On the behaviour of fine sediment in settling basins

Improving the understanding and prediction of return water quality assessments by a comparative modelling study

T.F.J. (Tjerk) Veenman

Delft University of Technology

TU Delft

Van Oord
Marine ingenuity

On the behaviour of fine sediment in settling basins

Improving the understanding and prediction of return water quality assessments by a comparative modelling study

by

T.F.J. (Tjerk) Veenman

in partial fulfilment for the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday August 28, 2020 at 09:30 AM.

Student number:	4270614	
Project duration:	May 1, 2019 – August 28, 2020	
Thesis committee:	Prof. dr. ir. M. van Koningsveld,	TU Delft | Van Oord DMC (chair)
	Prof. dr. ir. Z. B. Wang,	TU Delft
	Dr. ir. B. van Prooijen,	TU Delft
	Dr. J. de Vries,	Van Oord DMC

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.

Summary

Dredging is required to construct and maintain marine infrastructure like ports and waterways or to reclaim land. Dredging projects are executed in the marine environment where sensitive organisms as coral, sea grass and other underwater life may be present. Therefore, environmental legislation is in place to prevent any negative impact on the environment. Dredged material is either dumped offshore or used in reclamation (or dumped on land). Dumping directly into open water could cause turbidity; turbidity blocks sunlight and buries organisms. Therefore turbidity harms underwater life. Instead, settling basins are used to trap fine sediment and prevent increased levels of turbidity by high concentrations of fine sediment.

In the tender phase the first design of a settling basin is made. The design is often bound by the available space on the project site. At Van Oord, the performance of the settling basin (measured by the outflow concentration of suspended sediment) is estimated by an in-house developed model, the Return Water Quality (RWQ) model. The RWQ model verifies the compliance with imposed environmental legislation when using a settling basin.

In the development of the RWQ model, assumptions have been made to simplify the model. The main assumptions are width uniform conditions and neglecting the effect of density differences. Although the model seems to perform within the range of reference projects, there are questions on the validity of the assumptions of the model. This research arises from the need for a straight-forward but robust method to evaluate the effectiveness of a settling basin design in meeting outflow criteria, based on a solid process understanding. A (comparative) modelling study is used to increase process understanding and evaluate the performance of the current approach. The models used are the RWQ model and Delft3D. The **objective of this study** is:

> To **establish and (where necessary and possible) improve** the current method for assessment of outflow concentrations of settling basins (on dredging and reclamation works), while **balancing increased levels of detail with practicability** during the tender stage of projects.

The RWQ model is a 2DV model which calculates water motion and sediment dispersion in a settling basin. The model neglects the influence of density differences and assumes an average profile (2DV) to be representative for the full width. Delft3D is a 3D, numerical modelling program made by Deltares. Delft3D is larger applicable than only settling basin (e.g. coastal morphology modelling). The program requires more input than the RWQ model, but is also capable of implementing more processes.

With Delft3D and the RWQ model four scenarios are modelled to research the validity and the effect of the ”width uniform conditions”-assumption, density differences and wind. In addition a sensitivity analysis is performed. In the results the focus lies on the dispersion of sediment through the basin, the flow pattern and the outflow concentration.

The comparative modelling study shows the estimation of outflow concentration is in the same order of magnitude for both models. However, for cases with low settling velocities the results diverge more. The study shows the main assumptions (width uniform conditions and neglecting density differences) are not valid. The model simulations with Delft3D show density driven currents are the main transport mechanism for sediment concentration and the sediment is spread through the whole basin. Density differences damp the mixing induced by wind. However, despite the different processes, outflow values are similar. A more detailed conclusion per scenario:

- **Width uniform conditions:** Both sediment dispersion and flow pattern are not width uniform for a case without density differences. The variability over the width (in sediment concentration and flow pattern) is too large.
- **Density differences:** Density driven transport causes sediment to spread through the whole basin and is therefore an important transport mechanism that should not be neglected. Due to the spread throughout the basin, the 2DV assumption of the RWQ model is valid. Further, the density dampens the mixing over the water column.

- **Wind effects:** Wind induces more mixing and secondary flow throughout the basin. Different than the RWQ model concluded, only the mixing increases the outflow concentration.
- **Combined wind and density effects:** Density driven currents reduce mixing, wind increase mixing. When combining both effects, density effects suppress the mixing by wind until 10 m/s. When the wind gains in strength, the additional mixing due to wind is stronger than the effect of density differences. This is confirmed with the Ri number in basin.
- **Sensitivity analysis:** The outflow concentration as estimated by the Delft3D model is most sensitive to the settling velocity of the sediment (grain size distribution) and the wind velocity (strength). The model is less sensitive for wind direction, mean inflow concentration of the sediment, width/length (W/L) ratio and depth.

In the next part of the research a relation between filling a basin, particle size of sediment and outflow concentration is researched. The settling velocity is assumed to be governing. Other sediment parameters are chosen representatively. Wind is assumed not to have influence on the development of the bathymetry.

Different filling behaviour is observed, dependent on the particle size (settling velocity). The sediment will directly settle and form a hump, growing form inflow towards the outflow (coarse sediment) or sediment will disperse through the full basin resulting in more uniform settling (fine sediment). Between these two extremes, there are more intermediate forms of settling.

The trends in the outflow concentration can be divided into three stages. During the first stage the water in the basin gets saturated with mixture and the outflow concentration increases. In the second stage the basin is fully saturated and the bathymetry changes, here the outflow concentration stays constant. The third stage starts when the outflow concentration starts to increase. The basin is near filled (70-80 %) which reduces the performance of the basin (higher outflow concentration). The basin should be emptied. The time per stage is dependent on the particle size; coarser material causes shorter times per stage.

The RWQ model is incorrect from a physical/theoretical point of view, but from a practical point of view the same (order of magnitude) outflow concentration is estimated as with Delft3D. By assuming uniform sediment concentrations over the width of the basin, one of the most important effects of density differences is (unintentionally) implemented. This research shows that individually these assumptions are incorrect (width-uniform conditions and neglecting density differences), but combined the result is approximately equal (as is done in the RWQ model). With rules of thumb on the input parameters; the settling velocity (min= $2.5x10^{-5}$ m/s), dimensions (use basin dimensions instead of expected flow pattern) and wind (most critical direction), the reliability of the RWQ model is increased. For difficult or uncertain cases the assessment could be extended by a Delft3D model. However, this would require more input and will possibly compromise the increased reliability when input needs to be estimated. For a future version of the RWQ model, it is recommended to implement the effect of density differences.

When evaluating the overall assessment, its is advised to optimize the design in terms of overall costs instead of only minimizing the outflow concentration. The costs of equipment are often an order of magnitude higher than mitigating measures like adding coagulants (as for example the Grensmaas project). It could therefore be more efficient to use inefficient (but effective!) mitigating measures to comply with environmental legislation, while maximizing the dredger its efficiency.

Measurements could be used to improve the assessment. During the tender phase often not much information is available and contains therefore many uncertainties on sediment properties, weather conditions and estimated production. In this phase the assessment could be improved by more accurate measurements on settling velocity and wind conditions. During execution of the project, measurements on the sediment concentration distribution could be used to check/validate an advanced model (Delft3D or similar). Further, measurements could be used as prediction for the risk of violations in the near future. This to prevent exceedance and project downtime.

Validation of model results with practical data has not been possible in this research. The conditions of the main influences (inflow mixture and wind) are variable. Lastly, using a more complex model for the assessment will require more input. As this input is often not known, assumptions need to be made. Therefore, more complex models do not always make the assessment more reliable. It is recommended to do more research into mitigating measures.

Preface

This thesis complements my masters in Hydraulic Engineering. After studying for nearly seven years at the Delft University of Technology I finished my bachelor and master in Civil Engineering.

Over the last year I did this research in close corporation with Environmental Engineering at Van Oord. Environmental Engineering is an unique group within the Engineering and Estimating Department of Van Oord. With increasing awareness for collateral damage to the environment by dredging works, the environmental engineer is getting more and more important on dredging projects.

Next to preventing collateral damage, Van Oord has in their environmental engineers an unique selling point. Care for the environment and improving local nature is the way to be distinctive as a large marine contractor in a competitive market. With more local players on the market and state-owned dredging companies, being distinctive in tenders is essential. During my thesis at Van Oord, the members of Van Oord Environmental Engineering showed me there expertise and motivation for being unique selling points next to preventing collateral damage.

My thesis should primarily be used to prevent collateral damage to sea grass and corals in the neighbourhood of a dredging project. The damage induced by a careless executed dredging project is immense and could ruin the life environment of local communities. My research has increased the knowledge of the determining mechanisms inside a settling basin. This increased knowledge should improve the predictive capabilities on outflow concentrations and therefore the capabilities to prevent environmental damage from occurring. I believe that my research will (in)directly contribute to the careful approach of Van Oord to the environment.

