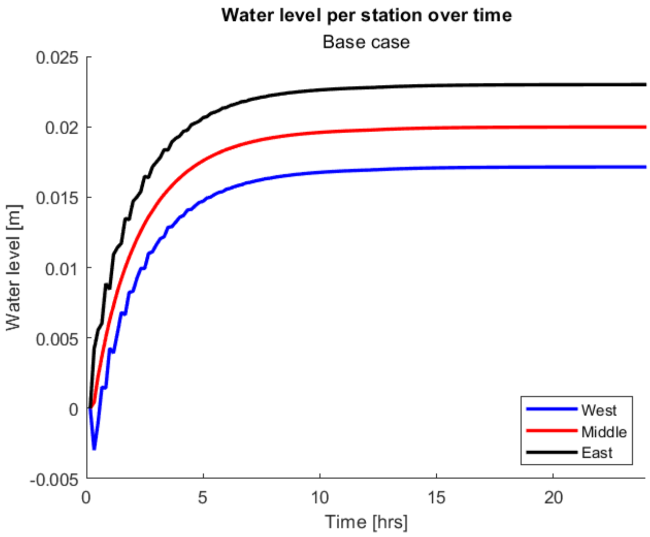


Figure 3.9: Water level over time in the three observation stations in the first simulation day, showing the effect of spin up.

3.2.3. FLOW FIELD

The goal of this subsection is twofold. First, the general flow pattern in the basin is checked for different scenarios. A scenario with discharge only is checked, and a scenario with wind is checked. Finally, the near field effect is quantified by viewing flow profiles over distance from the discharge area.

To analyze general flow profiles in the basin, a fully developed velocity profile is desired. Therefor, the profiles in the middle station are used (Figure 3.6). Figure 3.10 shows the velocity profile for a discharge only case. Next to it, the theoretical flow profile for a uniform open channel flow. Both profiles look similar in shape. The flow profile for a case with wind is depicted in Figure 3.12. Next to it, in Figure 3.13, a theoretical velocity profile for wind over a lake given by Myrbo et al. (2012). Both shapes are quite similar. Figure 3.12 shows a stronger boundary gradient. This is most likely due to a greater bottom friction used for a lake, where vegetation is part of the bottom.

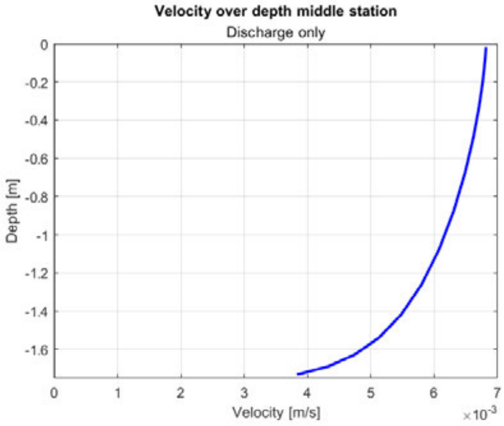


Figure 3.10: The velocity profile over depth in the middle of the basin for the Delft3D model. The case shown is a discharge only scenario, with no other processes considered.

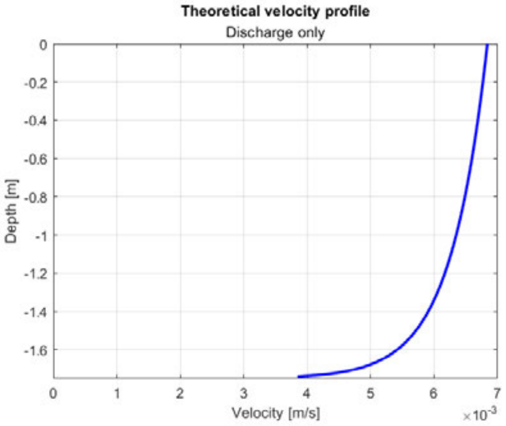


Figure 3.11: The theoretical velocity profile that fits with the scenario shown in Figure 3.10.

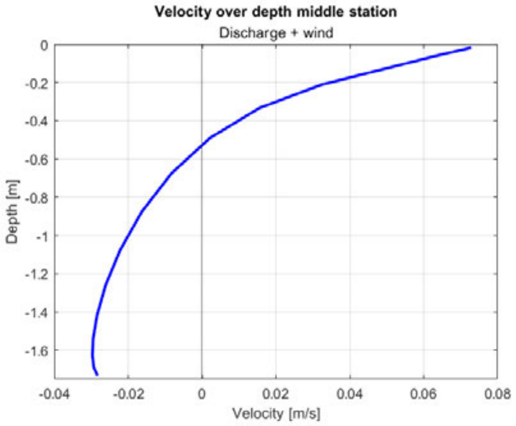


Figure 3.12: The velocity profile over depth in the middle of the basin for the Delft3D model. The case shown is a discharge plus wind scenario, where wind velocity is 7.5 m/s.

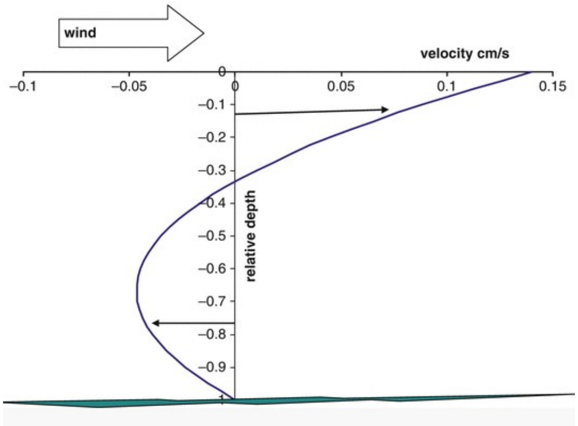


Figure 3.13: A qualitative theoretical velocity profile for Figure 3.12, as no analytical solution for this velocity profile was found Myrbo et al. (2012).

To quantify the near field effect of the discharge, the velocity profiles over depth are displayed below. Figure 3.14 shows the velocity profiles with increasing distance from the discharge. The case considered here is a discharge of 3 m^3/s. On the right, in Figure 3.15 shows the same, but for a case with a discharge of 3 m^3/s, and wind velocity of 7.5 m/s. Both cases are the same as those of Figure 3.12 and Figure 3.10 respectively. The velocity magnitude and the influence of the discharge drops rapidly at first. After the initial drop, changes become more gradual. For both cases, at 317 m the velocity profile is close to normal once again, and it has merged at 484 m. Figure 3.16 shows the depth averaged discharge with distance from the discharge. This shows the same, that around grid cell number 30 (484 m), the depth averaged discharge equals the transient depth averaged discharge.

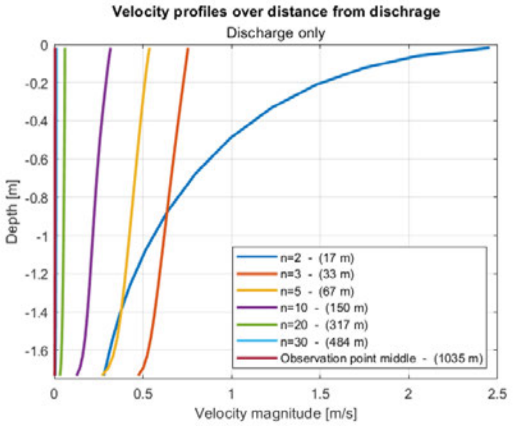


Figure 3.14: Delft3D model velocity profiles with increasing distance from the discharge location for a discharge only scenario. The discharge value is 3 m^3/s. The value for n is the grid cell number, where the discharge location is a grid cell n = 1.

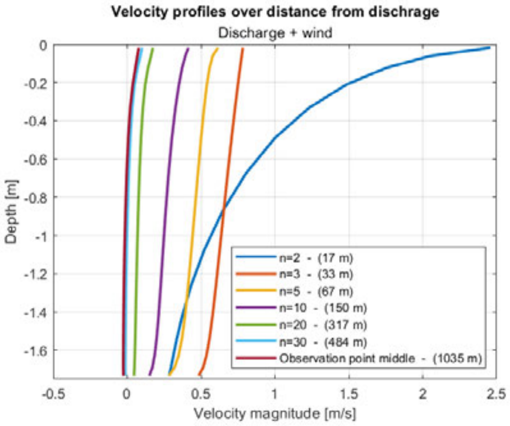


Figure 3.15: Delft3D model velocity profiles with increasing distance from the discharge location for a discharge and wind scenario. The discharge value is 3 m^3/s and the wind velocity is 7.5 m/s. The value for n is the grid cell number, where the discharge location is a grid cell n = 1.

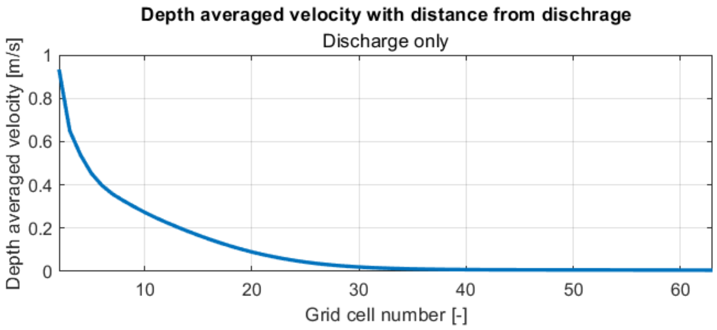


Figure 3.16: Depth averaged velocity in the Delft3D model with increasing distance from discharge located in grid cell number 1.

Concluding, in this subsection, the transient flow profiles where verified with literature. These had the same shape as literature showed. The boundary layer however was not very large. Next the goal was to find the extent of the near field effect at the discharge. This effect takes approximately 484 m to die out, and is independent of wind effects.

3.2.4. TURBULENCE PROFILE

For both Subsection 3.2.4 and Subsection 3.2.5, two runs were used for verification. The first run is one where only a flow rate of 3 m^3/s is used. The second run is a run in which, in addition to a flow rate of 3 m^3/s, a wind of 7.5 m/s is also included. Both the shear stress and waves resulting from this wind are included in the run. The wind direction is in the direction of the discharge.

Next to verifying the velocity profiles as a result of the forcing parameters, the goal of this subsection is to qualitatively verify the turbulence profiles in the basin. The turbulence profile in the three stations are analyzed (see Figure 3.6). This is done for the same cases as Subsection 3.2.3; a case with discharge only and a case with discharge and wind.

Hanmaiahgari et al. (2017) show turbulence intensity profiles for uniform flow in an open channel. The turbulence profiles ’Middle station’ and to some extent ’East station’ of Figure 3.17 can be compared to this. Both profiles have the same shape. The difference in the turbulence intensities at the bottom comes from flow accelerating, which is the case at the East station, as it is close to the boundary condition, also confirmed by Hanmaiahgari et al. (2017).

’West station’ in Figure 3.17 clearly shows the effect of the discharge. Overall the turbulent energy is significantly larger. It shows the same form as the turbulence intensity at larger flow velocities by Hanmaiahgari et al. (2017).

Figure 3.18 shows turbulent energies very much higher than those of Figure 3.17. Especially in the top layers of the profile high values are observed. This is a result of the wave field Holthuijsen (2007) in this layer. The development of the wave field can be seen over the stations. Where the fetch is smallest, the turbulent energy profile is smallest, even with the effect of discharge, at ’West station’. The middle station shows a significantly larger turbulent energy in the wave field. The East station shows a turbulent energy which is yet larger. The turbulent intensity as a result of the discharge only is, on average, larger than the turbulent intensity of the case with wind. Comparing the turbulent energy profile of Figure 3.17 with that of Figure 3.18 the enhanced turbulent energy in the top half of the water column is observed, a result of the wave field and wind shear stress.

Concluding, the turbulent energy profiles are congruent with those seen in literature for the states of flow observed.

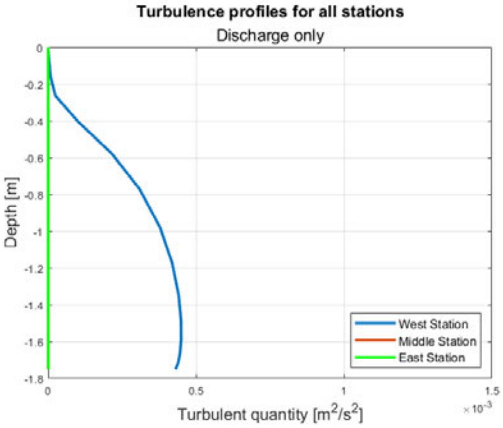


Figure 3.17: Turbulence profiles of the Delft3D model for all stations (see Figure 3.6) for a discharge only scenario (3 m^3/s).

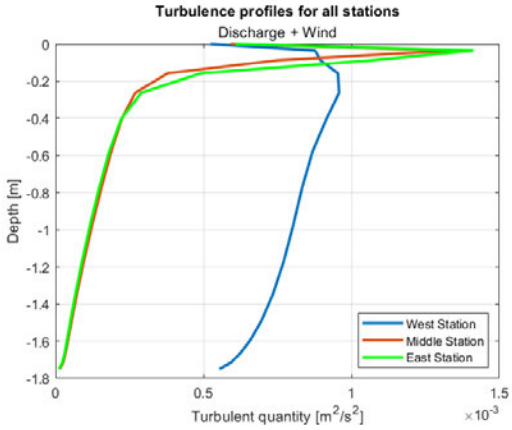


Figure 3.18: Turbulence profiles of the Delft3D model for all stations (see Figure 3.6) for a discharge and wind scenario (3 m^3/s) and (7.5 m/s).

3.2.5. SEDIMENT CONCENTRATION PROFILE

The goal of this subsection is to verify the sediment concentration profiles.

Figure 3.19 shows the concentration profile over time for a case with discharge only. Figure 3.20 shows the concentration profile over time for discharge and wind. Both cases consider the density effects of sediment. van Rijn (1984) shows that for increased turbulence, sediment will be well mixed over depth. This effect can clearly be seen between Figure 3.19 and Figure 3.20. Subsection 3.2.4 shows the turbulence for the case with wind is significantly higher. This effect can be seen in the sediment profile, due to the higher sediment concentration in the upper part of the water column for Figure 3.20 than for Figure 3.19

Moodie et al. show that the characteristic peak in concentration close to the bottom is caused by density effects. This is confirmed by running a simulation for discharge and wind without density effects. This result can be seen in Figure 3.21. In this figure, the tail in the bottom of the profile is gone, and sediment remains well mixed over the profile. This sediment concentration profile looks similar to the theoretical profiles provided by Rouse (1999) in Figure 3.22.

Concluding, sediment concentration profiles match with the literature on sediment concentration profiles.

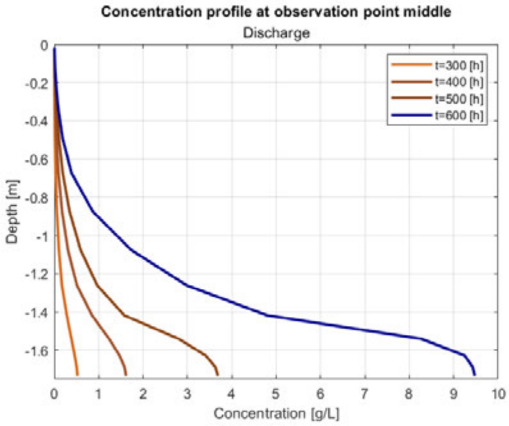


Figure 3.19: Delft3D model concentration profile over time in the middle of the basin. For this case discharge only (3 m^3/s) WITH density effects are considered.

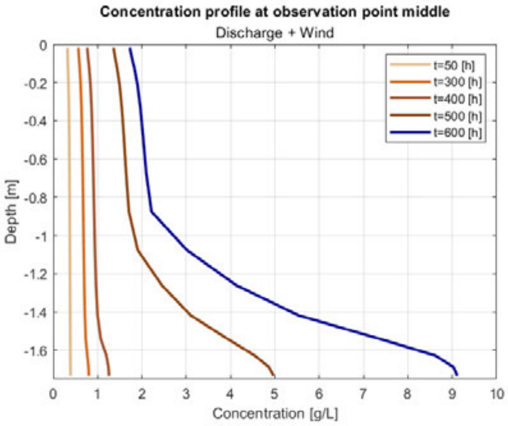


Figure 3.20: Delft3D model concentration profile over time in the middle of the basin. For this case discharge and wind (3 m^3/s), (7.5 m/s) WITH density effects are considered.

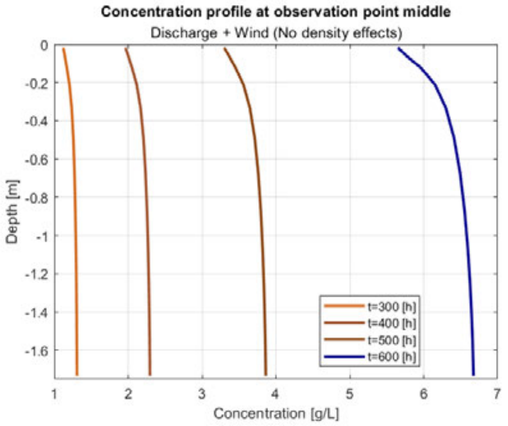


Figure 3.21: Delft3D model concentration profile over time in the middle of the basin. For this case discharge and wind (3 m^3/s), (7.5 m/s) WITHOUT density effects are considered.