I would also like to use this preface to express my sincere gratitude to several important persons during my research. First of all, I would like to thank all the people of environmental engineering with in particular Ilse Caminada, Marlies van Miltenburg, Erik van Eekelen and Jurre de Vries. Second, I am thanking the members of my graduation committee for their feedback and patience during my research: Mark van Koningsveld, Zheng Bing Wang and Bram van Prooijen. My gratitude also goes out to the other (graduate) interns within Van Oord; discussions about each others work but also trying to help each other out with Python codes and cycling tours outside the office. I hope to see you all around sometimes!

Last of all I would like to thank my family, with a special thanks to my premium supporters Frank and Marijke.

T.F.J. (Tjerk) Veenman
Rotterdam, August 2020

Contents

List of Figures

List of Tables

1 Introduction

Dredging projects are required for a variety of reasons: to support the navigability of rivers, waterways and harbours, improve the environment, reduce flood risk, remove contaminated sediments or enable maritime construction. Dredging projects are not only executed to remove sediments; often the goal of a dredging projects is to bring sediments to the land, like with a land reclamation, beach nourishment or extraction of sediments for the construction industry.

The main principle of dredging is removing sediments from the river- or seabed and placing them somewhere else. Removing the sediments can be done by cutting, jetting or scraping the bed. Dumping can be done by opening the hatches of a hopper offshore, pumping the sediments to the shore by a pipeline or rainbowing (spraying under high pressure). Each dredging operation asks for their own method of removing and dumping sediments. This is due to the different sediments, requirements by customers and environmental risks in the area.

Dredging imposes risks to the environment. Noise pollution by dredging equipment (draghead, cutterhead, engines) may create stress and hearing impairments for marine life [CEDA, 2011]. Suspended sediments in the water column (due to extraction or dumping of sediments) may cause turbidity [Pennekamp and Quaack, 1990]. Turbidity in the water has several negative effects on ecosystems: the limitation of light penetration through the water may harm phytoplankton, coral reef and seagrass [Erftemeijer et al., 2012]. Further, underwater plants like sea grass and coral can be buried by the sediments. Because these organisms are at the start of the food chain (primary production), the rest of the ecosystem may be influenced by these effects as well. Less primary production results in less (food for) fish, which results in less birds [Rogers, 1990]. Turbidity can therefore cause serious harm to an ecosystem.

Due to the environmental risks, often strict regulations are imposed for dredging companies to make sure environmental harm is reduced to a minimum. Sometimes, executing the project in a certain period of the year could reduce the environmental harm to an acceptable level. Examples of solutions to limit the emission of fine sediments are prohibiting the use of the overflow of a trailing suction hopper dredger (limiting the release of fine sediments, but making the dredger less efficient), using a silt screen to prevent fine suspended sediments from spreading, or using a settling basin to let fine particles settle before discharging the the water to the source.

Preventing the release of fine sediments by settling basins is often done by using multiple settling basins. In the first basin, the dredged mixture (water and sediments) flows in by a pipeline. Here, the mixture contains all sizes of sediments. In the first basin the large particles will settle quickly, while the smaller particles will stay longer in suspension. At the end of the basin, a weir to the next basin is installed. Only the upper part of the water column will flow over the weir to the next basin. In this second basin, this process is repeated but now the inflow mixture is less concentrated and the size of the sediments is smaller. Again, the flow velocity in the basin is very low, which should make settling possible. Multiple basins can be installed after each other, with each the same working method. After the last basin, the water will flow back to the source (river or ocean). Here, the suspended sediment concentration should be low enough, in order to comply with the environmental regulations.

This research mainly focuses on improving the assessment for designing a settling basin, as done by Van Oord. In the current assessment of settling basin designs, an in-house developed 2DV numerical model calculates the expected outflow concentration of a settling basin for a pre-described inflow and basin characteristics. Important in the design of a settling basin is to keep the flow velocity low, the residence time of the mixture high and the length of the basin long enough for fine sediments to settle. Improving the predictive capability of a settling basin will be reached by increasing the process understanding with a (comparative) modelling study.

Figure 1.1: A settling basin used for a project in Gladstone, Australia (August 2013).

1.1. Current return water quality assessment

The main working method of a settling basin is simple and straightforward. The residence time of the mixture entering the settling basin should be large enough for the finest particles (with the lowest settling velocity) to settle through the basin. Disturbances that could possibly stir up the sediment should be avoided. A very low flow velocity should both increase the residence time as well as the possibility of sediment getting stirred up again. This means one wants to create a basin with a large conveying area (width *times* depth) and a long distance between the inflow and outflow. What complicates the design of a settling basin, is the (often) limited amount of space available. Another complication in the design process is the often unknown settling velocity of the dredged sediment. As the dredged material may differ significantly, the outflow concentration could fluctuate.

During the tender phase of a project, the environmental engineer wants to determine the outflow concentration of the basin. To determine the probability of exceeding the prescribed outflow concentration limit, Van Oord uses the in-house developed Return Water Quality model (RWQ model). With this numerical model, a quick estimate can be made of the outflow concentration at the end of a settling basin. Only a limited amount of input parameters is required, making the model quick and easy to use. The model shows where each fraction of particle size will settle. This should provide more insight in the processes inside a settling basin. Based on the result of the RWQ model, an environmental engineer is able to determine the risk of exceeding the prescribed limits as well as determining the optimal design.

The RWQ model is mostly used in a tender stage. During this stage, usually not all information is available. Yet, there is a need to be able to determine the design of a settling basin in a robust way while understanding all key processes that determine the outflow concentrations. Important is to realise one needs to use easily accessible information in an efficient way. The challenge is not to fully determine the outflow concentration, but to approach the outflow concentration reasonably reliable without using (expensive) tests or extensive analyses.

Intermezzo: RWQ model description
The RWQ model uses simple input parameters such as: inflow (discharge [m3/s] and sediment concentration [kg/m3]), basin geometry (length [m], width [m], depth [m]), sediment properties (diameter of fractions [m], distribution over fractions [%] and minimum fall velocity [m/s]), bottom roughness [m], water temperature [deg C] and wind (velocity [m/s] and direction [deg]). More information is often not available.

The output of the model is the outflow concentration of suspended sediments. During the calculations, intermediate results are shown with the concentration through the basin. These plots show how the concentration is spread over the settling basin. If multiple basins are required, one can use the outflow of the first basin as input for the next basin.

The model simplifies the water movement by assuming the flow velocity is uniform over the width and height. This means the model assumes there are no cross-basin gradients, there is only flow in longitudinal direction of the basin. The 1D St. Vernant equations are derived from the Navier-Stokes equations to model the flow through the basin. Next, the sediment transport is calculated. For sediment transport the assumption of uniform flow over the depth does not hold. The sediment transport is therefore modelled by a 2DV approach. After the suspended sediment transport is calculated with the 2DV Navier Stokes approximation, the bed load transport is calculated. Next, these calculations are repeated for each time step. The model is further extended with the effect of wind on secondary flow in the basin. Further processes that can be included in the model are flocculation, an updated bed (due to deposition of sediments) and hindered settling (due to a high concentration).

1.2. Problem formulation

Although the model is able to show the change in suspended sediment concentration through the basin, validation of the model is limited. Some comparisons have been made, but there is still room for improvement. When using the model to predict the concentration of fines, some input values must be estimated which highly influence the outcome of the model. The uncertainty of these parameters often means the difference between an acceptable outflow concentration and a violation of the prescribed limit. A thorough comparison of the RWQ model with other, more complex models, should increase the reliability of the RWQ model in the process of designing a settling basin. It should be stressed it is essential to keep the model relatively simple (as the RWQ model is) without the need to validate the model for each project. Often there is not enough time nor information available to construct a complex 3D-model or do a validation campaign. Therefore, a straight-forward but robust method is necessary to evaluate the effectiveness of a settling basin design in meeting outflow criteria, based on a solid process understanding.

The current problems with the return water quality assessments can be listed as follow:

- **(Width) Uniform flow:**
  The current return water quality model assumes width averaged flow. This assumption is made both for simplicity as well as the (supposed) limited effect of the 3D elements (inflow pipe, outflow weir) in a real basin. With a more comprehensive model (taking a third dimension into account) the validity of the 2DV assumption can be defined and guidelines are to be set when not valid.
- **Influences by density differences:**
  The effects of density differences are assumed to be negligible [Lange, 2011]. This assumption

is based on low concentrations of fines and the small influence this would have on the density of the mixture. However, because no measurements have been done it is not certain if these small differences will induce currents or not, while theoretically these will be formed.

- **Influences by wind:**
  From earlier research [Lange, 2011] followed the influence by wind driven currents could be significant on the outflow concentration. With the expansion of the assessment to 3D, the influence of the wind should be further researched. Earlier research showed wind could be a determining factor in complying with the environmental regulations.

- **Filling behaviour:**
  The influence of the degree of filling is not clear. Filling will change the area available for settling and the water depth. As the effects are not clear, it is also not clear how to implement the different levels of filling in the assessment.

- **Compared to measured data:**
  A model always needs some degree of calibration and there needs to be a way to check the correctness of a model. Measurements are therefore required.

- **Application future project:**
  While multiple assumptions are tested, the question stays when the current RWQ model could be applied for an assessment and when the RWQ model is not applicable. For the assessments were the RWQ model is not applicable a different method should be introduced, keeping the assessment easy and quick.