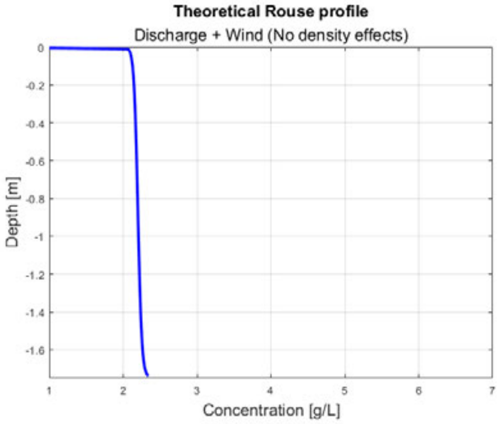


Figure 3.22: The theoretical Rouse profile for Figure 3.21, for t=400. Verifying a the theoretical Rouse profile for a density case is difficult as density effects alter the concentration profile.

3.2.6. 3D GATE

The goal of this subsection is to verify whether the 3D gate has the desired effect on the flow in the basin. To do this, the flow field around the gate is checked.

As Figure 3.23 shows, the flow velocity at the part blocked by the gate is 0 m/s. This leads to an increased flow velocity over the free part of the cross section. The velocity at the wall is strictly vertical. The result of this should be a concentration within the gated area which is lower than the surrounding concentration in the lower layers. Figure 3.24 shows the concentration at layer 12 in the gate and surrounding the gate. The lower concentration can clearly be seen. The lower concentration in the gate is a result of very little turbulent energy in that area. The lower concentrations around the gate

Concluding, the 3D gate functions as it should in the model, in creating a zero velocity around the open boundary.

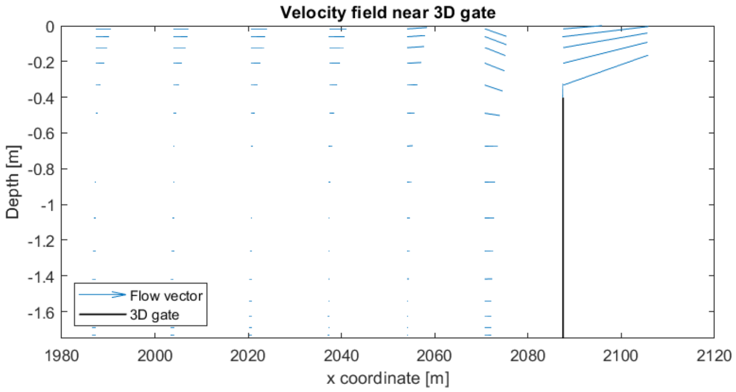


Figure 3.23: A cross section visualizing the flow field and the 3D gate in the Delft3D model .

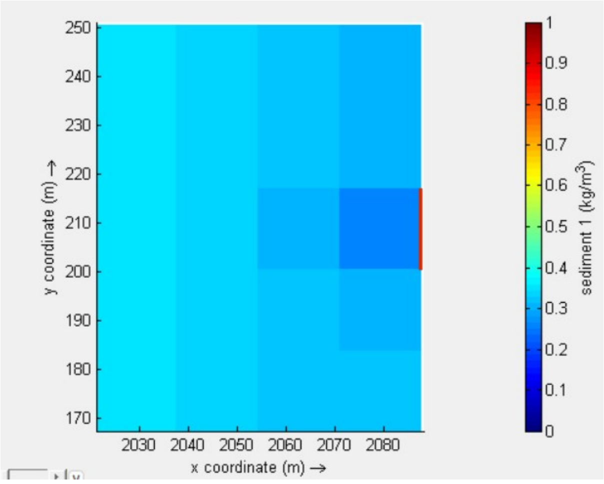


Figure 3.24: Sediment concentration surrounding the 3D gate, and the location of the open boundary. The open boundary is shown in red, and the gate surrounds the grid cell next to the open boundary. This visualization is in layer 12, near the top of the water column. Within the gate the concentration is clearly lower. Around the 3D gate, the concentration is lower as well, due to reduced turbulence, leading to a concentration profile which is less well mixed.

3.2.7. INITIAL CONDITIONS

The model assumes the initial concentration to be 0 kg/m^3, see Subsection 3.1.4. To check the sensitivity of this parameter on sediment outflow concentrations, runs are performed with differing initial sediment concentrations. Three situations are compared to each other through sediment outflux. The first is the base situation with 0 kg/m^3. Next a situation with 0.01 kg/m^3 (light ambient turbidity) and 0.1 kg/m^3 (heavy ambient turbulence).

Figure 3.25 shows the initial outflux of the system. The outflux of the system starts at the initial condition. As the initial sediment settles out of suspension, and the discharge sediment has not reached the outflow, sediment fluxes drop over time. At around T = 0.4 days all fluxes are equal, as the sediment from the discharge reaches the outflow and initial concentrations have dropped below the discharge level. Figure 3.26 shows the outflux over time until the basin is full. The outflux with varying initial conditions does not vary greatly over time. Figure 3.27 shows the absolute difference between the initial conditions and the base case. Here, the initial difference can be seen, and an increasing difference over time. As a percentage of total flux however, this remains small, as can be seen in Figure 3.26. It seems that most sediment is settles from suspension before the effects of the discharge are seen and become dominant in the outflow concentration.

Concluding, in practice, the initial conditions in a mud disposal basin do not significantly influence the sediment outflux. The assumed value of 0 kg/m^3 is therefore a safe assumption.

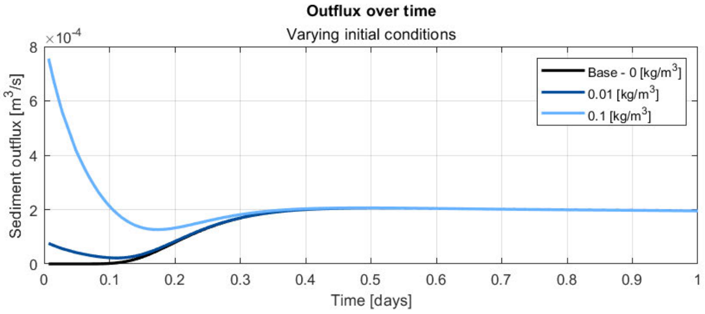


Figure 3.25: Sediment outflux over time for varying initial conditions for the first day.

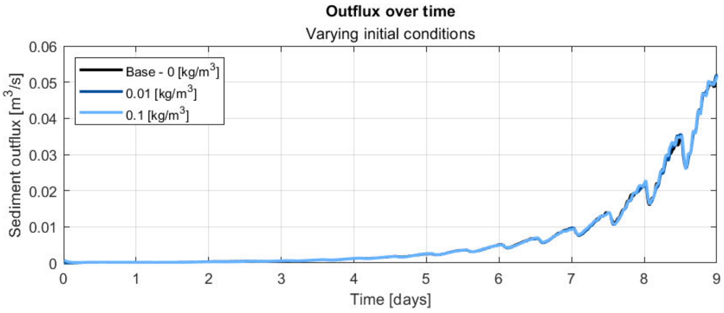


Figure 3.26: Sediment outflux over time for varying initial conditions until the basin is full.

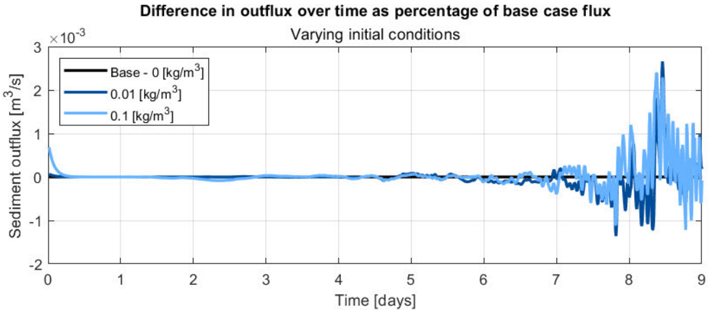


Figure 3.27: Absolute difference between sediment outflux of Figure 3.26, where the base case is taken as zero.

3.2.8. SPIN-UP EFFECTS

This subsection aims to show the effect of spin up, the effect of the smoothing time, and finally the effect of starting the sediment simulation with flow only until the spin up time is over. This is to justify the choices for these parameters in Subsection 3.1.6 and Subsection 3.1.7. The effects are quantified through sediment outflow concentration.

First, to quantify the spin up duration, the water level over time is shown in the basin for the model case with discharge (3 m^3/s) and wind (7.5 m/s). This is seen in Figure 3.9. After 12 hours, the initial effects diminish, and the model stabilizes.

Using a spin up time of 720 min does not allow morphological changes for the given period. The sediment that is in suspension cannot settle, so sediment concentrations in the water continue to rise. This results in concentrations close to, or exceeding the bed concentration itself. When the spin up period is finished, this directly settles and turns into the new bed level. In this period, the hydrodynamics behave in a way that there is no bed. This is something which can give incorrect results. The effect on the outflow concentration over time is seen in Figure 3.28. Four scenarios are plotted in the figure. These are scenarios where different methods have been used to counteract spin-up effects. What is striking is that the use of spin up produces lower outflow concentrations over time than not using spin up. This is most likely the result of the slowdown in bed level change. After all, the amount of sediment in the model is different for both spin-up cases.

A potential way to solve the issues caused by the spin up is to allow the discharge to only discharge water in the first 720 min. Only after this period will a sediment flux be added. The effect of this can be seen in Figure 3.28. The rise of the initial outflow concentration as a result of this is belated by the same margin as the spin up. However, even though this case gives a lower cumulative influx into the model, the outflux joins with the case with spin up time. The only difference between the two is the change of bed level change which is allowed. As a result, the bed level growth over time is responsible for this deviation in outflow concentration.

A way to reduce spin up time is to add a smoothing time. In this time, the boundary condition is increased over time to the forced level by the user. This reduces boundary induced waves forced into the model. In the model, this value is chosen at 60 min. The effect on the spin up time is shown in Figure 3.29. Without the 60 min smoothing time, the model becomes unstable as the water level time series shows. The effect on the outflow concentration is shown in Figure 3.28. Even though the model is not stable, the effect on the outflow concentration is small compared to the run with 60 min of smoothing time.

Concluding, a smoothing time of 60 min is crucial for model stability. The spin up as a result of the smoothing time does not provide very different results in sediment outflow concentration, thus the choice to use no spin up mitigation effects for sediment transport in the model is accurate. The change in bed level which is stopped or made possible as a result of the spin up in this case has a great effect on sediment outflow concentration over time.

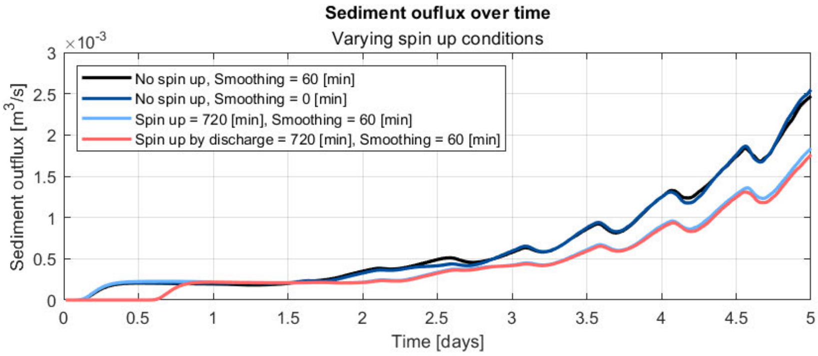


Figure 3.28: The effect of varying spin up measures on the sediment outflux in the first five simulation days of the Delft3D model.

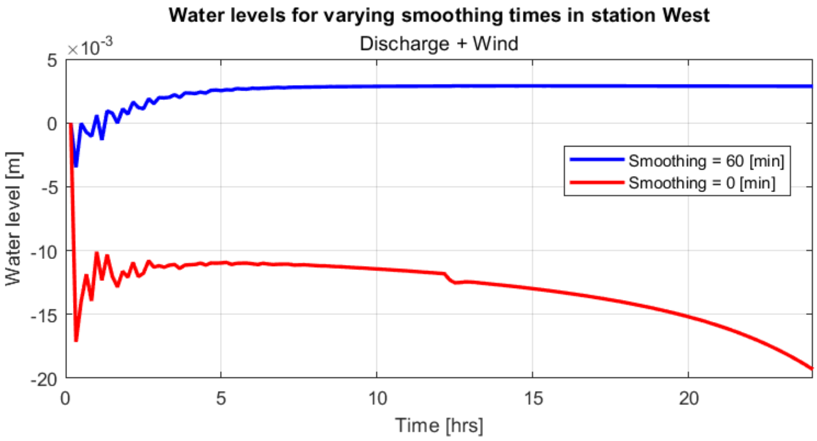


Figure 3.29: The effect of varying smoothing times on the water level in the Delft3D model.

3.2.9. WAVE COUPLING

The calculation of the wave field for the flow field and bathymetry is performed every 720 min in the model. The goal of this subsection is to show the impact of this coupling interval by showing a shorter wave coupling period and a longer wave coupling period. All simulations are performed on a wave field with an associated wind velocity of 7.5 m/s. The wave field for this scenario is shown in Figure 3.30 The quantification of the effect of the coupling interval is shown through the sediment outflow concentration.

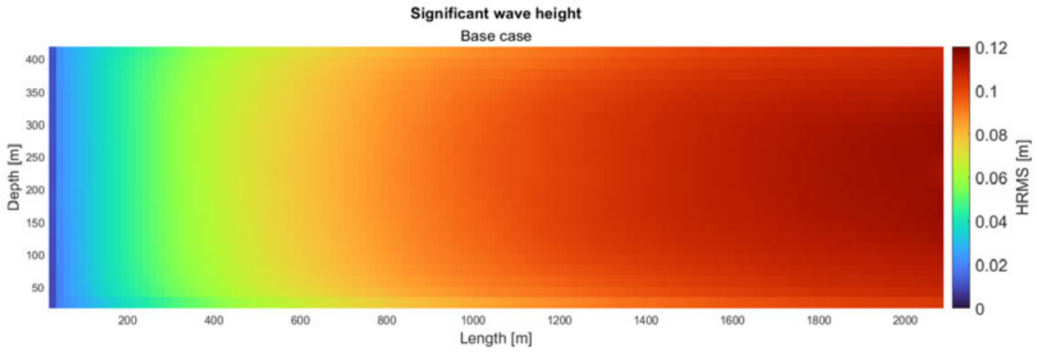


Figure 3.30: The significant wave height over the basin for an associated wind velocity of 7.5 m/s for the Delft3D model.

The first run is performed with a wave coupling interval of 30 min. The second run is performed with a wave coupling interval of 6 [days], so once at the beginning of the simulation, and once half way. The computation times as a result of this can be seen in Table 3.2. Figure 3.31 shows the outflux as a result of the varying wave coupling intervals. For both of these extremes in wave coupling interval, a steady scenario exist. This gives the idea of an upper bound and a lower bound. The difference between the 30 min coupling interval and the 6 days coupling interval is on average + 45% as compared to the 30 min coupling interval. When wave coupling is 720 min the average flux is + 23%. As with frequent wave coupling the simulation time nearly doubles, this is something which is not desirable. A wave coupling of six days however, is not physically accurate. Given the consideration, a coupling interval of 720 min is chosen as a compromise between both.

Coupling interval min	Computation time [s]
30	5463
720	3198
8640	3035

Table 3.2: Computation times for the varying wave coupling intervals used in the WAVE coupling sensitivity.

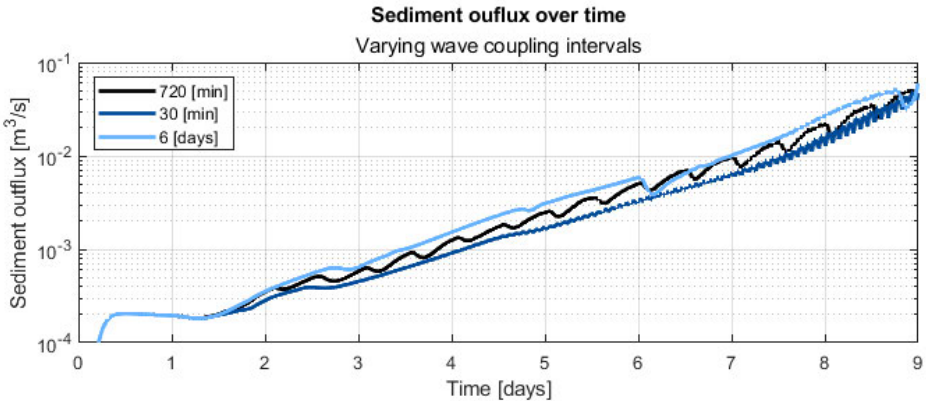


Figure 3.31: Sediment outflux on the log scale as a result of varying wave coupling intervals in the Delft3D model.

4

BASIN HYDRODYNAMICS

This chapter addresses the fourth research goal: *Quantify the dominating processes and parameters for the flow field and turbulent quantity of a basin.* The effect of processes will be quantified, as well as a sensitivity of parameters.