1.3. Objective

The objective of this study is:

> To **establish and (where necessary and possible) improve** the current method for assessment of outflow concentrations of settling basins (on dredging and reclamation works), while **balancing increased levels of detail with practicability** during the tender stage of projects.

Establish and (where necessary and possible) improve: The validity domain of the current assessment (by means of a 2DV model) should be defined. This should inform users when the RWQ model is a good approach and when other methods will be more suitable. In order to define the validity domain, process understanding needs to be improved and compared to the processes as assumed in the RWQ model.

Balancing increased levels of detail with practicability is about keeping the model simple. These kind of assessments are mostly done during a tender phase. In this phase, there is not much information, time or funding available and therefore a thorough analysis of the situation is impossible to do. The assessment method should be efficient in using the input information. Only the most determining factors could be further investigated during the assessment. The proposed assessment method should keep this in mind as a requirement.

1.4. Research questions

In pursuit of the above stated research objective, the following sub-questions are defined:

- What are the governing physical processes that cause suspended sediment concentrations and particle size distributions to change along a settling basin and over time?
- For what geometries of a settling basin is a 2DV-model (RWQ model) applicable, and when is a 3D-model (Delft3D) more appropriate to use for modelling?
- What is the effect of different influences on the flow pattern (like wind, density driven currents and fill rate of the basin) and how does this affect the outflow concentration of suspended sediment concentration?
- What (measurable and predictable) conditions are most governing for the processes in the basin and the resulting outflow concentration?
- What is the validity (domain) of the current return water quality assessment and how could this be improved?

2

Methods

This chapter describes the methods used for the comparative modelling study on settling basin assessments. The comparative modelling study has two goals:

- Achieve more insight in relevant processes (density differences, wind) and their influence (sediment dispersion and flow pattern) ;

- determine the validity domain of the RWQ model.

Delft3D gives the possibility to take more processes into account than the (2DV) RWQ model. This possibility enables research into the relevant processes in settling basins, others than currently implemented in the RWQ model. The different processes that are researched by the comparative modelling study are (the assumption of) uniform flow over the width of the basin, (the assumption of) density differences induced by sediment concentration, wind induced secondary flow and mixing, and the combined effect of these assumptions and effects. An overview of the methods of the comparative modelling study is shown in Table 2.1.

Name of scenario	**Underlying assumptions**	**Goal**	**Methods section**
Uniform flow	No wind, no density differences	Test the assumption of uniform flow (2DV) in the RWQ model for different geometries	2.2.2
Density differences	No wind, density based on sediment concentration	Determine the influence of density differences and the occurrence of density driven currents	2.2.3
Wind effects	Wind from all directions and different velocities, no density differences	Show influence of wind and occurrence of secondary flow	2.2.4
Density & wind combined	Density differences on and wind on, multiple combinations	Show the combination of density differences and wind effects on the internal processes and the outflow concentration	2.2.5

Table 2.1: Summary of methods.

Models are always a representation of reality. Although a model that takes more processes into account (like the Delft3D model compared to the RWQ model) should give a more realistic presentation of the situation, the model will still differ from reality. Additional measurements and validation will always be necessary to validate a model. In the absence of usable results from a measurement campaign

(Chapter 5), the Delft3D model is assumed to be closest to the truth.

This chapter will first describe the performance indicators used when comparing different models. Next, a description of the different scenarios with their cases will be given. The used settings for the RWQ model and the Delft3D model will be given at the end of this chapter.

2.1. Comparison methods

The results of the cases are interpreted by the following performance indicators:

- **Dispersion of sediment through the basin:**
  Insight into the dispersion of sediment should help to determine the governing physical processes. The sediment concentration pattern throughout the basin will provide the background of the measured outflow concentration. The dispersion of sediment can also show the rate of uniformity and therefore the validity of the 2DV approach.

- **Flow pattern:**
  The flow pattern should give more insight into the uniformity of the basin and therefore the validity of the model. Combined with the sediment concentration the driving mechanisms behind the dispersion of sediment can be identified.

- **Outflow concentration:**
  The outflow concentration can be used as a performance indicator for the different (geometry) cases. The outflow concentration gives the possibility to objectively compare scenarios with each other.

2.2. Description of scenarios

This section describes the motivation and the set-up per scenario. Each scenario contains a number of base case model runs. First, the conditions for the base case are described. Second, the scenario specific conditions are elaborated.

2.2.1. Base cases

The different scenarios are evaluated by a base case and seven geometry-cases (cases A to G). The base case is used to improve the process understanding. The seven geometry-cases compare the used settings for different geometries. The seven geometry-cases are also used to establish the validity domain of the RWQ model.

The base case is set up by the input values as described in Table 2.2.

	Input	**Unit**
Length	200	$[m]$
Width	100	$[m]$
W/L-ratio	1/2	$[-]$
Inflow rate	2	$[m^3/s]$
Inflow concentration	15	$[kg/m^3]$
Settling velocity	$1x10^{-4}$	$[m/s]$
Density differences	Off	
Wind velocity	0	$[m/s]$
Wind direction	0	$[°]$

Table 2.2: Input values for the base case

The seven geometry-cases are all rectangular. The total volume is equal for all cases. This makes the cases comparable. Table 2.3 gives the width and length per case. The W/L-ratio (Width/Length-ratio) is mentioned to compare the cases in the results. All other input values are the same as the base case. Notice the base case (Table 2.2) is the same as geometry case C.

Case	Width	length	W/L-ratio	
A	50 m	400 m	1/8	= 0.125
B	70 m	280 m	1/4	= 0.25
C	**100** m	**200** m	**1/2**	**= 0.5**
D	140 m	140 m	1/1	= 1
E	200 m	100 m	2/1	= 2
F	280 m	70 m	4/1	= 4
G	400 m	50 m	8/1	= 8

Table 2.3: Different geometry-cases. Geometry-case C is the same as the base case.

2.2.2. Width uniform flow

The 'width uniform flow'-scenario validates the assumption of uniform flow conditions over the width of a settling basin. By assuming uniform flow (as is done in the 2DV RWQ model), cross-basin currents are neglected. Flow dispersion and flow contraction by the in- and outflow are assumed to have a minor influence.

The assumption of width uniform flow conditions should at least hold when wind and density driven currents are absent. Therefore, for this scenario there is uniform density and no wind. The assumption is applicable when the sediment concentration over the width of the basin is uniform, the flow pattern over the width is uniform and the outflow concentration is equal to the RWQ model. The geometry cases are used to derive a validity range for uniform conditions over the width.

2.2.3. Density differences

In the development of the RWQ model (and research by Lange [2011]) the assumption was made that density differences would not be of significant influence and could be neglected. However, high sediment concentrations can cause an increase of the mixture density. Even slight increases in density (of 1%) might cause density currents to form. To validate the assumption, the 'density difference'-scenario is set up.

This scenario has three goals with a different case set up. The cases are modelled with both uniform density (Delft3D and RWQ model) and density determined by the sediment concentration (only Delft3D). The goals are:

1. Increase process understanding on the effect of density differences in sediment basins;
   Base case (Table 2.2) with density differences

2. Investigate the effect of density differences for different geometry-cases.
   Geometry cases (Table 2.3) with density differences

   In the Appendix the results of extra scenarios for increased processes insight are included:

3. Get insight in the influence of sediment properties on density currents;
   Base case with modifications on sediment properties (Table 2.4) with density differences

Scenario	Input	Unit
Sediment concentration		
	05	$[kg/m^3]$
(base case settings)	15	$[kg/m^3]$
	30	$[kg/m^3]$
	45	$[kg/m^3]$
Particle fall velocity		
	2.5 $x10^{-3}$	$[m/s]$
	1 $x10^{-3}$	$[m/s]$
	2.5 $x10^{-4}$	$[m/s]$
(base case settings)	1 $x10^{-4}$	$[m/s]$
	2.5 $x10^{-5}$	$[m/s]$
	2.5 $x10^{-6}$	$[m/s]$

Table 2.4: Input values for cases on the influence of sediment properties on density currents

2.2.4. Wind effects

In the 'Wind Effects'-scenario the influence of wind is validated. Cases with different wind directions and velocities are compared with each other and to the base case.

The base case is the same as earlier described (Section 2.2.1) and does not contain wind. Four main wind directions are identified (with respect to the general flow direction). These are:

- 0° (downwind)
- 90° (headwind)
- 180° (crosswind)
- 270° (crosswind)

Next, combining the wind directions makes four oblique wind directions:

- 45°
- 135°
- 225°
- 315°

The two crosswind directions are assumed to give the same result but in the opposite direction. Therefore, only one crosswind direction is modelled: 90°. Following this assumption, only two oblique wind directions should be modelled: 45° and 135°.

The main wind directions are modelled for moderate wind velocities (5 m/s), quite powerful (10 m/s) and heavy storm conditions (25 m/s) ([KNMI, 2020]). For efficiency, the oblique wind directions are only modelled for wind velocities of 10 m/s.

An overview of the modelled wind cases is shown in Table 2.5. All cases are modelled with both Delft3D and the RWQ model.