4.1. APPROACH

To answer the research question, the hydrodynamic version of the Delft3D model is used. This is the model without the sediment constituent included. The effect of the following processes are tested:

- Discharge
- Wind shear stress
- Wind waves

Next to that, the sensitivity of the following parameters is tested:

- Discharge
- Wind velocity
- Wind direction

The effect of processes and parameters is quantified by the turbulent energy over depth in the three observation stations, see Figure 3.6. Turbulent energy is used because it is a result of all shear stress production, through the bottom, the surface, and flow gradients. Turbulent energy also is an important parameter for sediment mixing, as it is the only upward flux in sediment transport.

To determine the impact of both processes and parameters a base case is defined. The magnitude of the processes is important for the effect that the process has on the turbulence. From this base case, the parameters given above will be altered, and the impact is analyzed. The base case is seen in Table 4.1. The reasoning for the the parameter values is explained in Subsection 4.1.1. The runs which are performed to analyze the effect of processes are seen in Table 4.2. The runs which are performed to analyze the effects of parameters are seen in Table 4.3.

Parameter	**Value**	**Unit**
Discharge	4.5	m^3/s
Wind speed	7.5	$[m/s]$
Wind direction	270	[°]

Table 4.1: Parameter values used for the base case in the Delft3D model.

Run nr	**Discharge**	**Wind Shear**	**Wind Waves**
RUN 1	yes	yes	yes
RUN 2	yes	no	no
RUN 3	yes	yes	no

Table 4.2: Runs for process sensitivity of the hydrodynamic model, used in Section 4.2, in which the effect of processes is tested.

Run nr	**Discharge**	**Wind velocity**	**Wind direction**
Units	$[m^3/s]$	$[m/s]$	deg
BASE	4.5	7.5	270
RUN 4	3		
RUN 5	6		
RUN 6		0	
RUN 7		15	
RUN 8			0
RUN 9			90

Table 4.3: Runs for the parameter sensitivity of the hydrodynamic model, used in Section 4.3, in which the effect of parameters are tested. Values differing from the base case per run are given.

4.1.1. PARAMETER MOTIVATION

Discharge into the basin is usually determined by dredger production. The slurry is pumped through a pipe with a given diameter at a given velocity. From these metrics, the flow can be calculated. Typical values for pipe diameter are in the range of $0.7-1\ m$. Velocities out of the pipe are in the range of $6-8\ m/s$. This gives a discharge range of $2.5-6.5\ m^3/s$. The discharges of 3, 4.5 and 6 m^3/s are well in this range.

Wind speed is chosen at no wind (discharge only), a mild wind which happens quite often (7.5 m/s) (KNMI, 2022b), and a somewhat strong wind, which is the start of a storm (15 m/s). This is classified according to KNMI (2022a). The direction of the wind is based on the modeled orientation of the mud disposal basin. The most significant and least significant orientations are chosen, as wind waves are considered. The normative situation is one where the fetch is greatest, and wave height is largest at the weir box. The situation that is least significant is the situation where the fetch is the smallest. This would be over the basin width. Finally, as De Lange et al. (2011) concluded, wind in opposing direction to the flow having impact, this situation is tested as well. A visual reference of the basin and wind directions can be seen in Figure 4.1

Figure 4.1: Visualization for wind directions used with respect the mud disposal basin in the Delft3D model.

4.2. SENSITIVITY PROCESSES

This section shows the results for the turbulent energy over depth for the processes mentioned in Section 4.1.

Table 4.4 shows the quantification of the process runs. Figure 4.2 shows three turbulence profiles. The red is the profile for discharge only. Blue is a turbulence profile for discharge and wind shear. Finally, the black line represents discharge, wind shear and wind waves. A large difference can be seen between these different processes. As the shape and magnitude of both smaller quantities are small compared to the turbulence cased by waves, these are plotted individually. Turbulence as a cause of wind shear is seen in Figure 4.3. Turbulence for discharge only is seen in Figure 4.4.

Qualitatively, a few things stand out. Where the discharge has an increasing turbulent quantity with depth, wind effects have a decreasing turbulent quantity with depth. This is due to the shear stress production. For discharge only, the only shear production is from the bottom, which is dissipated towards the water surface. For wind cases, the wind shear on the surface is much higher than the bottom shear stress. Because of this, a flipped profile is observed, where shear stress dissipates towards the bottom. Next to that, the peak of turbulence near the surface stands out as well. This is because of the waves that are present. The run with wind shear stress only does not show this peak, and the inclusion of waves is the only difference between these runs.

Quantitatively, the maximum turbulence caused by wind shear dominates the maximum value for the discharge by three orders of magnitude. When waves are also considered, the maximum turbulent quantity compared to wind shear is larger by another order of magnitude. This is not a linear profile however as turbulence peaks in the top 10% of the water level. Table 4.4 shows the mean and max turbulence variation in station middle as a result of different processes. The case with discharge and wind shear is chosen as a base, for else results are infinite considering the flipped profile of the discharge turbulence.

Concluding, additional processes next to discharge only are very significant on turbulence profiles in the basin. In mean difference alone between discharge and discharge + wind shear stress there is a difference of (3 $\mathcal{O}$). Next to that, including wind waves as a result of the same wind which causes the shear stress, the turbulence increases again, albeit not with the same significance as wind shear (1 $\mathcal{O}$).

Processes	Max change turbulence	Mean change turbulence
Discharge	-99.9%	-99.5%
Discharge + Wind shear	0%	0%
Discharge + Wind shear+ Wind waves	+573%	+117%

Table 4.4: Sensitivity of varying processes on turbulence over depth in the Delft3D model.

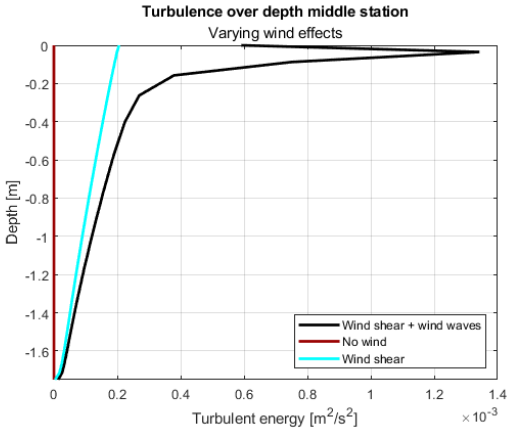


Figure 4.2: Turbulence profiles for varying wind effects in the middle station for the Delft3D model.

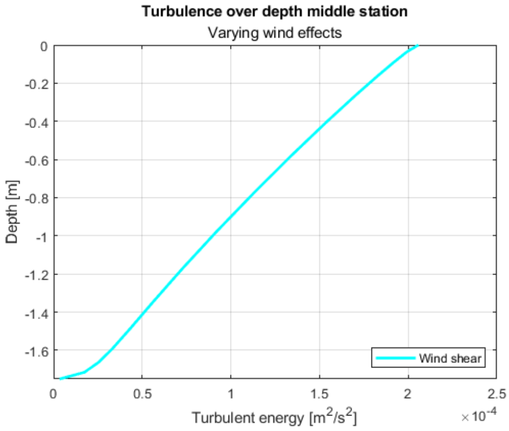


Figure 4.3: Turbulence profile in the middle station for wind shear in the Delft3D model. This is a zoom in for Figure 4.2

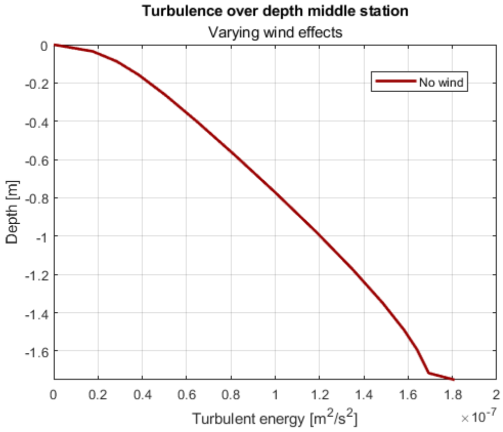


Figure 4.4: Turbulence profile in the middle station for discharge only in the Delft3D model. This is a zoom in for Figure 4.2

4.3. SENSITIVITY PARAMETERS

This section goes into the sensitivity of the parameters responsible for turbulence.

4.3.1. DISCHARGE

The effects of the variation of the discharge parameter on the turbulence quantity is shown in Table 4.5. Figure 4.5 shows the turbulence profiles for turbulent energy over depth for the base case as defined in Table 4.1. As concluded in Section 4.2, turbulence due to discharge is very insignificant compared to turbulence cause by discharge and wind effects. Because of this, Figure 4.6 shows the turbulence profiles as difference compared to the base case.

The biggest differences are seen in the turbulence peak due to waves. When discharge becomes larger, the turbulence due to waves decreases and vice versa. This is logical, as when flow increases, flow velocity over the basin increases, and the relative wind speed decreases, decreasing shear stress. In the lower parts of the water column, turbulence slightly increases due to the higher discharge (and lowers due to a lower discharge) due to the increased or decreased flow velocity respectively. A large change is observed in Table 4.5 for the maximum change of turbulence for a discharge of 6 m^3/s. This seems like a large change. The This peak change however happens near the bed. Near the bed, turbulence is small. A change in turbulence here then results in a large percentage change compared to the base case as a result. The absolute change in turbulence here is small though, and thus the effect remains insignificant.

Table 4.5 shows the peak difference and the mean difference as a result of the parameter variation. The turbulent energy increases as a result of a decrease in discharge and vice versa. In a case without wind effects this would be the other way around, as wind effects dominate.

Concluding, the discharge does not have a significant effect on the turbulent profiles of a mud disposal basin. For variations of 33%, the mean did not change more than 1.5% for each scenario.

Discharge [m^3/s]	**Variation discharge**	**Max change turbulence**	**Mean change turbulence**
3	-33%	+5%	+0.4%
4.5	0%	0%	0%
6	+33%	-25%	-1.5%

Table 4.5: Turbulent sensitivity of the discharge parameter in the Delft3D model.

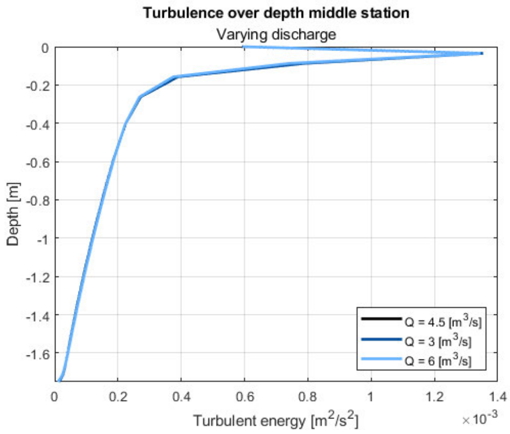


Figure 4.5: Turbulent energy profiles in the middle observation point for varying discharge in the Delft3D model.

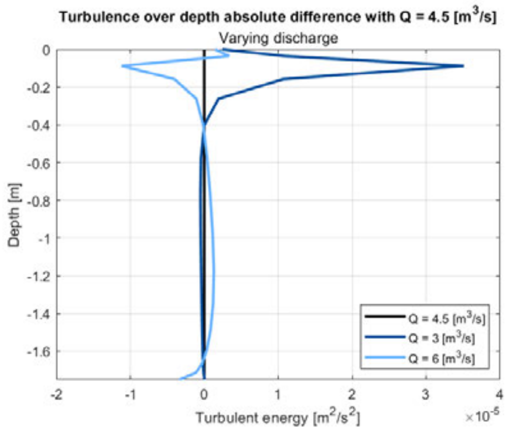


Figure 4.6: Absolute difference profiles of turbulence profiles for varying discharge. Absolute difference with discharge = 4.5 m^3/s.

4.3.2. WIND VELOCITY

Table 4.6 shows a quantification of the mean and peak changes for the sensitivity. Figure 4.7 shows the turbulent profiles as a result of varying wind velocities for wind shear and wind waves. The absolute difference between these is shown in Figure 4.8.

Between the case of v = 7.5 m/s and 15 m/s, the difference can be seen in two ways. First, the turbulence peak in the wave field is larger. This is a result of the larger waves caused by a stronger wind. At the location of the observation point, the significant wave height for the 7.5 m/s wind is 0.14 m, and the significant wave height for the 15 m/s wind is 0.29 m. Next, the shear stress induced by the wind is seen in the linear part of the turbulence in the lower half of the profile. A higher wind speed results in a larger shear stress which is transferred over the water column. Compared to a wind speed of 0 m/s, the turbulence is higher for both wind speeds, as concluded in Section 4.2.

Concluding, the wind velocity has a significant effect on turbulent profiles in the mud disposal basin. Doubling the wind speed from 7.5 to 15 m/s leads to a 5x of the mean turbulent quantity in the turbulence profile. The largest difference however is due to the turbulence peak from the wave field as a result of this wind.

Wind velocity [m/s]	**Variation velocity**	**Max change turbulence**	**Mean change turbulence**
0	-100%	-99.9%	-99%
7.5	0%	0%	0%
15	+100%	+890%	+493%

Table 4.6: Turbulent sensitivity of the wind velocity parameter in the Delft3D model.

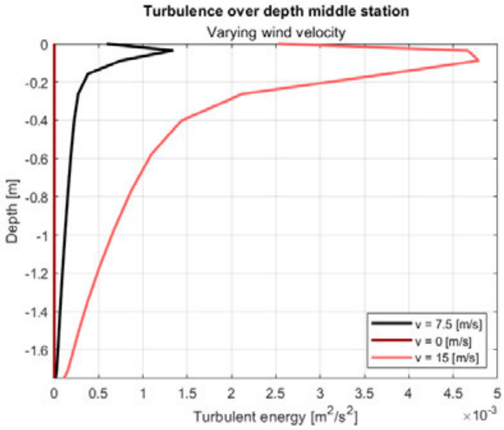


Figure 4.7: Turbulent energy profiles in the middle observation point for varying wind velocity in the Delft3D model.

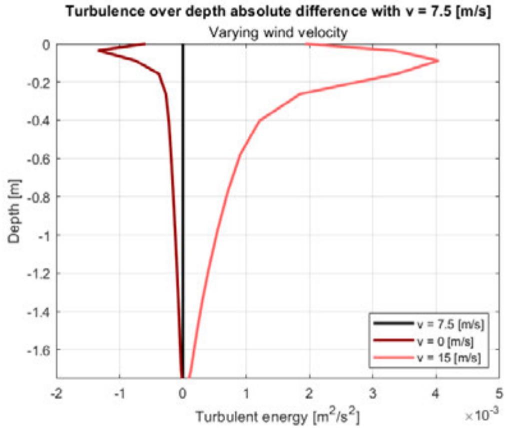


Figure 4.8: Absolute difference profiles of turbulence profiles for varying wind velocity. Absolute difference with velocity = 7.5 [m/s]

4.3.3. WIND DIRECTION

Table 4.7 shows the quantification of the results of the wind direction sensitivity shown in Figure 4.9 and the difference in wind direction shown in Figure 4.10. Here, there are two things which stand out. First, the difference in turbulent peaks caused by the wave field. The shorter the fetch is, the smaller the wave height, the smaller the turbulent quantity. This can be seen for the wind direction of 0 deg. The small fetch of 210 m gives a lower turbulent quantity then the wave fields from 270 and 90 deg with a fetch if 1045 m. The wind directions 270 and 90 deg show a small difference in turbulence peak caused by the waves, even though the fetch is the same. This is caused by the discharge, where the wind from 90 deg has the higher turbulent quantity. This is because the flow field faces a headwind, which leads to a higher relative wind speed.

The turbulence intensity in the bottom layer of the vertical profile is almost the same for every run.

This is the result of the wind shear stress, which is the same regardless of direction. The difference in turbulence profiles is mainly visible in the upper part of the vertical profile. Here the turbulent intensity is mainly created by waves. The changeable wind direction results in a different fetch, which results in a different wave height, and thus ultimately turbulence intensity as a result of the wave field.

For the wind direction of 90 deg, the largest relative change in turbulent energy comes from the bottom. This is because for this case, the velocity near the bottom is lower, causing less turbulence due to the shear with the bottom than for the case with 270 deg. This is due to the combination of the circulation caused by the wind combined with the discharge.

Concluding, the wind direction does not have a very large difference on the turbulent energy in the profile. Mean differences are relatively small. Peak differences are somewhat larger due to the differing fetches.

Wind direction $[deg]$	**Variation direction**	**Max change turbulence**	**Mean change turbulence**
0	+90 deg	-41%	-5%
270	0 deg	0%	0%
90	+-180 deg	-12%	-0.6%

Table 4.7: Turbulent sensitivity of the wind direction parameter in the Delft3D model.

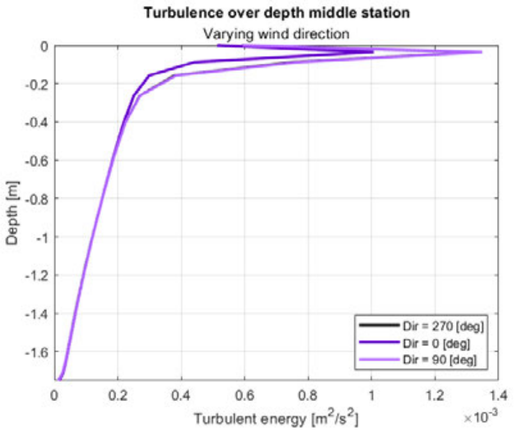


Figure 4.9: Turbulent energy profiles in the middle observation point for varying wind direction in the Delft3D model.