Scenario	Wind direction [°]	Wind velocity [m/s]
Base case	0	0
Downwind	0	5
	0	10
	0	25
Oblique wind	45	10
Crosswind	90	5
	90	10
	90	25
Oblique wind	135	10
Headwind	180	5
	180	10
	180	25

Table 2.5: Modelled wind cases

Only one basin size is used for this scenario: L = 200 m, W = 100 m (base case). For efficiency the geometry cases (A to G) are not modelled with all wind directions. Note that in the wind scenario the effect of density differences is not taken into account (yet). This might give an unrealistic result, but does show the effect of solely the wind. Section 2.2.5 will describe the scenario for combining wind and density differences.

2.2.5. Density & Wind combined

This scenario combines the effect of density differences and wind.

Process understanding

Process understanding is improved by setting up cases with different wind conditions (direction and velocity) and density determined by the sediment concentration. The base case is used with wind from the main wind directions (0 °, 90 °, 180 °) and all main wind velocities (5 m/s, 10 m/s, 25 m/s). The sediment properties (inflow concentration = 15 kg/m^3, settling velocity = 0.1 mm/s) are kept constant. These cases should show the combined effect of wind and density differences. An overview of the input parameters of the cases is given in Table 2.6:

	Input	Unit
Geometry	200 x 100	$[m]$ x $[m]$
Inflow rate	2	$[m^3/s]$
Inflow concentration	15	$[kg/m^3]$
Settling velocity	$1x10^{-4}$	$[m/s]$
Density differences	On	
Wind velocity:		
	5	$[m/s]$
	10	$[m/s]$
	25	$[m/s]$
Wind direction:		
	0	[°]
	90	[°]
	180	[°]

Table 2.6: Input values for the combined cases of density and wind

Model comparison

Three sets of cases are set up. Each set consists of all geometry cases (A to G, with $\frac{W}{L} - ratio$ = $\frac{1}{8}$ to 8) and wind velocities of 10 m/s and 25 m/s.

Set 1 experiences wind from 180 ° and settling velocity of $1x10^{-4}$ m/s. Set 2 experiences wind from 0 ° and again a settling velocity of $1x10^{-4}$ m/s. Set 3 experiences wind from 180 ° and a settling velocity of $2.5x10^{-5}$ m/s. An overview is given in Table 2.7.

The different geometries are required to define a validity range based on the geometry. The different wind velocities are used to show the difference in prediction for either wind or density dominated cases.

	Input			Unit
Inflow rate	2			$[m^3/s]$
Inflow concentration	15			$[kg/m^3]$
Density differences	On			
Wind velocity:				
Case .10	10			$[m/s]$
Case .25	25			$[m/s]$
Geometry:	W x L			
Case A..	50 x 400			$[m]$ x $[m]$
Case B..	70 x 280			$[m]$ x $[m]$
Case C..	100 x 200			$[m]$ x $[m]$
Case D..	140 x 140			$[m]$ x $[m]$
Case E..	200 x 100			$[m]$ x $[m]$
Case F..	280 x 70			$[m]$ x $[m]$
Case G..	400 x 50			$[m]$ x $[m]$
	set 1	**set 2**	**set 3**	
Settling velocity	$1x10^{-4}$	$1x10^{-4}$	$2.5x10^{-5}$	$[m/s]$
Wind direction	180	0	180	[°]

Table 2.7: Input values for the combined cases of density and wind

2.3. RWQ model

The RWQ model is a 2DV model. The 1D Saint-Venant equations are used to describe the flow in 1D. These are derived from the 3D Navier-Stokes equations. A logarithmic velocity profile is assumed [van Rijn, 1993], to model the sediment transport. More information on the RWQ model can be found in Lange [2011]. Here, only a brief summary of the used approach is given.

2.3.1. Grid

Because the model is in 2D, the grid size is only specified in length and height. The length of one grid cell is here set to 2 m. 40 layers are used over a water depth of 3 m, which means: $\frac{3m \textit{ (depth)}}{40 \textit{ (number of grid cells)}} = 0,075m/layer$. The length and width are different for each case and can therefore be adjusted by the user.

A weir is located at the end of the basin. The main purpose of the weir is to sustain the water level. The assumption is this weir has influence on the sediment transport as well. This assumption is based on the blockage of fluid over the lower part of the water column. In the lower part of the water column the sediment concentration is the highest. Blocking water with the highest sediment concentration will lower the average sediment transport over the weir. This effect by the weir is simulated in the model by only taking the average sediment concentration of the upper 25 % of the water column as the outflow concentration.

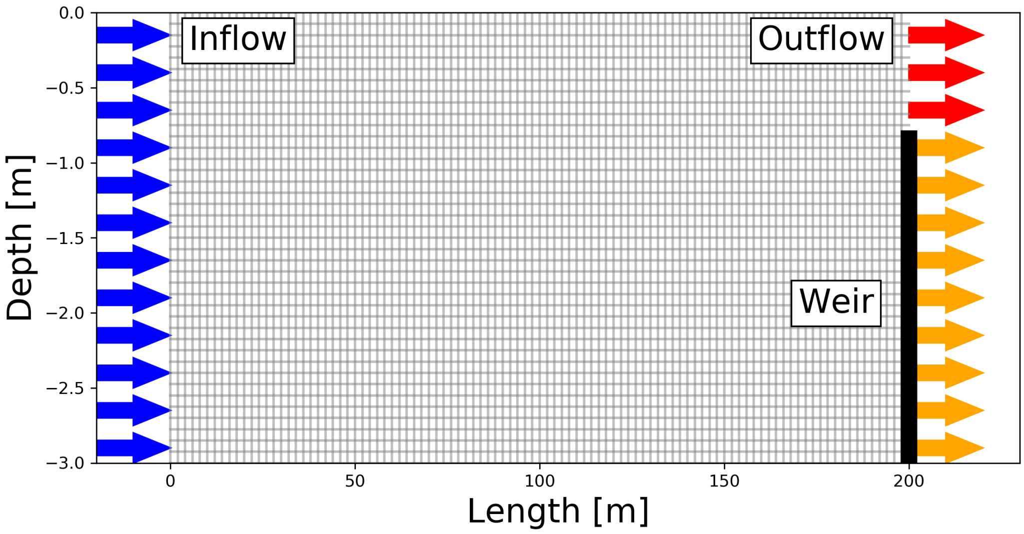


Figure 2.1: Grid of the RWQ model in 2DV. Vertical axes: depth [m]. Horizontal axes: length [m]. Blue arrows: inflow. Orange and red arrows: outflow. Red arrows: upper 25 % of the water column determining the outflow concentration. The grey grid shows the computational area.

2.3.2. Simulation

The default time step is 1080 s and the number of time steps is 100. This is equal to 30 hours. The RWQ model is mostly used to calculate stationary conditions, which can be reached by increasing the number of time steps until no changes are noticed any more. This is dependent on the scenario.

2.3.3. Boundary conditions

The inflow boundary is specified by an inflow discharge $[m^3/s]$ and inflow concentration $[kg/m^3]$. The outflow boundary is defined by a water level. The required outflow rate is calculated by the model. At the bed boundary the flow velocity is zero. At the surface boundary the flow velocity is determined by the wind shear stress.

2.3.4. Physical parameters

The turbulent kinetic energy is calculated with the Algebraic closure model. The Algebraic closure model is a function on both the shear stress at the bed and the surface. The model is based on the eddy viscosity concept of Kolmogorov [1942] and Prandtl [1945]. The Algebraic closure model is a zero order closure scheme for the turbulent kinetic energy (k) and the mixing length (L). The model could take the effect of a vertical density gradient on the amount of turbulent mixing into account. However, this would require an extension on the current RWQ model.

2.3.5. Sediment parameters

The inflowing sediment is defined by different fractions. The model calculates the settling velocity. An additional minimum settling velocity needs be defined to ensure that the very small fractions will still settle in the model. The model is also capable of updating the morphology, based on the amount of settled sediments.

From user experience it was found that the minimum settling velocity is highly influential for the outflow concentration. Lange [2011] advised to define the minimum settling velocity between $2.5x10^{-4}$ m/s to $2.5x10^{-6}$ m/s. This is a large range (order 100) and often different values for the minimum settling velocity are used to get an indication of the risk. Since the determination of this value is currently causing a lot of uncertainty, correct determination is very important.

2.3.6. Wind

The wind is user specified for both direction and velocity. The model takes shear stress and water level set up into account. With the Algebraic closure model for turbulence the additional mixing by the shear stress is determined. Water level set up induces secondary circulation and is determined with the equations as taken from Hutter et al. [2011].

2.4. Delft3D

This section describes the used setting in Delft3D for this research. For further information on Delft3D one is referred to the Delft3D manual, Deltares [2011a].

2.4.1. Grid

The grid is generated with the RGFGRID-tool by Deltares [2011b]. A square shaped grid is used with a grid cell size of 5 m x 5 m. This grid cell size is assumed to be small enough to capture all important cross boundary currents near the in- and outflow boundaries of the grid. The grid cell size does ensure efficient modelling. The width and length of the basin are dependent on the case. For the base case a total grid is defined with width (W) = 100 m and length (L) = 200 m. The depth (D) = 3 m divided over 20 layers over the vertical.