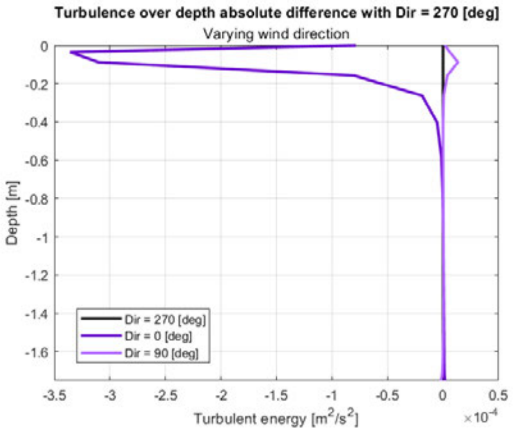


Figure 4.10: Absolute difference profiles of turbulence profiles for varying wind direction. Absolute difference with Dir = 270 $[deg]$

4.4. CONCLUSION

Concluding this chapter, it is the processes of wind shear and wind waves which affect the turbulent energy in the middle of the basin most. The addition of wind shear stress and wind waves over the discharge only case are significant for turbulent intensity. From the parameters, wind speed significance stands out among other parameters. Wind direction can be significant on turbulent intensity as a result of the fetch being increased or decreased. Overall, the conclusion that wind speed and fetch affect turbulence most.

5

MUD DISPOSAL BASINS: SEDIMENT OUTFLOW CONCENTRATIONS

This chapter addresses the fifth research goal: *Quantify the dominating processes and parameters for sediment outflow concentration of a basin.* This chapter will have the same setup as Chapter 4.

5.1. APPROACH

To answer the third research question, the same hydrodynamic model is used as in Chapter 4. A sediment constituent is added to this model. The entire model setup, and also the sediment part, can be found in Chapter 3. The 'dominating factors' are divided into processes and parameters. The effect of both are tested. The processes tested are the following:

- Density effects
- Wind shear stress
- Wind waves
- Resuspension

The sensitivity of the following parameters are tested:

- Discharge
- Settling velocity
- Wind velocity
- Wind direction
- Sediment influx

The effect of the processes and parameters are quantified by the sediment outflow concentration, as this is the main usage for the models. In testing the impact of processes on the sediment outflow concentration, the parameters are given a base value, which can be seen below. The same values for parameters are used as a base for the sensitivity analysis of the parameters.

Parameter	**Value**	**Unit**
Discharge	3	$[m^3/s]$
Sediment flux	900	$[kg/s]$
Settling velocity	25	$[mm/s]$
Wind velocity	7.5	$[m/s]$
Wind direction	270	$[deg]$

Table 5.1: Base case for sediment model

The runs which are performed for the quantification of processes are seen in Table 5.2. The runs performed for the quantification of parameter sensitivity are seen in Table 5.3.

Run nr	**Density effects**	**Wind shear stress**	**Wind waves**	**Resuspension**
RUN 1	yes	yes	yes	yes
RUN 2	no	yes	yes	yes
RUN 3	yes	yes	no	yes
RUN 4	yes	no	no	yes
RUN 5	yes	yes	yes	no

Table 5.2: Runs for process sensitivity of the sedimentary model, used in Section 5.2, in which the effect of processes is tested.

Run nr.	**Discharge**	**Settling vel.**	**Wind vel.**	**Wind direction**	**Sediment influx**
Units	$[m^3/s]$	$[mm/s]$	$[m/s]$	$[deg]$	$[kg/s]$
BASE	3	0.25	7.5	270	900
RUN 6	4.5				
RUN 7		0.05			
RUN 8		0.15			
RUN 9		0.35			
RUN 10		0.45			
RUN 11			0		
RUN 12			15		
RUN 13				0	
RUN 14				90	
RUN 15					100
RUN 16					10

Table 5.3: Runs for the parameter sensitivity of the sedimentary model, used in Section 5.3, in which the effect of parameters are tested. Values differing from the base case per run are given.

5.1.1. PARAMETER MOTIVATION

Motivation for the chosen parameters is given below.

For the discharge, the same values are chosen as in Chapter 4. This is due to dredger production characteristics.

The values for settling velocity serves two purposes. First, different particle sizes are represented by this settling velocity. This is because flocculation is often modeled as an effective settling rate for all sediment particles as a function of concentration. With this you impose a fall speed on the sediment, which is also done here. The same conclusions can therefore be drawn about flocculation with the results of the settling velocity parameter. Secondly, as only cohesive sediments are considered, effectively, the effect of flocculation is considered. The diameter which coincides with the chosen settling velocities is shown in Table 5.4. The particles sizes are distributed over the silt and clay particle sizes. Clay particles can be much smaller, however, these particles have high change of flocculation, which makes considering velocities of that magnitude unrealistic.

Run nr	**Particle settling velocity**	**Particle diameter**
$[-]$	$[mm/s]$	$[\mu m]$
RUN 1	0.05	7.8
RUN 2	0.15	13.6
RUN 3	0.25	17.5
RUN 4	0.35	20.8
RUN 5	0.45	23.6

Table 5.4: Sediment settling velocities and accompanying diameters used in Subsection 5.3.2.

For wind velocities and wind directions, the same values are chosen as for the Chapter 4.

Finally, the sediment flux is chosen tenfold lower, and one hundred fold lower. This is because the influx of 900 kg/s coincides with a concentration of 300 kg/m^3. These are concentrations which are that of a siltation basin, in which a large quantify of fines are stored. As a result, the quantification is done for this inflow concentration. In case of a settling basin, where a basin lies behind a reclamation, the inflow concentration is very much lower. Due to the lower concentrations, there is a chance that different effects may take hold. Therefore the sensitivity of this is tested.

5.2. SENSITIVITY PROCESSES

This section shows the results of the sensitivity tests of varying processes. The base is a run with all processes included, and this is compared to a run without one of the processes, as shown in Table 5.2.

5.2.1. DENSITY EFFECTS

Table 5.5 shows the quantification of the effect of density currents in the outflow concentration. Figure 5.1 shows the sediment outflow concentration for density effects and no density effects. In the case where density currents are not considered, stratification does not occur. Because of this, sediments are well mixed over the water column. This results in a higher concentration in the top of the water column than in case of stratification, leading to a larger outflow concentration over time. This is confirmed by the Richardson numbers in a cross section of the basin during filling, in Figure 5.2. In the case where density effects are not considered, a very well mixed system is shown. When density effects are considered, a strongly stratified system is shown.

Concluding, the effect of the sediment on the fluid density has quite a significant impact on the sediment outflow concentration, by creating a stable stratified system close to the bottom of the basin.

Intermezzo - the Richardson number

The Richardson is a dimensionless number which describes the ratio of turbulence and buoyancy of the water. It is given by the following equation:

$$Ri = \frac{N^2}{S^2} \tag{5.1}$$

Where:

$$N^2 = \frac{-g\left(\frac{\delta\rho}{\delta z}\right)}{\rho_0} \quad , \quad S^2 = \left(\frac{\delta u}{\delta z}^2 + \frac{\delta v}{\delta z}^2\right)$$

In the case where the Richardson number is lower than the critical Richardson number (Ri_c), the system is well mixed, and stratification does not hold. When the Richardson number is higher than the critical Richardson number, the system is stratified, and buoyancy terms dominate. Galperin et al. (2007) gives Ri_c is between 0.25 and 1. The values mainly depends on the ratio between inflow velocity and basin velocity. As in a mud disposal basin the velocity generally is low compared to the inflow, the lower bound is chosen as critical value.

Run	**Mean concentration** $[kg/m^3]$	**Change of C to base** [%]
All processes	5.85	0
No density effects	11.26	+92.48

Table 5.5: Mean concentrations of Figure 5.1 for varying cases of density effects.

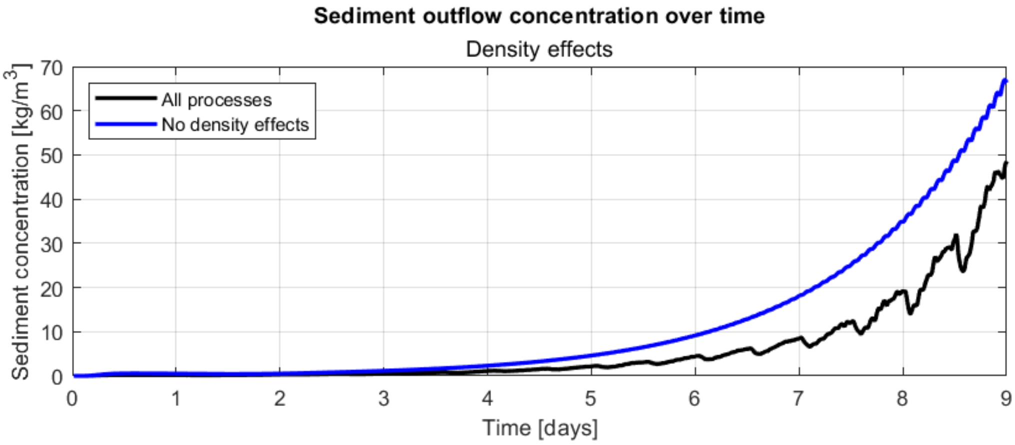


Figure 5.1: Sediment outflow concentration over time for varying density effects in the Delft3D model.

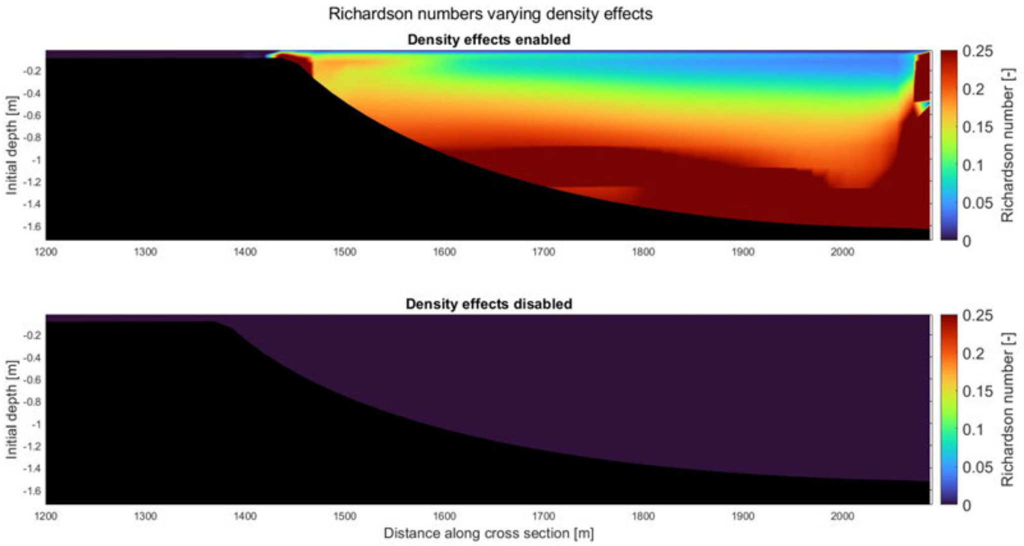


Figure 5.2: Richardson numbers and filling effects in the basin for above: WITH density effects, and below: WITHOUT density effects in the Delft3D model.

5.2.2. WIND EFFECTS

The effect of wind shear stress on the water surface and the effect of wind waves on the sediment outflow concentration are shown in Table 5.6 and Figure 5.3. It is striking that, a very large difference in Chapter 4 was found on the turbulence profiles for these effects, and that the effects on the sediment outflow concentration are not that large.

Run	**Mean concentration** $[kg/m^3]$	**Change of C to base** [%]
Wind shear + wind waves	5.85	0
Wind shear	4.92	-15.90
No wind	3.84	-34.36

Table 5.6: Mean sediment outflow concentrations for varying wind effects in the Delft3D model as visualized in Figure 5.3.

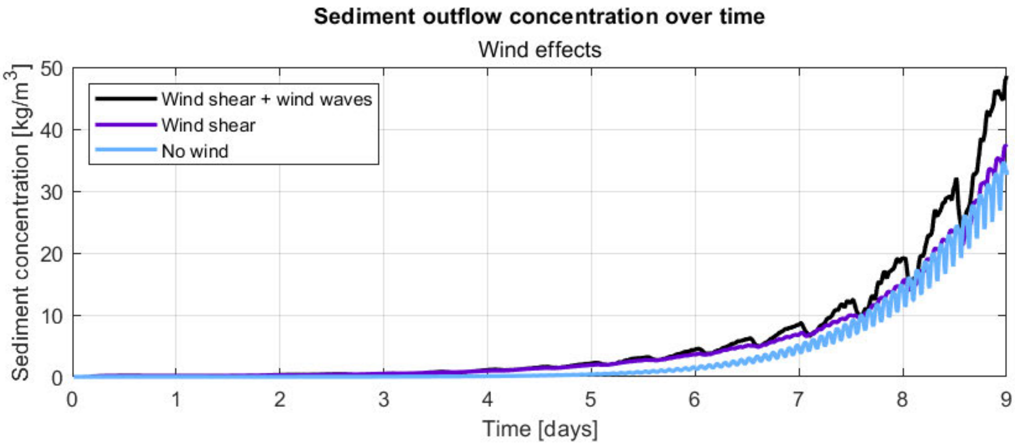


Figure 5.3: Sediment outflow concentration over time for varying wind effects at a wind velocity of 15 m/s in the Delft3D model.

A possibility of this is that the density effects are not overcome for this wind velocity, and the critical Richardson number is not reached. Figure 5.4 shows the Richardson number for the case with wind shear and wind waves, the case where the turbulence is highest. The result is a system which is still quite stratified. To overcome this, a runs with a wind velocity of 15 m/s are performed, and the outflow concentrations are compared once again. Now, a much larger difference can be seen between the runs. As Figure 5.4 shows, the Richardson number is below the critical Richardson number for most of the basin, suggesting a well mixed basin. There is no more stable stratification throughout the basin for the wind speed of 15 m/s. Remarkable is the filling effect as a result of the higher wind velocity, giving a more even fill. The quantification of these runs is seen in Figure 5.5.

At the wind velocity of 15 m/s, the stratification does not hold any longer, and the saw tooth shape, as a result of stratification for lower wind speed (7.5 m/s) is no longer as visible.

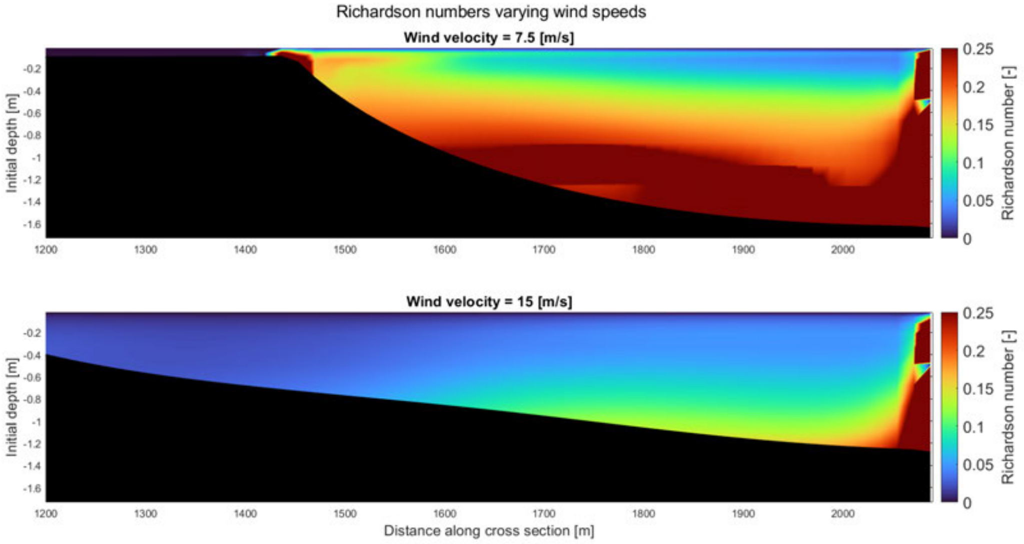


Figure 5.4: Richardson numbers and filling effects in the basin for wind shear stress and wind waves. Above: wind velocity = 7.5 m/s, and below: wind velocity = 15 m/s in the Delft3D model.

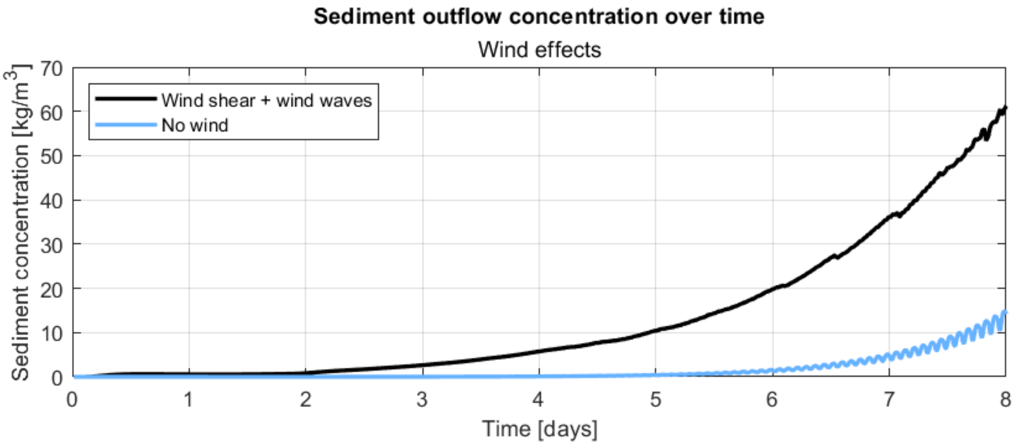


Figure 5.5: Sediment outflow concentration over time for varying wind effects at a wind velocity of 15 m/s in the Delft3D model.

Concluding, wind effects become significant at a critical wind velocity where stratification stability is overcome. This velocity is dependent, as shown later, on sediment concentrations, sediment settling velocity, and basin dimensions.

5.2.3. RESUSPENSION

Table 5.7 quantifies the mean difference between resuspension effects. The difference is quite insignificant. Figure 5.6 shows the outflow concentration for the base case, and with that a case where the critical bed shear stress is set to a several thousand N/m^2, such that resuspension does not occur. The result is not a very large difference in sediment outflow concentration over time. To visualize the difference between both, Figure 5.7 shows the difference between both concentration lines over time. The result is a line which is near zero in the beginning. This is logical, as there is not much sediment to erode, and as the basin is empty, the depth is still quite large, reducing the wave effect. As the basin fills more, a larger difference is seen in outflow concentration.

With that, comes the overestimation of the outflow concentration due to the wave coupling interval. As the wave coupling interval is 720 min, and the basin fills quite rapidly, the bathymetry adjusts but the wave field does not. The result is a bed shear stress which is too large. This means that in practice, the outflow concentrations should lie a little further apart than shown.

The concentration where resuspension is not possible shows the same saw tooth like behavior as where resuspension is possible. From this, it can be concluded that the saw tooth like behavior is a result of the stratification being overcome leading to a better mixed system resulting in a larger outflow concentration.

Concluding, the effect of resuspension is not very significant in a basin. This however is the case for the given parameters, and could be different at higher wind velocities, or lower sediment concentrations.In practice, the difference between both is probably somewhat larger. This is because the sediment outflow concentration is overestimated by the wave field coupling interval.

Run	**Mean concentration** $[kg/m^3]$	**Change of C to base** [%]
All processes	5.85	0
No resuspension	5.87	0.34

Table 5.7: Mean sediment outflow concentrations for varying resuspension effects in the Delft3D model as visualized in Figure 5.6.

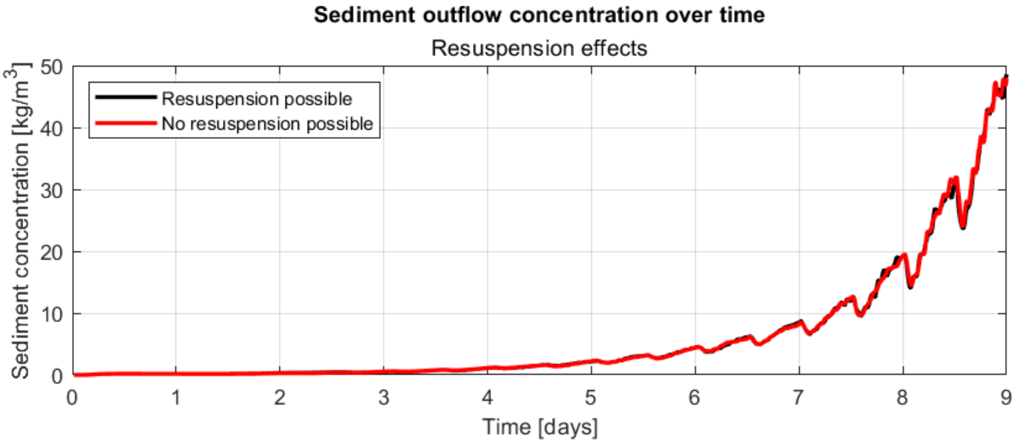


Figure 5.6: Sediment outflow concentration over time for varying resuspension effects in the Delft3D model

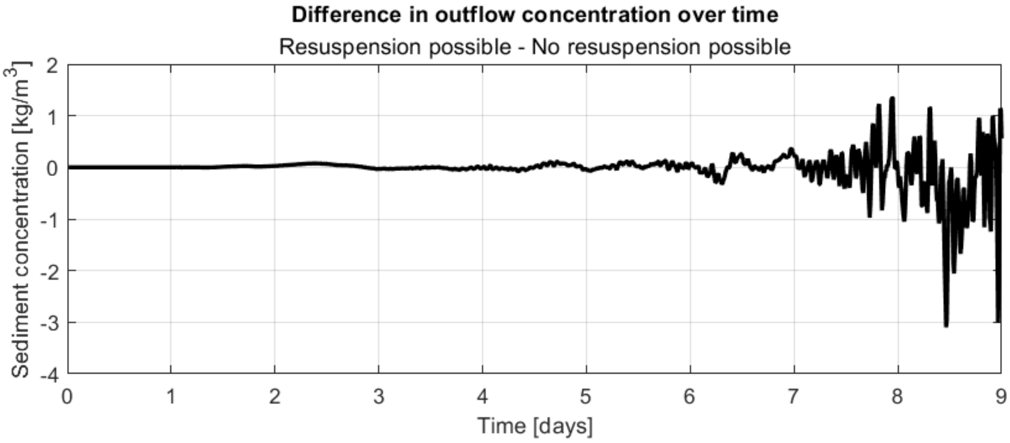


Figure 5.7: Difference between outflow concentrations of the case WITH resuspension and WITHOUT resuspension shown in Figure 5.6.

5.3. SENSITIVITY PARAMETERS

This section shows the results of the sensitivity analysis of the parameters.

5.3.1. DISCHARGE

The sensitivity of the discharge parameter is shown below in Table 5.8. What is striking, is that the outflow concentration drops as a result of a higher discharge as shown in Figure 5.8. This is the result of the outflux being divided by the flow, which in the case of the higher discharge is larger as well. When looking at the outflux only, this is corrected for, and as expected, due to the higher turbulence, a higher outflux is reached. This is shown in Figure 5.9, and quantified in Table 5.8. In both cases, the sensitivity of this parameter is not very large as it is lower than the initial change in parameter.

Run $[m^3/s]$	**Change of Q to base** [%]	**Mean concentration** $[kg/m^3]$	**Change of C to base** [%]
Q = 3 (BASE)	0	5.85	0
Q = 4.5	+50	4.93	-15.90
Run $[m^3/s]$	**Change of Q to base** [%]	**Flux** $[m^3/s]$	**Change of flux to base** [%]
Q = 3 (BASE)	0	0.0066	0
Q = 4.5	+50	0.0083	+25.76

Table 5.8: Mean sediment outflow concentrations for varying discharge in the Delft3D model as visualized in Figure 5.8.

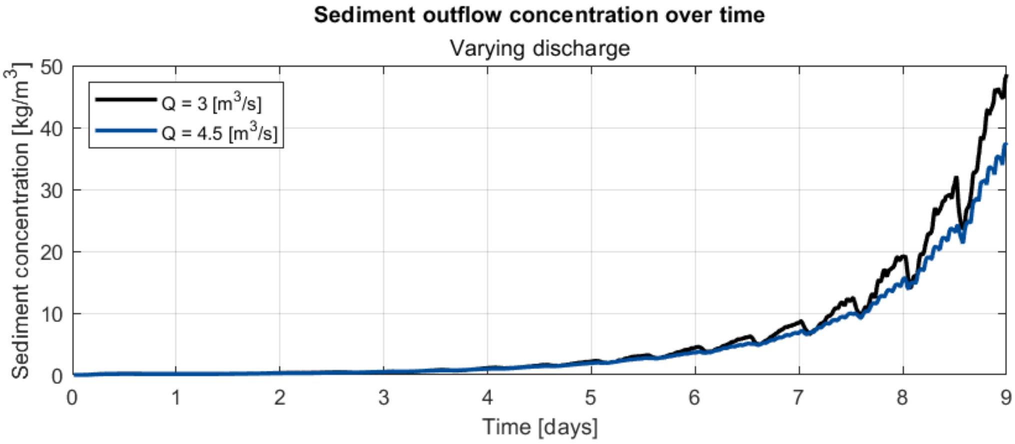


Figure 5.8: Sediment outflow concentration over time for varying discharge in the Delft3D model.

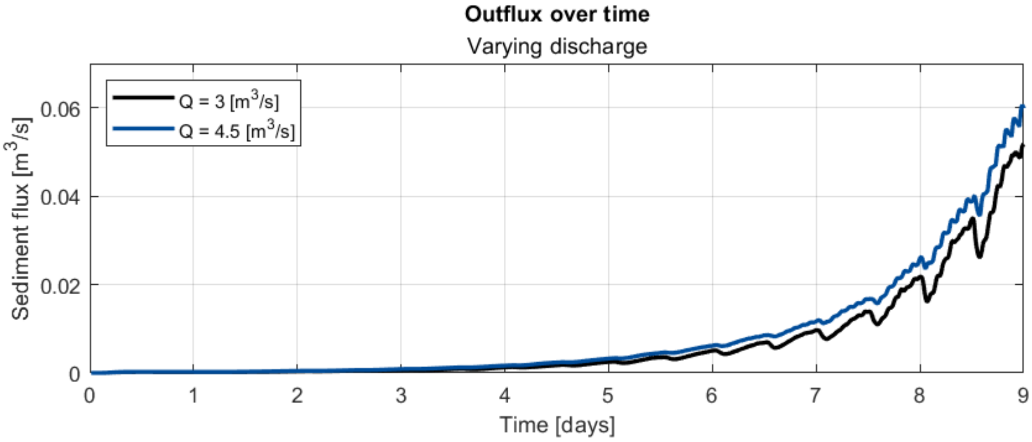


Figure 5.9: Sediment outflux over time for varying resuspension effects in the Delft3D model

5.3.2. SETTLING VELOCITY

Table 5.9 shows the quantification of the sensitivity runs for the settling velocity on the sediment outflow concentration. Figure 5.10 shows the effect of varying setting velocities on the sediment outflow concentration over time. The model is especially sensitive to lower settling velocities. A settling velocity of 0.05 mm/s is the only sediment fraction which shows a significant initial peak, and breaks the pattern of all other outflow concentrations over time.

Run [mm/s]	**Change of w to base** [%]	**Mean C** [kg/m^3]	**Change of C to base** [%]
w = 0.25 (BASE)	0	5.85	0
w = 0.05	-80	48.71	+732.6
w = 0.15	-40	11.69	+99.8
w = 0.35	+40	3.65	-37.6
w = 0.45	+80	2.54	-56.7

Table 5.9: Mean sediment outflow concentrations for varying settling velocities in the Delft3D model as visualized Figure 5.10.

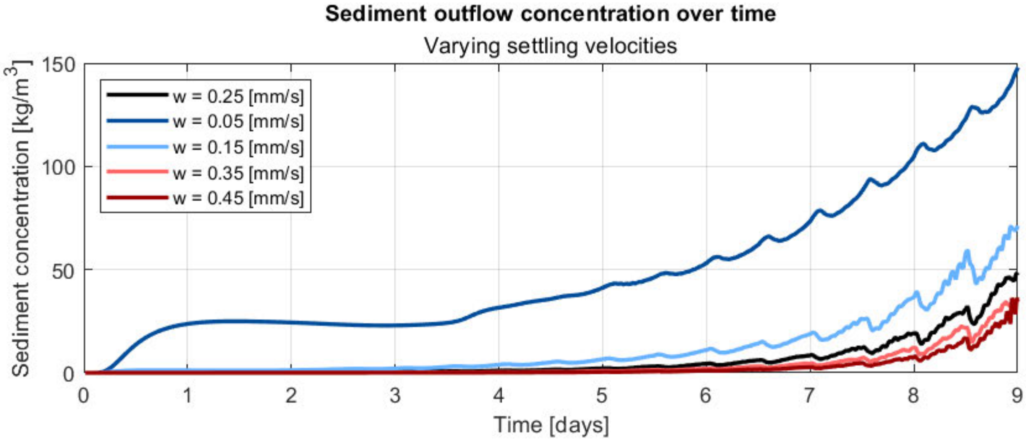


Figure 5.10: Sediment outflow concentration over time for varying settling velocities in the Delft3D model.

A possibility for the sensitivity towards smaller settling velocities is so high is that this impacts the Richardson number of the basin, and thereby the stratification stability. To check this, The Richardson number is checked for the settling velocity of 0.05 mm/s and 0.45 mm/s. This result is seen in Figure 5.11. The mean Richardson number is tenfold higher in for the case with a lower settling velocity. This is a result of the concentration profile due to differing sediment settling velocities. The area of critical Richardson number is visually higher for the case with a larger settling velocity, leading to a larger area with stable stratification. The comparison is made at the same timestep, however, the filling effects are different for both cases however, as the smaller settling results in a more shallow slope, generating different turbulence profiles and flow profiles. The comparison in Richardson number is therefore also a function of the filling effects.

Concluding, the model is very sensitive to settling velocity. Especially a lower settling velocity results in a very much larger outflow concentration. This is amplified by the effect of stratification, which is more stable for higher settling velocities.

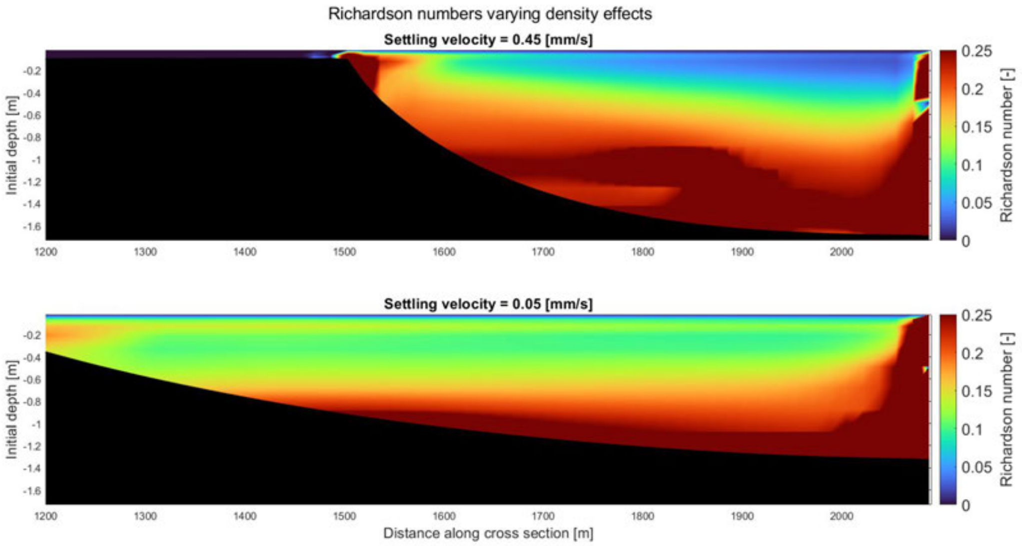


Figure 5.11: Richardson numbers and filling effects in the basin for varying settling velocities. Above: settling velocity = 0.45 $[mm/s]$, and below: settling velocity = 0.05 $[mm/s]$ in the Delft3D model.

5.3.3. WIND VELOCITY

The difference between no wind and wind of 7.5 m/s is quite small on the outflow concentration, as shown in Table 5.10. Figure 5.12 shows the outflow concentration as a result of varying wind velocities. However, when the same change is made by increasing wind velocity, the effect is very significant and concentration skyrockets. The effect hereof is described in Subsection 5.2.2. At a wind speed of 7.5 m/s, it is stratification which dominates the system, causing little increase in sediment outflow concentration. When the wind speed rises to 15 m/s the stable stratification is broken and outflow concentration rises. When the Richardson number in the basin drops below the critical Richardson number, the stratification is broken, and outflow concentration significantly goes op. This is a function of both wind velocity and sediment density. This sediment density is a function of inflow concentration, as shown in Subsection 5.3.5.

Concluding, wind can have a significant effect on sediment outflow concentration. This happens when the critical Richardson number is surpassed in the basin.

Run $[m/s]$	**Change of v to base** [%]	**Mean C** $[kg/m^3]$	**Change of C to base** [%]
v = 7.5 (BASE)	0	5.85	0
v = 0	-100	3.84	-34.36
v = 15	+100	20.91	+257.44

Table 5.10: Mean sediment outflow concentrations for varying wind velocities in the Delft3D model as visualized in Figure 5.12.