The in- and outflow boundaries are located opposite to each other. Dry points direct the flow into the settling basin. At the end of the settling basin a local weir is implemented. Behind the weir an area of 100 m is added before the outflow boundary is defined. This should prevent the outflow boundary from influencing the measured sediment concentration. The concentration is measured just behind the weir.

The implementation of a weir is described in the Delft3D-FLOW manual ([Deltares, 2011a], 2D/local weir). The height of the weir is defined as +0 m with respect to the local reference level. The weir is located between two water level points, the fluid needs to flow over the weir. These small scale influences by the weir on the sediment concentration are not modelled representatively in Delft3D. Delft3D is not very suitable for dynamics on this scale. Therefore, Delft3D could estimate the transport of bed load transport wrong. However, due to only suspended sediment transport and fluid flowing perpendicular to the weir, Delft3D would still be able to calculate the sediment transport correctly (Vuik [2010]).

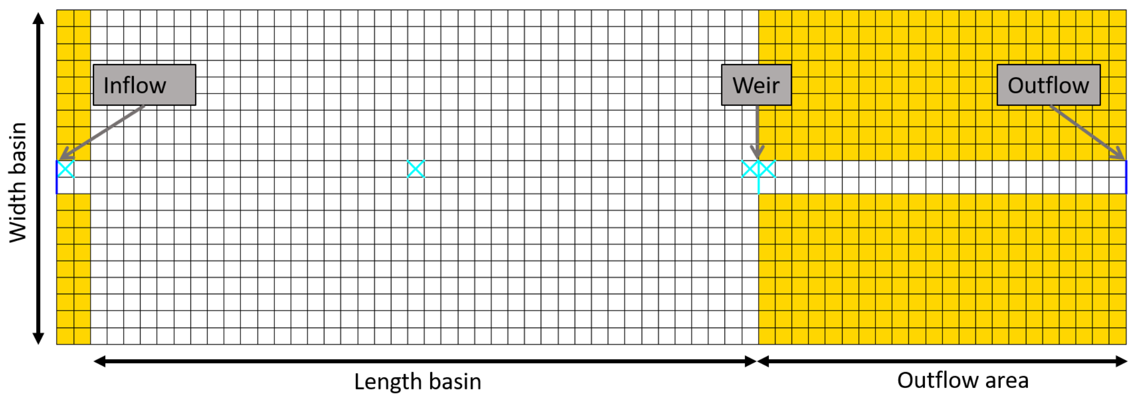


Figure 2.2: Presentation of Delft3D grid. This figure (from Delft3D) presents the grid of the base case with important elements accented. White grid cells: computational area. Yellow grid cells: dry points (used to mark the edge of the basin and inactive cells).

2.4.2. Simulation

For all cases (except where settling behaviour is researched) stationary conditions are used. This means the simulation time should be long enough for stationary conditions to originate. With $\frac{200[m]*100[m]*3[m]}{2[m^3/s]*3600[s]} = 8.33[h]$ as the average retention time, simulations show stationary conditions are reached after approximately 1 day. To ensure stationary conditions are reached, the simulation time is increased to 2 days (48 hours).

The used time step is calculated with the conditions for consistency by the Courant (Friedrichs-Lewy) number (CFL condition) [Deltares, 2011a]:

$$C = \sqrt{gH}\frac{\Delta t}{\Delta x} \leq 10 \tag{2.1}$$

With:

g	=	9.81	$[m/s^2]$
H	=	3	$[m]$
Δx	=	5	$[m]$

To fulfil the CFL condition, $\Delta t \leq 9.22 sec$. Δt is chosen as 6 sec (=0.1 min). The initial conditions are clear water with no sediments in the basin. The water level is everywhere at +0 m with respect to the local reference level.

2.4.3. Boundary conditions

The grid is enclosed by closed boundaries, except for the inflow and outflow boundary. These are open boundaries were the mixture enters and exits the basin.

The inflow boundary is defined by a total discharge boundary. The outflow boundary is located 100 m downstream of the weir. This ensures the basins outflow concentration is not influenced by the models outflow boundary. The outflow boundary condition is defined by a constant water level (+0 $[m]$ with respect to the local reference). The required discharge rate to sustain this water level is determined by Delft3D. Delft3D also determines the outflow concentration.

For the bottom boundary condition, a Chézy roughness coefficient of 60 $[\sqrt{m}/s]$ is used (based on several examples in [Koller et al., 2017] and the default value of Delft3D). The wall roughness are defined with free slip conditions, as these should not have any influence. The surface boundary is determined by the wind conditions (described in Section 2.4.6).

2.4.4. Physical parameters

The used 3D turbulence model is the $k-\epsilon$ closure model. This turbulence closure model is a second order model. The turbulence model asks for a calibration or background value for the horizontal and vertical viscosity and diffusivity. Based on the Delft3D-FLOW manual [Deltares, 2011a] and personal communication with Prof. dr. ir. Wang of Delft University of Technology, these background values are estimated. Important considerations in the determination of the background diffusion and viscosity coefficient was the relative importance of diffusion through the basin compared to advection. The flow velocity is relatively low (O ~0.01 $[m/s]$), therefore the horizontal diffusion coefficient should be equal or smaller than $u * h$ (<0.03 $[m^2/s]$) or $u * \Delta x$ (<0.05 $[m^2/s]$). This means the diffusivity should be equal or smaller than 0.03 $[m^2/s]$.

The relation between the eddy viscosity and diffusivity is described by the turbulent Schmidt number:

$$Sc_t = \frac{\epsilon_t}{D_t} \tag{2.2}$$

Here, a turbulent Schmidt number of 1 is used. The background horizontal eddy viscosity should therefore be 0.03 $[m^2/s]$. The value of $Sc_t = 1$ is based on a large comparison study by Gualtieri et al. [2017] and personal communication with Prof. Dr. Ir. Wang and Dr. Ir. van Prooijen. The background vertical eddy viscosity and diffusivity have a minor influence and therefore set to $1e^{-}5$ $[m^2/s]$ (personal communication with Prof. dr. ir. Wang). An overview for the background viscosity and diffusivity is given in Table 2.8.

Parameter	Value	Unit
Background horizontal eddy viscosity	0.03	$[m^2/s]$
Background horizontal eddy diffusivity	0.03	$[m^2/s]$
Background vertical eddy viscosity	$1x10^{-5}$	$[m^2/s]$
Background vertical eddy diffusivity	$1x10^{-5}$	$[m^2/s]$

Table 2.8: Overview of the used input values for viscosity and diffusivity in Delft3D.

2.4.5. Sediment parameters

Sediment in Delft3D is categorized as cohesive or non-cohesive. Since most fines are cohesive sediment, this research only describes the use of cohesive sediments. Multiple fractions can be added with different properties. All input values are shown in Table 2.9. The sediment properties are representative for sediment found in settling basins. The sediment input values are in line with the RWQ model input.

Parameter	Value	Unit
Settling velocity	$1x10^{-4}$	$[m/s]$
Reference density for hindered settling	1600	$[kg/m^3]$
Specific density	2650	$[kg/m^3]$
Dry bed density	1200	$[kg/m^3]$
Critical bed shear stress for sedimentation	1000	$[N/m^2]$
Critical bed shear stress for erosion	0.5	$[N/m^2]$
Erosion parameter	0.0001	$[kg/m^2/s]$
Initial sediment layer thickness at bed	0.05	$[m]$

Table 2.9: Overview of sediment parameters for Delft3D

2.4.6. Wind

Uniform wind conditions are defined by velocity $[m/s]$ and direction [°]. Because only stationary conditions are researched, the wind is kept constant and uniform. The wind drag coefficients are determined by the following statements (Lange [2011]):

Wind drag coefficient	Wind speed
0.001287	$U_{10} < 7.5[m/s]$
(0.8+0.065 x U_{10})x10^{-3}	$U_{10} > 7.5[m/s]$

The wind drag coefficient is used for the calculation of the shear stress exerted on the water level as the boundary condition.

3
Results

3.1. Estimation of outflow concentration

A first estimate of the outflow concentration is made. This estimate is based on the residence time of the mixture and the distance a particle needs to overcome before settling. Uniform flow is assumed and the settling of sediment is assumed linear over the basin. The sediment particles should settle fast enough to overcome the settling distance (water depth) before the flow reaches the end of the basin. This can be written as the following equation:

$$\frac{\textit{Water depth}}{\textit{Settling velocity}} < \frac{\textit{Length of basin}}{\textit{Flow velocity}} \tag{3.1}$$

Or:

$$\frac{D}{v_s} < \frac{L}{Q/(B*D)} \tag{3.2}$$

Rewriting this equation gives:

$$v_s > \frac{Q}{L*B} \tag{3.3}$$

With the base case properties:

- Q = $2m^3/s$
- L x B = $20.000m^2$

Thus:

$$v_s > 1x10^{-4}m/s$$

As Q and L x B are constant, this can be used for all cases. In this first estimate the concentration is not included.