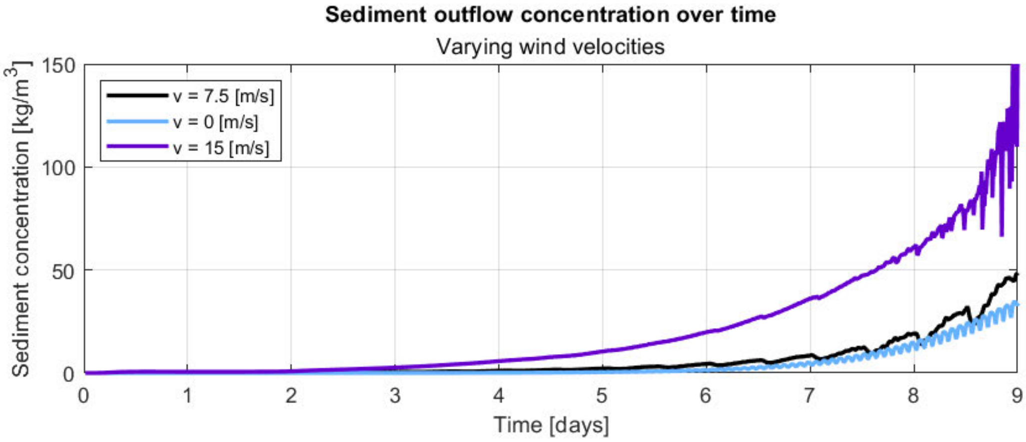


Figure 5.12: Sediment outflow concentration over time for varying wind velocities in the Delft3D model.

5.3.4. WIND DIRECTION

As the quantification in Table 5.11 shows, the difference in sediment outflow concentration as a result of differing wind directions is very small for the parameters used. The effect of varying wind directions on the outflow concentration is shown in Figure 5.13. As concluded in Subsection 5.2.2, the system is strongly stratified as a result of the wind speed and sediment inflow concentrations. Subsection 5.3.3 shows that for a wind speed of 15 m/s this is not the case anymore for the other given parameters. For this case, the same runs are performed, but with a wind velocity of 15 m/s. This should show wind effects. The result of this can be seen in Figure 5.14.

A much larger difference is now seen with a wind direction from 270 deg. Against the conclusion of De Lange et al. (2011), when wind comes from an opposing direction, 90 deg, it does not lead to a significant rise in sediment outflow concentration compared to other wind directions. The opposite conclusion is actually true for this model. The wave coupling interval plays a role in the effects seen. As time goes on from the last coupling interval, the wave field remains the same, and the bathymetry keeps updating. The result is (too) large waves in a very shallow water. When waves are opposing the direction of bathymetry growth, this slows down the front more than in the physical case, where the wave field is smaller. Vise versa, when the wind is in the same direction as bathymetry growth, the (too) large waves cause the bathymetry to move forward more quickly than the case is in a physical correct case.

Concluding, especially a wind direction in the direction of the flow and in the direction of the outflow leads to higher outflow concentrations. However, the wave coupling interval plays a role in this effects as well, where the resulting effects are amplified.

Run (Vel = 7.5 $[m/s]$) $[deg]$	**Mean C** $[kg/m^3]$	**Change of C to base** [%]
Dir = 270 (BASE)	5.85	0
Dir = 0	5.89	+0.68
Dir = 90	5.60	-4.27
Run (Vel = 15 $[m/s]$)		
Dir = 270 (BASE)	20.91	0
Dir = 0	12.19	-41.70
Dir = 90	10.81	-48.30

Table 5.11: Mean sediment outflow concentrations for varying wind directions in the Delft3D model as visualized in Figure 5.13.

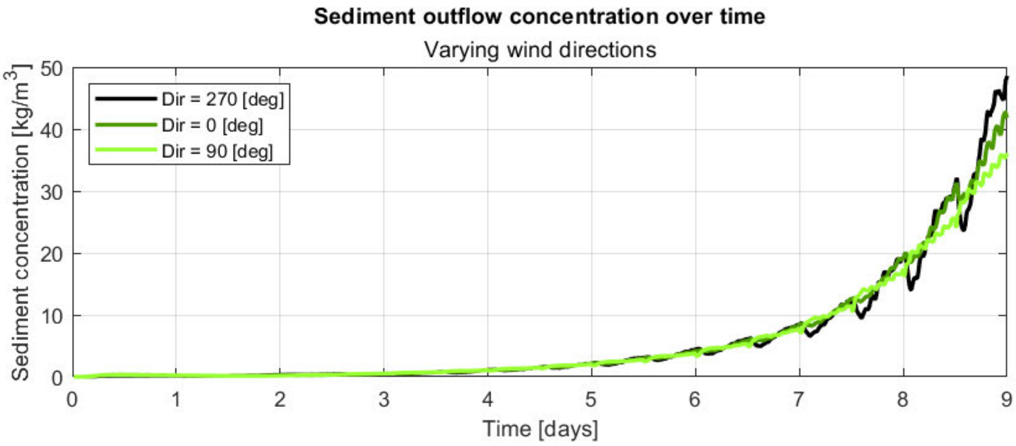


Figure 5.13: Sediment outflow concentration over time for varying wind directions in the Delft3D model, wind velocity = 7.5 m/s

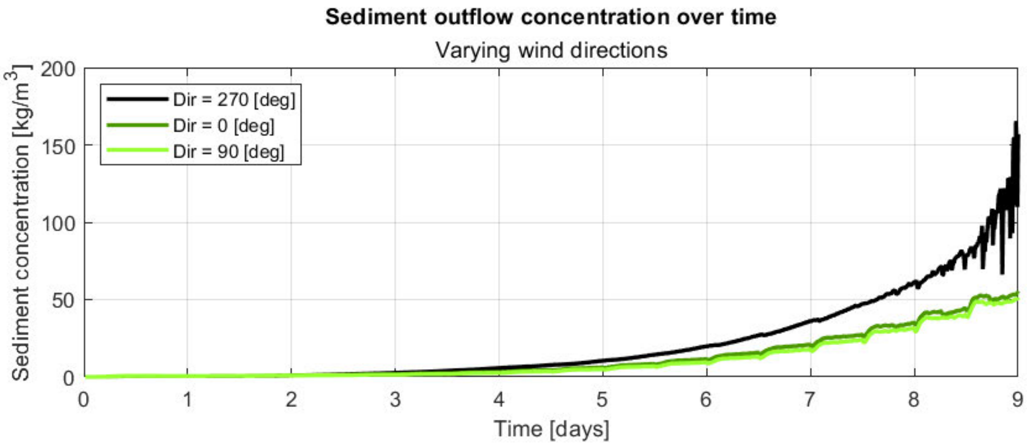


Figure 5.14: Sediment outflow concentration over time for varying wind directions in the Delft3D model, wind velocity = 15 m/s

5.3.5. SEDIMENT FLUX

The mean concentration for the runs changes in the same order of magnitude as the influx as shown in Table 5.12. Figure 5.15 shows the outflow concentration over time with varying sediment influx. The duration of the simulation is not the same. This is because the basin takes longer or shorter to fill depending on the flux. What is striking is that the sediment outflow concentration peak is very much lower with a lower flux. The peak of the outflow concentration is between 20 and 30 % of the initial concentration. The Richardson numbers for the basin as a result of the varying fluxes change quite significantly, as shown in Figure 5.16. The larger the influx is, the more stratified the system is, and as the concentrations become lower, turbulent effects start dominating more.

Concluding, a varying influx can has a significant impact on the sediment outflow concentration. This difference is seen in the final peak concentration. The mean difference is the result of the buildup towards this peak. The Richardson number varies quit significantly for each case, where stratification effects decrease with decreasing influx. This has complications for the conclusions drawn for settling basin design. As this study is performed for a fines storage, or a siltation basin, concentrations are very high. In case of a settling basin, concentrations are very low. In this case, the density effects will be less on the system as shown here.

Run $[kg/s]$	**Change of flux** [%]	**Mean C** $[kg/m^3]$	**Change of mean C** [%]	**Peak C** $[kg/m^3]$	**Change of peak C** [%]
Flux = 900 (BASE)	0	5.85	0	60.74	0
Flux = 300	-33.3	4.50	-23.08	27.29	-55.07
Flux = 100	-88.9	1.29	-77.95	6.63	-89.08

Table 5.12: Mean sediment outflow concentrations for varying sediment influx in the Delft3D model as visualized in Figure 5.15.

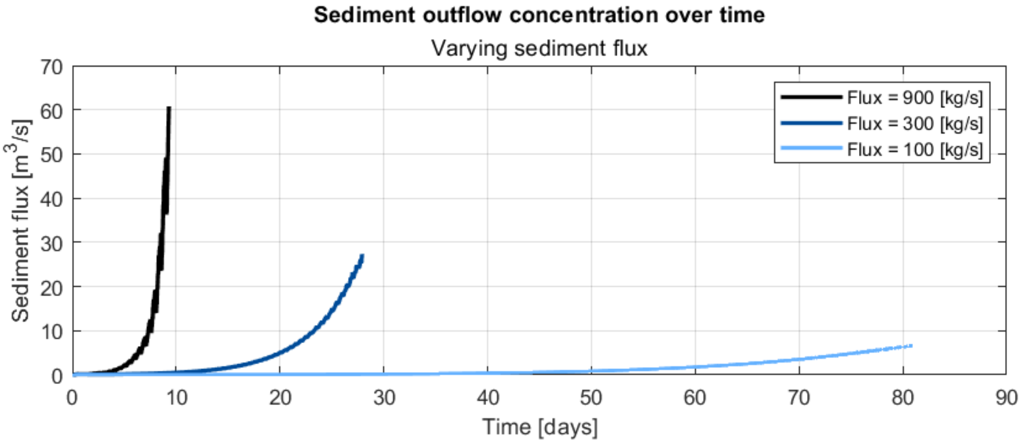


Figure 5.15: Sediment outflow concentration over time for varying sediment influx in the Delft3D model.

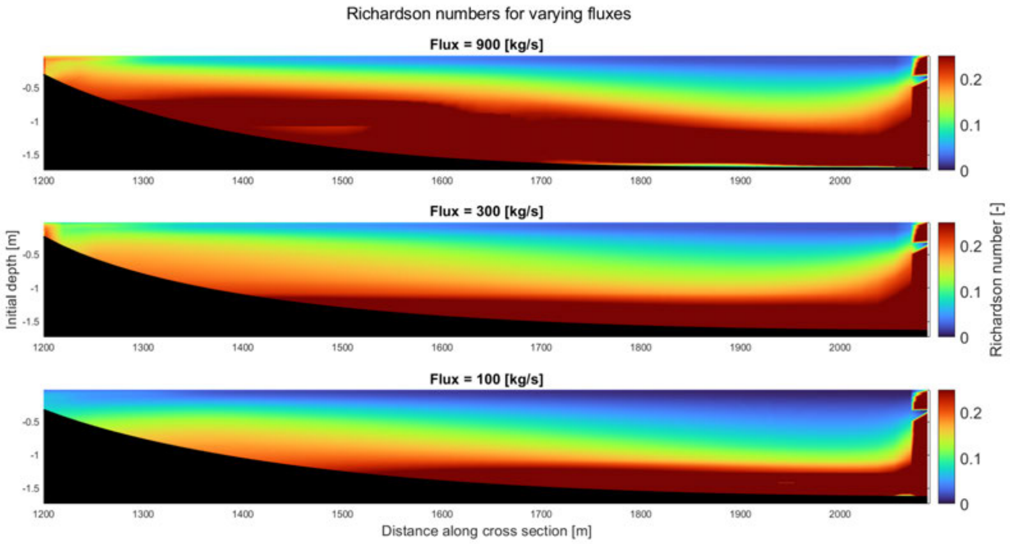


Figure 5.16: Richardson numbers and filling effects in the basin for varying sediment influx. Time steps vary, shown at an equal cumulative sediment influx. Above: flux = 900 kg/s, middle: flux = 300 kg/s, and below: flux = 100 kg/s.

5.4. CONCLUSION AND DISCUSSION

CONCLUSION

A basin is dominated by the balance between buoyancy and turbulence, by the so called Richardson number. When the Richardson number is below the critical Richardson number of 0.25, the basin is well mixed. In this case, the sensitivity of turbulence parameters is very high. When the Richardson number is above the critical Richardson number, the sensitivity of turbulence parameters is very low. It is the parameters which impact the Richardson number the most which are most significant to the basins outflow concentration.

Regarding the sensitivity of processes, it is density effects which are most significant. Without density effects, stratification is not possible, and the basin is always well mixed. The effects of wind shear and wind waves are significant only if a critical wind velocity is reached, by which the critical Richardson number is reached. In that case, the effect of wind shear is very large, and the added effect of wind waves is significant as well. Resuspension is not significant for the base case. However, this base case is stratified, so the effect of resuspension may become significant when the basin is well mixed.

Regarding the sensitivity of parameters, it is the settling velocity which is the most impacting, resulting in a +733% mean change for a -80% in settling velocity. Wind velocity is the next parameter which is most sensitive, as elevating wind velocity above the critical wind velocity dominates stratification effects, increasing sediment outflow concentration. For a +100% increase in wind velocity, a +257% mean increase in sediment outflow concentration is found. In this increase, the critical Richardson number is surpassed. Decreasing wind velocity, keeping it in the range of a stratified system, the results are less impacting. -100% wind velocity gives -34% mean sediment outflow concentration. Sediment flux is impacts the Richardson number as well, on the buoyancy side. A change of -89% reduces stratification, and results in a mean change of -89% sediment outflow concentration. Wind direction can be impacting in case of a wind speed above the critical wind speed -48% for shortest fetch compared to longest fetch. Finally, discharge seems to have very little impact, leading to a +25%

increase of mean sediment outflow concentration over a +50% increase in discharge.

In the end, the sediment outflow concentration comes down to the Richardson number of the basin. When the critical Richardson number is surpassed, turbulent parameters start to impact the sediment outflow concentration in the same way as concluded in Chapter 4, and the basin is dominated by turbulence. When the basin is stratified, the sediment outflow concentration is largely a product of the buoyancy terms. Chapter 4 concludes that the dominating turbulence terms are wind velocity and wind effects. As such, the critical Richardson number is a function of a critical wind velocity. This critical wind velocity depends somewhat on basin dimensions, but mostly on the buoyancy term of the Richardson number. Wind shear stress is independent of basin dimensions, as it units are $[N/m^2]$. However, the wind waves are a result of the fetch, which is a result of basin dimensions.

When designing a mud disposal basin, the sediment settling velocity, the sediment influx, and the wind are the most important factors to consider.

DISCUSSION

The base case of all runs consisted of all processes and parameters included. As processes impacted one another, the impact of certain parameters may be skewed. As Figure 5.3 shows, the difference for varying wind effects is negligible due to the dominating density effects. When wind velocity is raised, these effects are suddenly incredibly important. This may result in resuspension being underestimated, in case where the critical wind velocity is surpassed. Next to that, the effect of sediment flux is quite significant. For this study, a high inflow concentration is used, to match that of a siltation basin, or a fines disposal. The classical settling basins, basins behind a reclamation project, receive influxes which are several magnitudes smaller. Therefor, the results are very specific to the parameters used. As concluded in Subsection 3.2.9, the result of the wave coupling interval is an overestimated sediment outflow concentration. Comparing to runs without the wave module can be overestimated as well.

The runs are performed until the basin was ’full’. This was done by verifying the outflow concentration peak and the bed level. When the bed level almost reached the final cell, the outflow concentration significantly peaked. At this point, the results were manually cut off. This results in human subjectivity to the results.

Analyzing the mean value for the concentration over time may be a primitive way to compare results. This disregards the variation over time; varying insightful values, varying slopes, varying peaks. This potentially gives results which are more insightful than only mean values.

6

COMPARING SETBAS AND 3D MODEL

This chapter addresses the sixth research goal, *Compare the SetBas tool and the model and show the practical implication the conclusions of research goals 4 and 5.* In the approach, the model setup and runs are described. The performance of both models is done via the outflow concentration, as this is the main purpose of these models.

6.1. APPROACH

In this section, the approach to how the model is compared to SetBas is described. The complexity between the model and SetBas varies. The model considers more processes than SetBas. The comparison between both therefor is not always straight forward, and can be comparing apples to oranges. To combat this, the complexity in comparison is built up. First, SetBas and the Delft3D tool are compared as closely as possible with the same processes. Next three scenarios are provided for the both to compare the performance in these cases of interest. The cases of interest are a storm event, a case where bunts are placed within the basin, and finally a case with multiple sediment fractions. These four scenarios are described below in how they physically look, and how they are modeled in both SetBas and the Delft3D model.

The performance of all cases are compared through the sediment outflow concentration. This is because this is the main use of both SetBas and the model. The simulation is divided into three equal parts, and for each part the mean outflow concentration is determined. This is because the outflow concentrations varies greatly for the Delft3D model. First the outflow concentration is very low, as the concentration has not reached the outflow yet. The next phase of three days, the sediment outflow concentration starts rising steadily, where in the last three days, the basin becomes full and outflow concentrations become exceedingly large.

First, the SetBas tool setup is given, as different set ups can give varying results.

6.1.1. SETBAS SET UP

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6.1.2. CASE 1: BASE CASE

In the base case, an as fair as possible comparison is made between both models. Starting with SetBas, the calibrated version is used as described by Monge (2018). This means both the turbulent settling module is used as well as the flocculation model. Of the inflow, 40% of the sediment mass is subject to the flocculation module, and the other 60% is subject to the turbulence settling model. As SetBas does not consider wind effects, the Delft3D model will not consider wind for this run. In Delft3D, a settling velocity is forced upon the model, and flocculation is not used. This is because salinity is assumed constant and flocculation is a function of salinity in Delft3D. The resulting model setup is given in Table 6.1

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 6.1: Model parameters for base case for the Delft3D model for the comparison with SetBas.

6.1.3. CASE 2: STORM EVENT

The next comparison run is a case of a storm. From practice, it is known that storms can have impact on the sediment outflow concentration of a mud disposal basin. SetBas does not consider the turbulence and other sediment transport effects caused by wind. Because of this, the model setup is the same as the base case for SetBas. Because of this, the potential of the Delft3D model is shown.

The storm event which is considered is the storm Eunice, a storm in the Netheralnds in the period 16-

02-2022 until 22-02-2022. The location for the wind data used is Hoek van Holland. For the Delft3D model, the wind velocity and wind direction are used as storm input for the model. The wind velocity over this period can be seen in Figure 6.1. The wind direction for this period can be seen in Figure 6.2. Notice that the duration of this wind file is six days. The duration of the simulation used is nine days, the time which it takes to fill the basin with the chosen sediment flux. Because of this, the wind will be used in the final six days of the simulation. This means that the first three days do not use wind, as the wind velocity is zero for this time. The reason the final part is chosen in stead of the beginning, is because this is the critical stage of the filling process where outflow concentration is highest.

This is input as a wind file over time into Delft3D. To ensure the wave height is up to date with the hourly wind changes, the wave coupling is set to one hour as well, instead of the standard 12 hours for the sediment model set in Chapter 3. The goal for this run is to show the increased usability of the Delft3D model over the SetBas tool which does not consider wind effects.

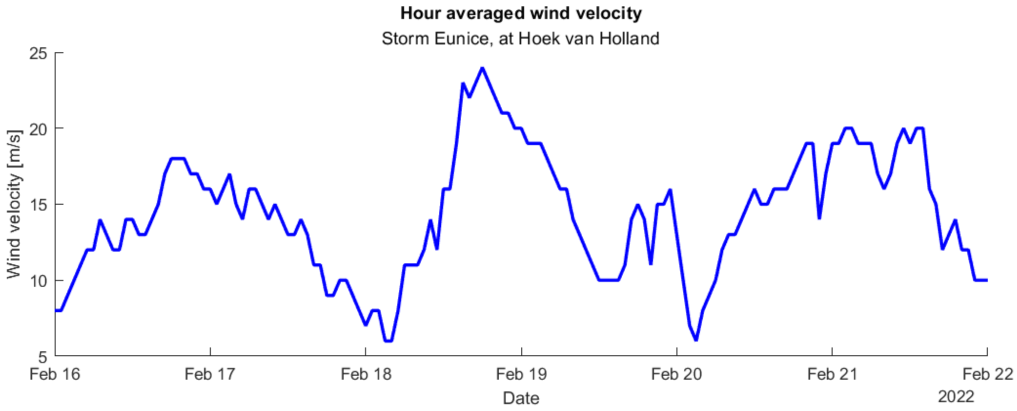


Figure 6.1: Wind velocity for storm Eunice over time from 16-02-22 to 22-02-22.

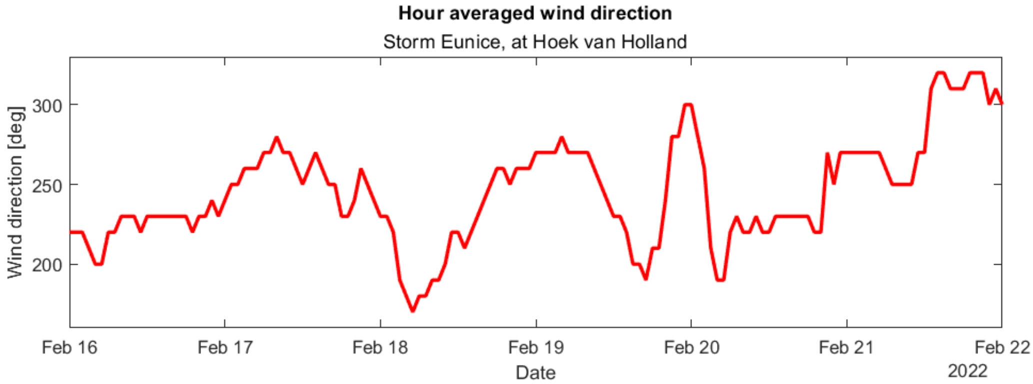


Figure 6.2: Wind direction for storm Eunice from 16-02-22 to 22-02-22.

6.1.4. CASE 3: BUNTS

Bunts in the basin is a measure sometimes taken in practice to enhance the effective settling length. The case which is considered here is shown in Figure 6.3. Bunts can be accounted for in both SetBas and the Delft3D model. SetBas considers this effect by increasing effective settling length (basin length L). As a consequence, the L/B ratio, retention time and hydraulic efficiency factor are altered. Instead of the value of L being determined by a straight line from discharge to outflux, the length is determined by the average flow length, which for this case is 3029 m.

In Delft3D, thin dams can be put into the system. The design of the dikes are shown below in Figure 6.3. For Delft3D, only the discharge and accompanying flux will be considered in the model.

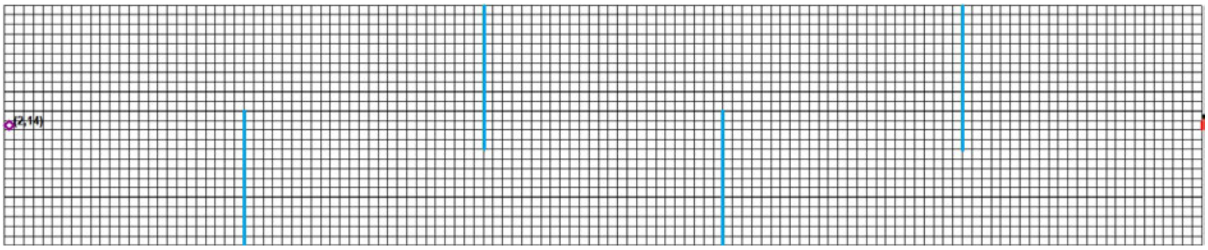


Figure 6.3: Representation of the basin through the Delft3D model grid. The location of the bunts is shown here. They are placed in the exact grid location as shown. For SetBas, the length of the average flow path as a result of the bunts is calculated.

6.1.5. CASE 4: MULTIPLE SEDIMENT FRACTIONS

In practice, multiples sediment fractions are always used, as sediment is never uniform. This effect is considered for this run. As the Delft3D model and the SetBas model consider the single component settling basin or siltation basin, the sediment fractions considered are all fine sediments.

Both models are able to consider multiple sediment fractions as influx. In Chapter 5, the sediment fractions used in the sensitivity matched with a settling velocity of 0.05, 0.15, 0.25 (base), 0.35 and 0.45 mm/s. For this case, the sediment fractions of 0.05, 0.25 and 0.45 mm/s are chosen. The settling velocities and accompanying diameters are shown in Table 6.2. Each contribution of each sediment fraction is considered equal by weight. To keep the same inflow concentration, each fraction has a concentration of 100 kg/m^3, for a total of 300 kg/m^3.

Diameter *[μm]*	**Settling velocity** *[mm/s]*
7.8	0.05
17.5	0.25
23.6	0.45

Table 6.2: Sediment fractions used for the comparison of sediment fractions in both models

6.2. RESULTS

This section shows the results of the comparison between SetBas and the Delft3D model.

6.2.1. CASE 1: BASE CASE

The total outflow concentration for both models for the base case is shown in Figure 6.4. It shows an outflow concentration which is very much higher for Delft3D than for SetBas. Because of the very large concentrations towards the end of the simulation, the values in the beginning of the simulation for Delft3D and the values for the total simulation time for SetBas are difficult to see. To solve this, Figure 6.5 shows the outflow concentration of both models in the first four days, where this time SetBas has a higher outflow concentration than Delft3D. Table 6.3 quantifies the results of the outflow concentrations divided into three parts. The first three days, the middle three days and the final three days.

Next to the outflow concentration being very much higher for Delft3D then for SetBas, qualitatively it makes sense that the Delft3D outflow concentration starts lower than SetBas, as the 3D effects of the flow in the basin is considered. The constant value of SetBas therefor is likely not to happen in reality from filling the basin from empty until full.

Concluding, the quality of both lines is logical, considering the model types. The quantity of the sediment outflow concentration is very large compared to SetBas in the middle third and the final third of the simulation.

Run	Mean c days 0 - 3 $[kg/m^3]$	Mean c 4 - 6 $[kg/m^3]$	Mean c 7 - 9 $[kg/m^3]$
SetBas	0.077	0.077	0.077
Delft3D	0.0099	0.7509	33.43
Difference to SetBas	- 87%	+ 875%	+ 43 316%

Table 6.3: Mean sediment outflow concentrations for the comparison with the Delft3D model and SetBas for the case 'base' as visualized in Figure 6.4.

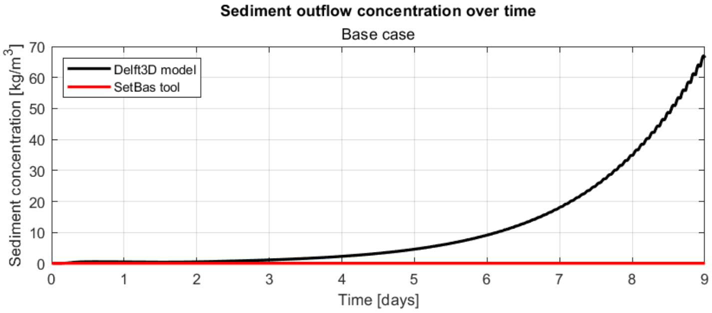


Figure 6.4: Sediment outflow concentration total simulation duration for base case comparison between the Delft3D model and SetBas.

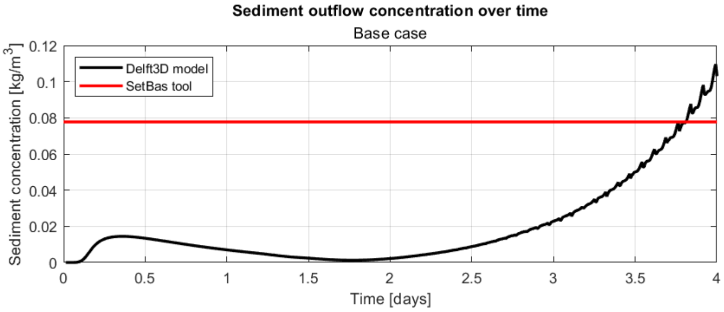


Figure 6.5: Sediment outflow concentration first four days of simulation base case comparison between the Delft3D model and SetBas.

6.2.2. CASE 2: STORM EVENT

The results of the run for the storm event are seen in Figure 6.6 in the form of the outflow concentration over time. This is quantified again in thirds, in Table 6.4. The same trend as in the base case is observed, that the outflow concentration of the Delft3D model is very large compared to the SetBas outflow.

The storm starts after four days, so the results of the comparison are exactly the same as the base case in the first third. It stands out that the storm event causes very large peaks in sediment outflow concentration. The three wind peaks which are observed in Figure 6.1 can be identified in the outflow concentration as well. The quantity of the outflow concentration in the last third, when the basin starts to reach a full state and the wind is very strong, is very large, 84 316% of the SetBas outflow concentration.

Concluding, the Delft3D model shows significant outflow concentration rises in the case of a storm, where wind velocity is high. This is something which cannot be modeled in SetBas. As a result, the sediment outflow concentrations are very much larger for Delft3D then for SetBas.

Run	Mean c days 0 - 3 $[kg/m^3]$	Mean c 4 - 6 $[kg/m^3]$	Mean c 7 - 9 $[kg/m^3]$
SetBas	0.077	0.077	0.077
Delft3D	0.0099	9.06	65
Difference to SetBas	- 87%	+ 11 666%	+ 84 316%

Table 6.4: Mean sediment outflow concentrations for the comparison with the Delft3D model and SetBas for the case 'storm' as visualized in Figure 6.6.

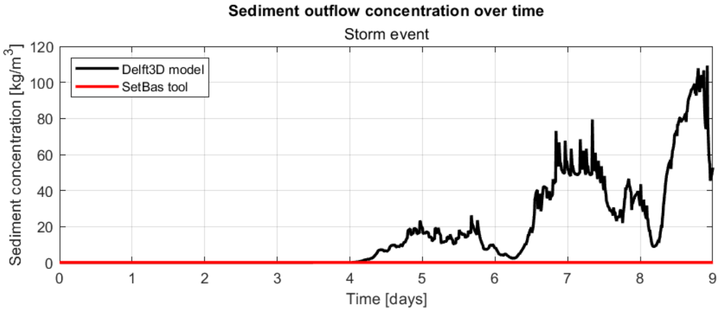


Figure 6.6: Sediment outflow concentration total simulation duration for storm case comparison between the Delft3D model and SetBas.

6.2.3. CASE 3: BUNTS

This section shows the results of the comparison case for bunts. Figure 6.7 shows the outflow concentrations over time for both models. Compared to the base case, the sediment outflow concentration of the Delft3D model rises slower. This is due to the effectiveness of the bunts. As a result of the bunts, the sediment outflow concentration of the Delft3D model remains lower then the SetBas model for longer, for the first 4.5 days. This can be observed in Figure 6.8.

Concluding, this case shows the same general behavior has the other cases. Initially the sediment outflow concentration of the Delft3D model starts lower. After a few days, it overtakes the constant SetBas outflow concentration, where in the last third it dwarfs the SetBas outflow concentration by several ten-thousand percent.

Run	Mean c days 0 - 3 $[kg/m^3]$	Mean c 4 - 6 $[kg/m^3]$	Mean c 7 - 9 $[kg/m^3]$
SetBas	0.0678	0.0678	0.0678
Delft3D	0.0010	0.3970	23.24
Difference to SetBas	- 99%	+ 486%	+ 34 177%

Table 6.5: Mean sediment outflow concentrations for the comparison with the Delft3D model and SetBas for the case 'bunts' as visualized in Figure 6.7.

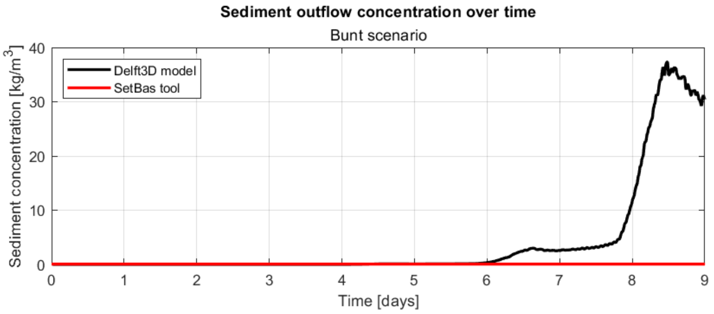


Figure 6.7: Sediment outflow concentration total simulation duration for bunt case comparison between the Delft3D model and SetBas.

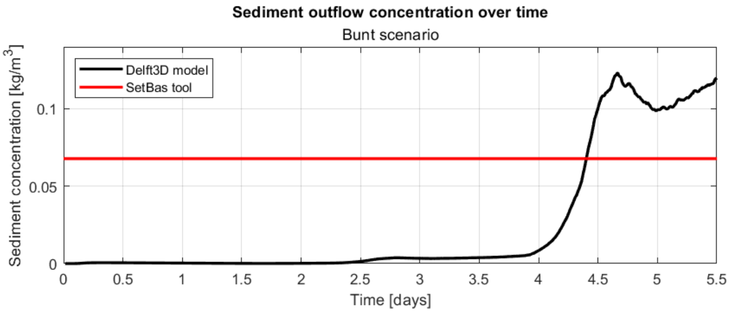


Figure 6.8: Sediment outflow concentration first five and a half days of simulation bunt case comparison between the Delft3D model and SetBas.

6.2.4. CASE 4: MULTIPLE SEDIMENT FRACTIONS

The final comparison run is shown below. In this run, multiple sediment fractions are input into both models. Qualitatively this shows a very different behavior to the other runs. Figure 6.9 shows the outflow concentrations for both models over time. The Delft3D model shows a visible increase in sediment outflow concentration right in the beginning. SetBas does not show a constant outflow concentration over time for this case. This is a result of the smallest sediment fraction, that with a settling velocity of 0.05 mm/s and a diameter of 7.8 μm. For SetBas, this is the only fraction which is not fully trapped by the turbulent settling model. For Delft3D the first third of the outflow concentration is almost fully caused by this sediment fraction.

As the sediment fractions become smaller, the difference between Delft3D and SetBas becomes more apparent, as the values for Delft3D are now significantly higher for each of the thirds; +18 374%, +33 473% and +100 860% respectively. This effect can be explained by the fact that flocculation is not considered in Delft3D, and this very small sediment fraction usually fully flocculates in saline water, leading to settling concentrations which are always higher than 0.05 mm/s. This effect can be strengthened by the fact that SetBas does not allow turbulence to ’affect’ the flocculated sediment, which leads to a flocculation trapping efficiency which is too large.

Concluding, both SetBas and the Delft3D model start to show very large differences the smaller sediment fractions become. The same pattern however still holds, that differences become increasingly larger over time.

Run	Mean c days 0 - 3 $[kg/m^3]$	Mean c 4 - 6 $[kg/m^3]$	Mean c 7 - 9 $[kg/m^3]$
SetBas	0.078	0.0792	0.08
Delft3D	14.41	26.59	79.96
Difference to SetBas	+ 18 374%	+ 33 473 %	+ 100 860%

Table 6.6: Mean sediment outflow concentrations for the comparison with the Delft3D model and SetBas for the case ’sediment fractions’ as visualized in Figure 6.9.