3.1.1. Comparison with modelling tools

The equation could also be rewritten to $L_{req} > \frac{Q}{v_s*B}$. The required length is now found for a settling basin for particles with settling velocity v_s.

For the base case this is:

- Q = $2m^3/s$
- L = $200m$
- B = $100m$

For this comparison, the settling velocity is ranged from 0.0025 mm/s to 1 mm/s. The outflow concentration is based on the fraction $\frac{L_{available}}{L_{required}} = \frac{C_{out}}{C_{in}}$, which assumes linear settling over the length. The results are shown in Figure 3.1.

The comparison shows this simple, back-of-the-envelope estimate is not sufficient for assessments with settling basins. Especially for slow settling, fine particles ($v_s < 1mm/s$) modelling software can make the required design of a settling basin more efficient.

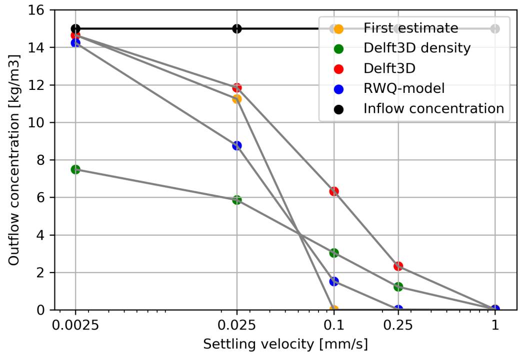


Figure 3.1: Comparison of outflow concentrations for base case with changing settling velocity compared when calculated with the simple sum.

3.2. Width uniform conditions

The assumption of width uniform conditions is only valid for narrow basins. This conclusion is based on the spatial distribution of sediment concentration and flow.

3.2.1. Flow pattern

The (depth averaged) flow pattern is shown in Figures 3.2 and 3.3. The inflow generates jet flow that can be observed over a long distance, depending on the inflow rate and W/L ratio. When the W/L ratio is low enough, the jet is able to stabilize through the basin and the flow velocity is uniform over the width. However, this is only for narrow cases (A and B). In wide basins large eddies are formed. The flow velocity in the eddies is low, but they deviate from the (assumed) width uniform conditions.

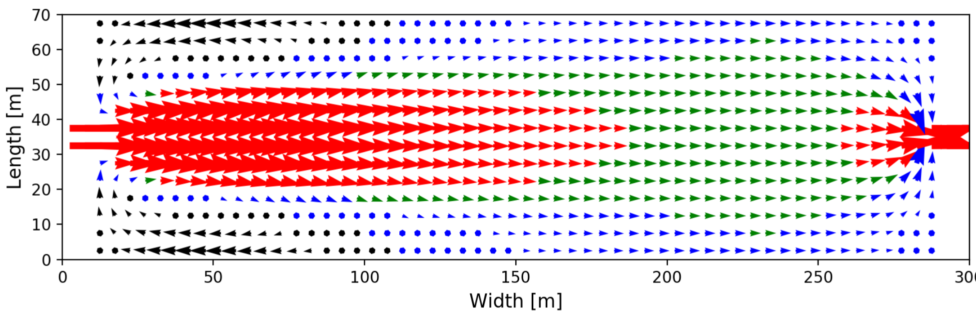


Figure 3.2: Case B: W = 70 m; L = 280 m; W/L-ratio = 1/4. Flow pattern shown by depth average flow velocity in 2DH. Green: ≈2DH flow velocity. Red: >2DV flow velocity. Blue: <2DV flow velocity. Black: no flow or <0 m/s.

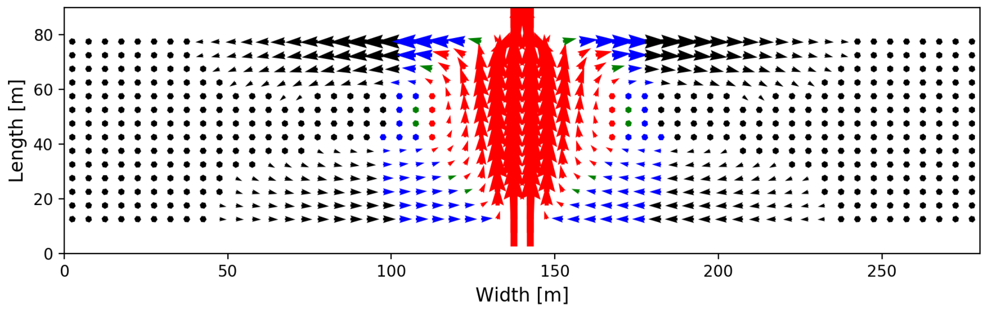


Figure 3.3: Case F: W = 280 m; L = 70 m; W/L-ratio = 4. Flow pattern shown by depth average flow velocity in 2DH. Green: ≈2DH flow velocity. Red: >2DV flow velocity. Blue: <2DV flow velocity. Black: no flow or <0 m/s.

The uniformity of the flow velocity over the width is ranked for the geometry cases (Figure 3.4). The depth averaged flow velocity per grid cell is compared to the average flow velocity over the width. If these two values are within 10 % of each other, the grid cell is assumed to be (near) uniform. The score is expressed in [%] of grid cells fulfilling to width uniform flow.

The narrow and long cases (low W/L ratio) score the best. The decrease of the score for wider cases is very fast. Basins with a W/L-ratio of 1/2 and larger score very poorly and averaging the flow (or a 2DV solution) does not seem representative.

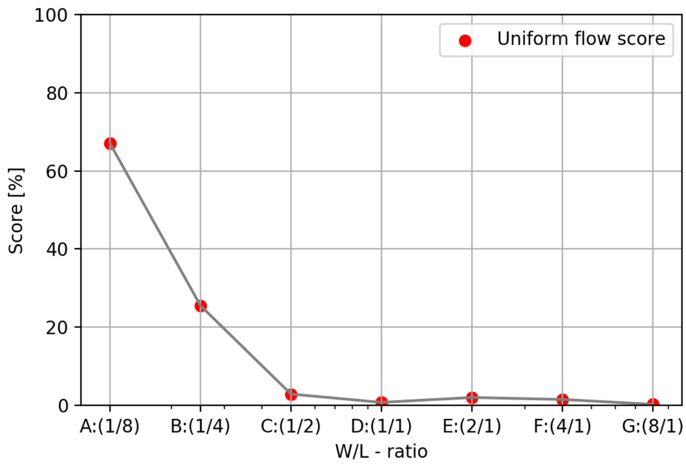
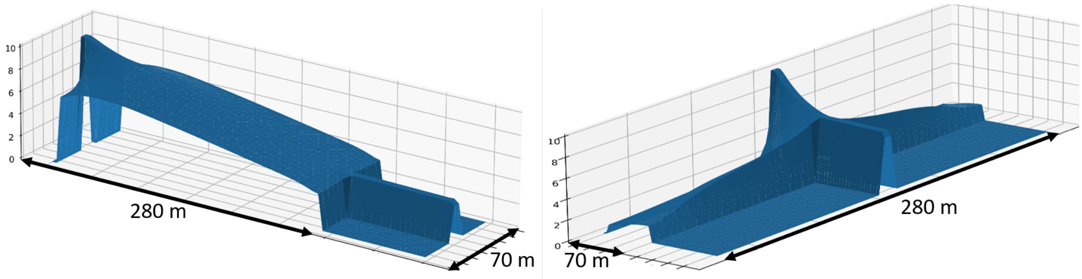


Figure 3.4: Width uniform flow conditions score. Horizontal axis: W/L-ratio (logarithmic scale). Vertical axis: uniformity score in percentages.

3.2.2. Dispersion of sediment

The distribution of sediment concentration throughout the basin depends on the W/L ratio of the basin. For narrow basins (W/L up to 1/4), the sediment concentration is approximately uniform over the width. Wider basins do not have a uniform sediment concentration over the width of the basin. This is visualized in Figure 3.5, here sediment concentration throughout basin B (W/L = 1/4) and basin F (W/L= 4/1) are shown. The sediment concentration in basin F is mainly concentrated in the middle and a large decrease can be observed towards the side of the basin.

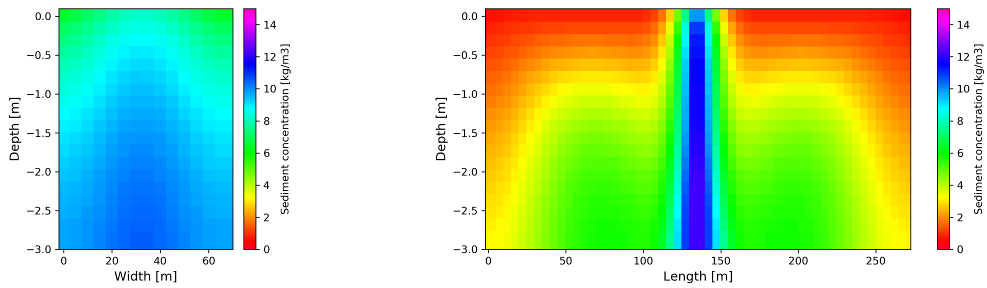


(a) Case B: W = 70 m; L = 280 m; W/L-ratio = 1/4

(b) Case F: W = 280 m; L = 70 m; W/L-ratio = 4

Figure 3.5: Sediment dispersion through two basins

A detailed view on the sediment concentration over the middle cross-section of the basin is shown in Figure 3.6. The middle cross-section of both basins is used. For case B this is at x = 140 m, for case F at x = 35 m. The sediment concentration over the width of case B is approximately uniform, while there are large differences in sediment concentration for case F.



(a) Case B: W = 70 m; L = 280 m; W/L-ratio = 1/4

(b) Case F: W = 280 m; L = 70 m; W/L-ratio = 4

Figure 3.6: Sediment dispersion over the middle cross-sections for two basins

The score for width uniform sediment concentrations is determined in the same way as the width uniform flow velocity (Figure 3.4).

Figure 3.7 shows the results of the comparison. On the x-axes the W/L-ratio is shown (on a logarithmic scale) and on the y-axes the score (in percentages) is shown. The different scores show a rapid decrease in uniformity for wider basins. Uniform sediment concentration is valid for narrow basins up to W/L = 1/4. Wider basins are not suitable for a 2DV approach.

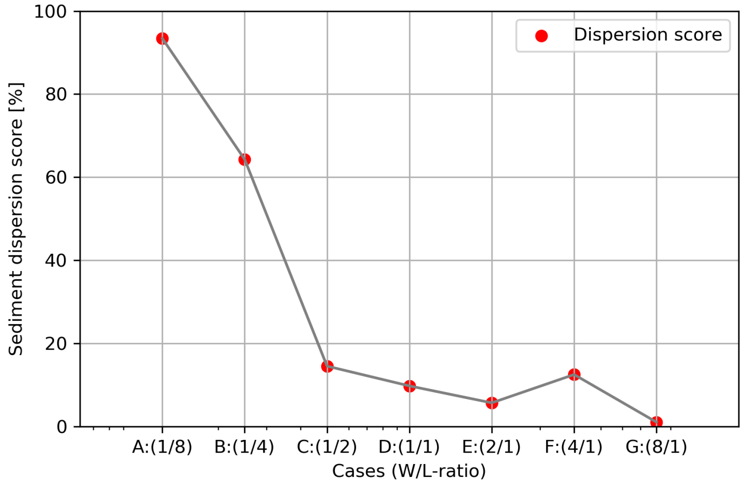


Figure 3.7: Width uniform sediment dispersion score. Horizontal axis: W/L-ratio (logarithmic scale). Vertical axis: uniformity score in percentages.

3.2.3. Outflow concentrations

The 2DV (RWQ model) and 3D (Delft3D) approach estimate the outflow concentration differently (Figure 3.8). As the 2DV model assumes the flow and sediment concentration is perfectly distributed over the width of the basin, the 3D model shows this is not representative (for these assumptions).

The increase of predicted outflow concentration by the Delft3D model for increasing W/L-ratio is due to less spreading over the basin: the mixture is flowing straight towards the outflow and is not using the complete basin to settle. The effective basin space is therefore much smaller. The RWQ model decreases in outflow prediction for an increasing W/L-ratio. The inflowing mixture is perfectly mixed over the complete width. The total area of the basin stays the same. As the inflow concentration is spread over a larger volume (larger width), the average concentration is lower and has more space to settle.

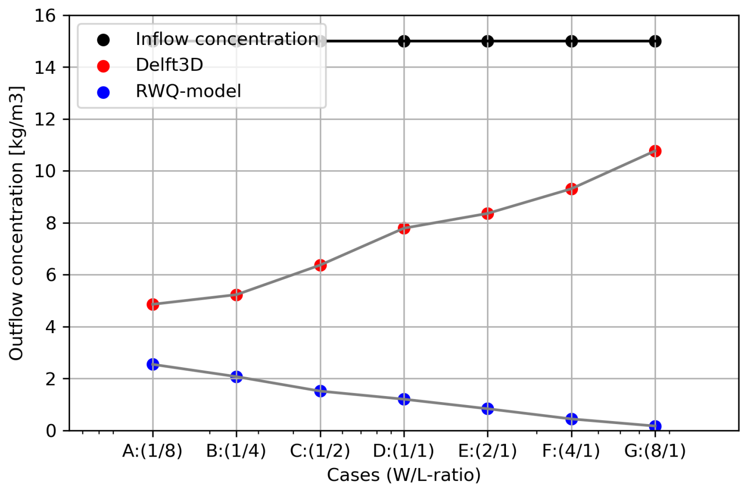


Figure 3.8: Outflow concentration for the geometry cases, width uniform conditions scenario. Red: Delft3D. Blue: RWQ model. Horizontal axes: W/L-ratio per case. Vertical axes: Outflow concentration.

Extra cases are made with a reduced inflow rate (Q= 1 m^3/s), but no differences are observed. Based on these additional cases, the conclusion is drawn the inflow rate is not of influence.
A note must be made here for the rest of the research. These cases are very simplified with uniform

density and without wind. However, the scenario shows the current assumptions are not valid (for wide basins).

3.3. Density effects

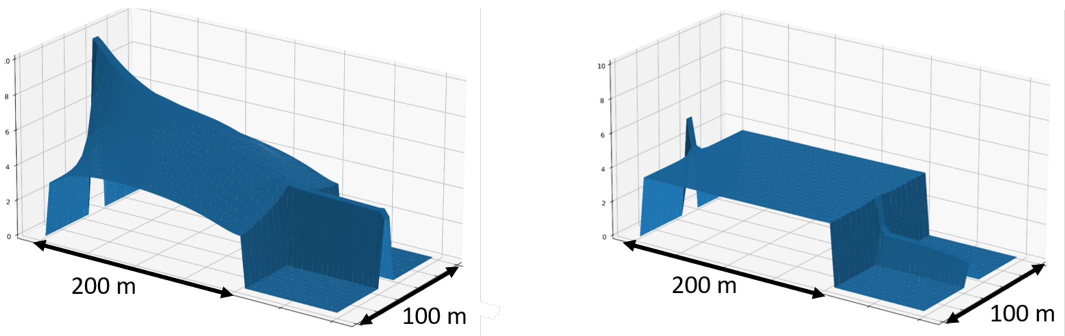
There are two transport mechanisms in settling basins. Advection by the inflow of mixture and density driven transport by the difference in density of the mixtures. The results of the scenarios show the density driven transport may not be neglected as it has large influence on the dispersion of sediment through the basin. The density driven currents minimize the gradients in sediment concentration over the width and length of the basin. The density driven currents make the flow pattern more complex and locally larger velocities can be found. The outflow concentration is estimated lower than without density differences. This is due to the (estimated) improved dispersion.

The set-up of the different cases is described in Section 2.2.3.

3.3.1. Dispersion of sediment: density driven transport

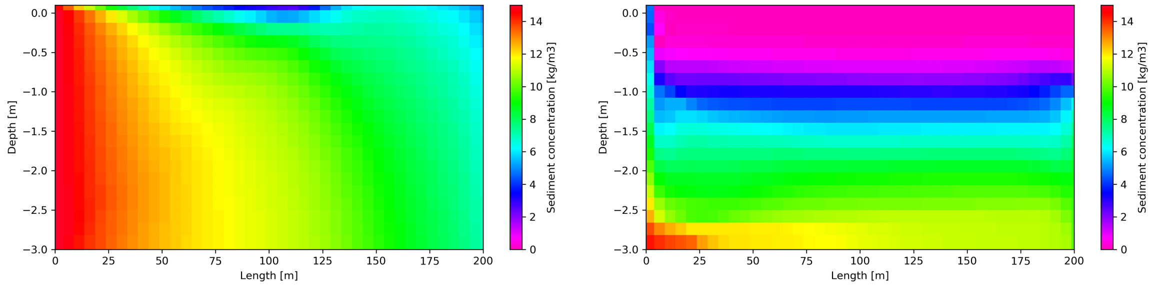
Due to difference in sediment concentration between the basin and the inflow, density driven transport will develop throughout the basin. High concentrated mixture will form a layer beneath low concentrated mixture. The hydrostatic pressure of the high concentrated layer is higher than water (or low concentrated mixture), resulting in the transport of high concentrated sediment over the bottom of the whole basin.

The difference in dispersion is illustrated with the results of two cases. For both cases, the base case dimensions are used (100 m x 200 m). Left, the result of the base case (uniform density) is shown. Right, the result of the same case but with density effects on. Figure 3.9b: The average sediment concentration is the same for every grid cell, due to density driven transport. The dispersion of sediment is further visualized by the cross-sections at 1/2W (Figure 3.10b) and 1/2L (Figure 3.11b). A layered system is formed, where the sediment concentration is constant over the horizontal plane. Differences in sediment concentration are only observed over the vertical axes (water column). This dispersion of sediment is completely different from the cases with uniform density (Figures 3.10a and 3.11a). The dispersion of sediment by density driven transport makes a 2DV solution applicable for settling basins, like is done by the RWQ model.