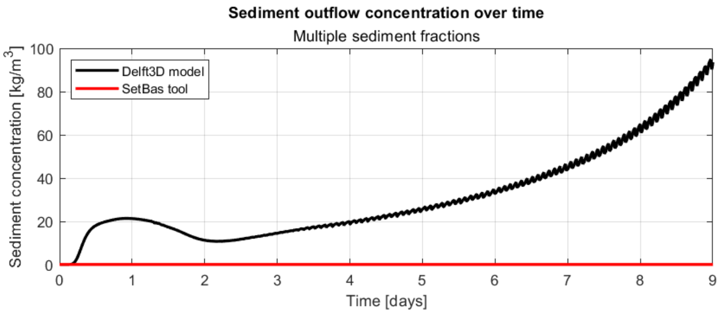


Figure 6.9: Sediment outflow concentration total simulation duration for multiple sediment fractions case comparison between the Delft3D model and SetBas.

6.3. CONCLUSION AND DISCUSSION

Concluding on this chapter, the difference in sediment outflow concentration between SetBas and the Delft3D model is very large, in the order of ten-thousand percent. Qualitatively, the difference usually follows the same pattern; In the initial third of the simulation time, Delft3D shows a lower sediment outflow concentration then SetBas, where it rises above the (near) constant SetBas levels in the second third, and finally dwarfs the SetBas outflow concentration in the final third, in which the basin is almost filled.

The difference between SetBas and Delft3D are very large. Although qualitatively Delft3D follows a concentration profile over time which is more logical with the real world, SetBas has been validated to be correct in the order of magnitude to real world results. In some cases, the large difference can be explained by the fact that wind effects considered in Delft3D cannot be considered in SetBas. On the other hand, the base case, in which both the same processes are used, the differences are very large as well. SetBas has been designed to use as a settling basin, where inflow concentrations are very low. The Delft3D model however, is set up as a siltation basin, where inflow concentrations are very high. SetBas has also been validated in a settling basin setting. This can effect SetBas performance for this case, where inflow concentrations are very much higher than for a settling basin. Next to that, the Delft3D model is not validated at all, so the value of the results cannot be proved.

7

DISCUSSION

In this chapter, the results of this thesis are discussed. In Chapter 3 the model setup is given. In the same chapter, a verification section is given on the model. Due to this, a discussion on the model setup will not be given. The discussion on the model results of Chapter 4, Chapter 5 and Chapter 6 is given in separate sections below.

7.1. BASIN HYDRODYNAMICS

Results from the modeling study described in Section 4.2 and Section 4.3 show that the turbulence profile of a basin is hardly affected by the discharge. However, even for small wind velocities (7.5 [m/s]), the mean turbulent quantity is 4 orders of magnitude larger compared to the effect of the discharge. This is important as it shows that the assumption made in SetBas to only use discharge for the turbulence quantity is incorrect. Previous studies on settling basins have confirmed that wind was a significant parameter in basin design. However, it was never explicitly found to effect the turbulence in this way.

The analysis on the turbulence profiles is taken in the middle of the basin. This was chosen for two reasons. First, as Delft3D is a far field model the near field effects of the model are not accurate (Deltares, 2021). Therefore, even though the theoretical near field effects of the discharge should show larger turbulence quantities, it is chosen not to use these for this reason. Another reason to choose for this solution is the variation of turbulent intensity over the basin for wind effects. Wind shear shows an equal distribution over the basin, so this would not matter. However, wind waves are a function of fetch. To cancel out the effects of opposing wind directions, the middle of the basin is used as fetch would be the same for opposing wind directions. A drawback of this method is overlooking local effects, especially close to the outflow of the basin. For future research it is suggested to validate this choice.

7.2. MUD DISPOSAL BASINS: SEDIMENT OUTFLOW CONCENTRATIONS

Further results from the modeling study show that mean sediment outflow concentrations from the basin are sensitive to density effects. This finding is confirmed by Veenman (2020), and is a result of 3D modeling. This is an important result, because density effects influence turbulent processes. This influence of density effects is seen for wind effects especially. The finding that density effects have an influence is important, as it shows that SetBas falls short. Density effects can only be analyzed in a 3D environment, which is not possible in SetBas.

The results show that wind above a certain wind speed is an important parameter when it comes to sediment outflow concentrations. Both the shear stress of the wind and wind waves then have a strong effect on the outflow concentration. For a wind speed of 7.5 m/s these wind effects turned out to be small, but for a wind speed of 15 m/s the effects on the outflow concentration were very large.

Looking at the literature, De Lange et al. (2011) concludes that wind shear stress for all wind speeds is an important parameter for basin design. Wind waves were not included in this study. Veenman (2020) gives a similar conclusion to this report. Veenman (2020) concludes that wind shear stress above a wind speed of 10 [m/s] is significant on the outflow concentration, and for wind speeds below that the effect is negligible. However, Veenman (2020) does not take into account the effect of wind waves. This difference in the conclusions of De Lange et al. (2011) and this report, and the agreement of findings between Veenman (2020) and this report could lie in including density effects. De Lange et al. (2011) works without density effects and Veenman (2020) does. The Richardson number shows that this may be due to stratification being broken above a certain threshold value of wind. It is striking that Veenman (2020) concludes that the threshold value for wind lies within the range of the threshold values given in this report. The basin Veenman (2020) uses is ten times smaller and has an influx twenty times lower than the basin used in this report. The finding that wind waves have an important influence on sediment outflow concentration from mud disposal basins has not yet been found in the literature. This is therefore a significant finding.

In the current version of SetBas, only turbulence from the discharge is included on the turbulent quantity. However, these findings show how important wind effects are not only for the turbulent quantity (Chapter 4), but also for the outflow concentration of the basin as a whole, and thus is an indispensable parameter in basin design.

It appears from the results of Figure 5.6 that resuspension effects are negligible. However, the run for resuspension was performed with a wind speed of 7.5 m/s. For other wind effects, this wind speed appeared to have little influence on the outflow concentration. This could possibly be a reason for the small effect of resuspension. Research into resuspension effects at higher wind speed is therefore recommended. No research on resuspension effects in mud disposal basins has been found that could reinforce or contradict this finding.

The sensitivity test in Section 5.3 shows that mean sediment outflow concentration is most sensitive to the sediment settling velocity. This finding is confirmed by both Veenman (2020) and De Lange et al. (2011). That all studies confirm this gives confidence in the results.

Furthermore, the sensitivity analysis shows that the effect of a flow rate has almost no influence on the outflow concentration. However, the sensitivity of the outflow concentration as a result of a changed sediment influx is high. This is an interesting finding, as De Lange et al. (2011) concludes that a change in flow rate and flux leads to an increased outflow concentration. The finding that the influence on the outflow concentration is due to the flux and not the flow is a new finding. This finding also has an impact on the wider application of the conclusions of this study. Since the influx parameter has a high sensitivity to the outflow concentration, the conclusions drawn for high influxes do not apply directly to low influxes. The parameter sensitivities and their application to a mud disposal basin (the application of this study) and the application to a settlement basin may therefore be different.

7.3. COMPARING SETBAS AND 3D MODEL

The results of comparing SetBas and the model are striking. This is because the difference in outflow concentrations between the two models is very large. The largest differences are found in a case with multiple sediment fractions and a storm case. This is something which is expected from the modeling study, as mean sediment outflow concentration is very sensitive to both parameters. The unexpected result is the base case. Here a situation with only flow rate is used in the Delft3D model, which should therefore give similar results as the SetBas results, since this also only uses turbulence of the flow rate. For this case however, the mean difference in sediment outflow concentration is 150 times larger. This difference is mainly caused by the final filling stage of the basin, where the mean sediment outflow concentration in the final three days is 440 times larger than that of SetBas. The large differences can potentially be explained by two factors. These are 3D effects and the way SetBas uses a free board.

SetBas is non dimensional, and gives a trapping efficiency for each time step as a result of the magnitude of the flow velocity for sediment in the turbulence model. For sediment in the flocculation model, a trapping efficiency is determined by the mean retention time in combination with the settling velocity. To reduce the numerical effects of the flow velocity approaching infinity when the basin is near full, a free board is introduced of 0.5 m. As a result, the flow velocities in the basin are always quite low, and the mean retention time is quite high, even when the basin is near full. This results in a trapping efficiency for both the turbulence model and the flocculation model which are quite high. This results in a low sediment outflow concentration over time. The fuller the basin becomes, the more the effect becomes apparent. This lead to a (near) constant sediment outflow concentration over time. In the Delft3D model, the minimal depth for sediment calculations is 0.1 m. This means a smaller free board. Also, the basin does not fill uniformly because the model is 3D. The effects of this compared to a basin which fills uniformly is an outflow concentration which is lower to start with, as all sediment is far away from the outflow. When the basin is near full, there is a lot of sediment close to the outflow, and outflow concentrations are very large. Overestimation of the outflow concentration of the Delft3D model also lies in the coupling frequency of the WAVE module, as discussed in Subsection 3.2.9.

However, comparing the models is like comparing apples and oranges. SetBas, despite being applicable to the three basin applications, has been validated for a purely settling basin application. The Delft3D model has been developed as a mud disposal area, partly due to cost determinations. The Delft3D model has not been validated, either for a settlement basin application or a mud disposal area application. For this reason, it is plausible that both models contain a margin of error. It is recommended to validate both models for a mud disposal area application, and to validate Delft3D for a settling basin application. This ensures that both models can be compared equally.

8

CONCLUSION AND RECOMMENDATIONS

8.1. CONCLUSION

The purpose of this research is described as: *"The aim of this study is to provide a better understanding on the potential improvements on the current design tool 'SetBas' used to evaluate settling/siltation basins at Boskalis".*

The different mechanisms for basin design are explored by literature and then numerical modeling. From literature, the important processes for settling basin design are identified. Processes which turn out to be important for basin design is wind shear stress and density effects. The importance of the wind shear stress parameter has been known for some time, and has been described in many researches. The importance of density effects has only recently come to light in a 3D numerical modeling study. Wind induced waves, and resuspension as a result of waves are not considered in the literature found.

Numerical modeling shows that density effects, wind effects (both wind shear and wind induced waves), sediment settling velocity and sediment influx are the most sensitive parameters for basin outflow concentration. The interplay between density effects and wind effects also seems to be very important. Below a certain threshold value of wind speed (7.5 m/s for the given model set up), the effect of wind shear stress and wind waves is small. From a higher wind speed (15 m/s for the given model set up), the influence of wind speed becomes large.

When comparing the numerical model to SetBas, there are major differences between sediment outflow concentrations, where the numerical model has higher mean outflow concentrations. The outflow concentration over time of SetBas appears to be constant, where the outflow concentration of the numerical model is exponential. This is because the numerical model is 3D, and SetBas is non-dimensional. The filling behavior is therefore different, leading to the difference in outflux over time.

The comparison between the numerical model and SetBas was made in four different scenarios. These are a base scenario, a storm (high wind) scenario, a basin bunt scenario, and a multiple sediment fraction scenario. Given that wind creates a high degree of turbulence, bunts emphasize the dimensional effect, and both models are very sensitive to sediment fall rate, the difference in the last three scenarios makes sense. However, the big difference in the basic comparison is striking. The numerical model with density effects and a discharge is compared with the SetBas model, which also only has a discharge. However, the difference in sediment outflow concentration between the two cases is on average 140 times higher in sediment outflow concentration for the numerical model. There are a number of hypotheses about the cause of this large difference between the models. These are the following:

1. SetBas underestimates the turbulent magnitude of the discharge in a large basin, making the trapping efficiency equal to 1. the result is that the only outflow still comes from the flocculation module. The flocculation module is not subject to turbulence. The trapped mass of the flocculation module is only a function of the half-life of the sediment concentration due to the specified sediment settling velocity. This actually gives an outflow concentration where turbulence is not included, which represents a very efficient basin.
2. SetBas uses a free board of 0.5 m in the water column. This ensures that the average flow rate, and thus the turbulent quantity, never becomes very high. This could potentially underestimate the trapping efficiency of the turbulence module.
3. The wave module of the numerical model has a coupling frequency of 720 [min] with the flow module. Subsection 3.2.9 indicates that there is an overestimation of the outflow concentration in case waves of more than 20 % are used.

Ultimately, the cause of the large difference is uncertain. Both models are now difficult to compare because they are based on completely different mathematical models. In addition, SetBas has been validated for a settling basin application, where the sediment influx is low. SetBas has also been validated for a small basin. The numerical model that has been developed has the application of a mud disposal area. This means that a sediment influx is taking place. In addition, the basin used in the numerical model is significantly larger than the basin used in SetBas. SetBas itself has not been validated for either case. The numerical model itself has not been validated either. In the further development towards a development tool for settlement basins or mud disposal areas, this is an important place to start. In this way insight can be gained into the causes of the large difference between the two models.

Besides the difference between the models in the base case, it is noticeable that the effect of wind shear stress, wind waves and density effects cannot be ignored in basin design. These three dimensional processes strongly influence the sediment outflow concentration of the numerical model, where there is no difference between the outflow concentrations of SetBas.

Concluding, this study gives insight into the potential improvements of SetBas. This improvement is first and foremost in the set-up of SetBas. The underlying mathematical models are oversimplified. Mathematical models that can include and consider multidimensional effects of sediment transport, wind shear stress, wind waves and density effects are the largest potential improvements of the tool.

8.2. RECOMMENDATIONS

This section contains the recommendations which follow from this research. The recommendations are a combination of recommendations for a basin design tool and recommendations for future research.

A number of steps still need to be taken for a design tool that can be used for settling basins and mud disposal areas. SetBas is a simplified model in which several sediment transport process are not included. Most importantly, include density effects and wind effects in an improved version of the tool. To do this, a 3D model must be used.

A logical approach would be to further develop the Delft3D model of this research into a design tool. However, there are still a few steps to take. First of all, a validation of the model is required. More ideally, this validation takes place in two scenarios. Firstly in the design of a mud disposal area, and secondly in the design of a settling basin. This will provide insight into whether the results hold true. In a validation it is interesting to measure the presence of density effects. Density effects mainly manifest themselves in a concentration peak above the bottom, which propagates at a higher velocity than the mean flow velocity. These can be measured with an ADCP, whereby there should be a higher speed above the bottom than in the top half of the water column. It is also interesting to validate the Rouse profile of the model. The Rouse profile also shows density effects due to increased concentration near the bottom. Further validation could take place on the effects of wind. When the wind is measured and compared with the sediment outflow concentration, there should be a positive relationship between wind speed and sediment outflow concentration. It is also recommended to validate the functioning of the weir box in the numerical model. The weir box function as it is used in practice is difficult to model in Delft3D. It could be measured whether the gate has the desired effect on the sediment concentrations around and in the weir box.

The most important thing about the validation is to qualify the difference between SetBas and the Delft3D model. As mentioned, SetBas is validated for a settling basin application, i.e. low influx in a small basin. The calibration parameters have shown that SetBas is order of magnitude correct with reality. However, the application as a mud disposal area has not been validated by SetBas, although it can be used for that purpose. The huge difference between the two models could thus be quantified by validating them and looking at the differences. This also provides a basis on which to build on for further development of a design tool.

To further convert the model into a design tool, the computation time must be considered. Currently, the run time for one day in the simulation is about eight minutes. When a project will continue for weeks or months, the run time will amount to several hours. This is not wanted for a design tool. Potential improvements for this lie in making the horizontal grid less refined, and increasing the time step at which the results remain good. It should also be looked at how an automatic model initiation can be made. Setting up a model in Delft3D is too time-consuming to do this every time in the context of a design tool.

With regard to knowledge development regarding settlement basins and mud disposal areas, the following matters need to be further investigated. The most important follow-up research lies in the behavior of stratification of basins. The results of this research and the results of Veenman (2020) (the first and only 3D studies on this type of basins) show that density effects play a major role in the behavior of settling basins and mud disposal areas. In combination with turbulence, it seems that sometimes turbulence has the upper hand and is enormously dominant in outflow concentration. On the other hand, somewhat lower levels of turbulence, which were found to be significant in Chapter 4, appear to have little influence on the sediment outflow concentration in Chapter 5. The interplay between these density effects and wind effects needs to be further investigated. It is especially important to find out the threshold value of the wind speed at which wind effects will play a major role. As also indicated in the discussion, this value seems to be in the same neighborhood for several parameters. If this is the case, general measures can be taken for basin projects around the world in the event that the wind velocity exceeds this threshold value. The effect of resuspension is related to this. This did not seem important for the sediment outflow concentration for the current run and the associated parameters. It is possible that resuspension will become important for wind speeds above the threshold value, which is between 7.5 and 15 m/s.

Something which can be further investigated are variable discharge conditions. In the numerical model, a constant discharge was considered. In practice, this often happens in intervals, where a ship has to alternate between dredging and unloading. The effect of this has not been studied before but may be interesting.

The effect of depth was not included in this study. The importance of depth as a design parameter has been debated in the literature, and this is something that could be further explored. However, it is difficult to compare this with practice. There one often starts with an empty basin, and continues to increase it until the desired storage is reached. The actual water depth is then not equal to the final siltation depth.

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