(a) **Uniform density**; (b) **Sediment concentration based density**;

Figure 3.9: Average sediment concentration over the water column through the basin.



(a) **Uniform density**; (b) **Sediment concentration based density**;

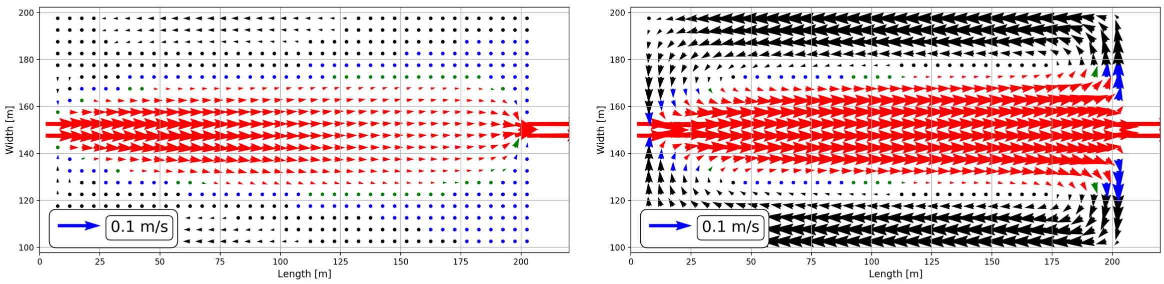
Figure 3.10: Cross-section of sediment concentration over the length of the basin (at y = 1/2 W).

(a) **Uniform density**; (b) **Sediment concentration based density**;

Figure 3.11: Cross-section of sediment concentration over the width of the basin (at x = 1/2 L).

3.3.2. Flow profile: density driven currents

The flow pattern changes due to the density currents. Locally, the flow velocity is higher. The depth average flow profile is shown in Figure 3.12. The left figure shows the depth averaged flow velocity for the base case with uniform density, the right figure for the case with density determined by the sediment concentration. The circulations are in the same direction, but the flow velocities are a different order of magnitude.

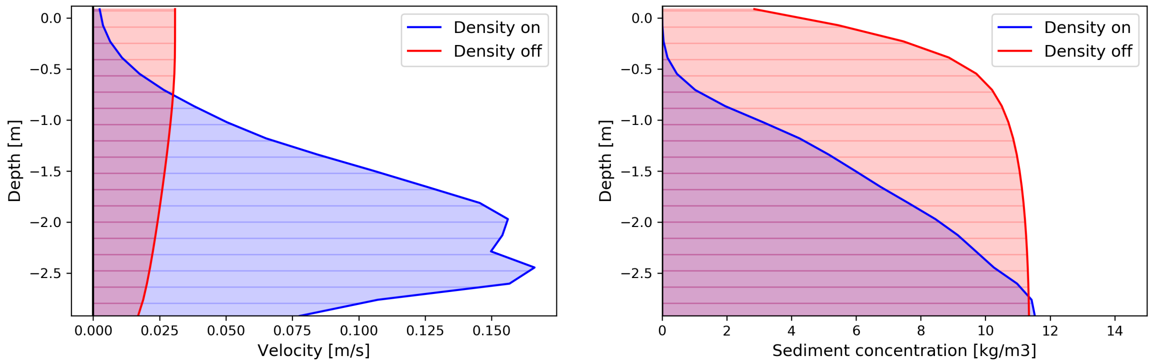


(a) **Uniform density**; (b) **Sediment concentration based density**;

Figure 3.12: Flow pattern for the base case (Case C). Comparison to show the influence of density driven currents.

To show the effect of density driven currents over the water column, the flow profile and the sediment concentration profile over the depth for the middle grid cell are shown. The flow velocity is higher for the case with density determined by sediment concentration. The sediment concentration is lower for this case. This shows two effects;

- Density driven currents develop in the basin, resulting in flow velocities that are much higher and distributed differently;
- The sediment concentration disperses faster for the case with density determined by sediment concentration.



(a) Flow profile (b) Sediment profile

Figure 3.13: Density driven currents in the middle grid cell of the basin. Left: flow profile. Right: sediment concentration profile.

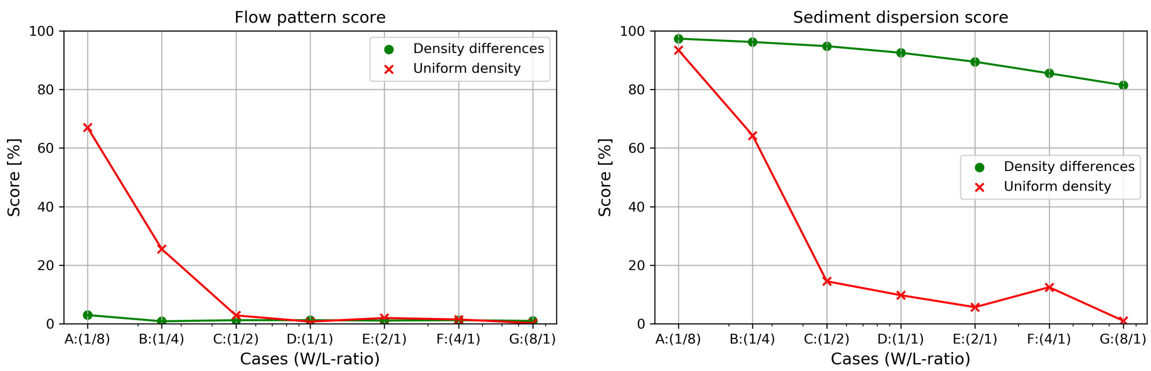
3.3.3. Outflow concentration

Due to density differences, the dispersion of sediment is improved. The sediment is moved over the entire bottom, where it has more space to settle. The available area of the basin is more efficiently used for settling.

Case	Outflow concentration	Unit
Delft3D:		
Uniform density	6.37	$[kg/m^3]$
Density determined by sediment concentration	3.08	$[kg/m^3]$
RWQ model:		
Uniform density	1.51	$[kg/m^3]$

3.3.4. Density difference implemented on geometry cases

The models show the dispersion of sediment is driven by density differences. This results in more uniform sediment concentration, and therefore higher 'sediment dispersion'-scores (calculated the same way as Figure 3.7). The sediment distribution seems approachable as width uniform, like is done by a 2DV model. The flow pattern gets more complex, and not uniform. The scores for width uniform conditions on the flow pattern (Figure 3.14a) and sediment concentration (Figure 3.14b) support these statements.



(a) Scores for uniform flow pattern. (b) Scores for uniform sediment concentration.

Figure 3.14: Flow pattern score and sediment dispersion score. Due to the density differences the flow pattern score decreases, while the sediment concentration score increases.

Figure 3.15 shows the estimated outflow concentrations for the geometry cases by Delft3D (with density differences and without density differences) and the RWQ model. Three trends are visible for an increasing W/L-ratio:

- Delft3D (no density differences): increasing outflow concentration. Due to a decreasing length of the basin and the fact the inflow mixture does not spread over the full width.
- Delft3D (with density differences): Stable outflow concentration. The density driven currents are the dominating transport mechanism and spread the sediment over the full width of the basin.
- RWQ model (no density differences): Decreasing outflow concentration. A larger width means better mixed (lower concentration/m^2) at the start of the basin, resulting in more space for the mixture to settle.

The (near) constant outflow concentration shows the independence of the geometry of a settling basin to the W/L-ratio when taking density driven currents into account.

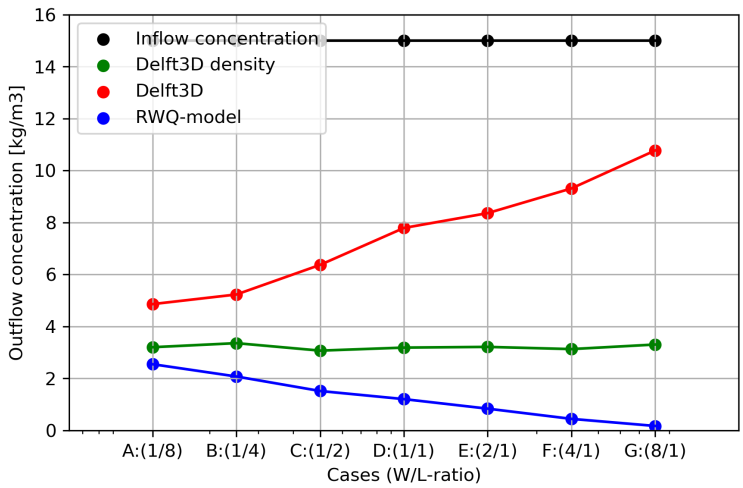


Figure 3.15: Outflow concentration for different basin geometries (W/L-ratio). Density differences on (Delft3D, green), density differences off (Delft3D, red) and RWQ-model (blue).

3.4. Wind effects

Wind induces two processes: additional mixing of sediments and secondary flow. Mixing opposes settling, and therefore higher outflow concentrations are found. The effect of secondary flow, where high concentrated mixture could be directed to the outflow, seems less influential. Therefore, the increase in outflow concentration is mainly caused by wind velocity; wind direction shows minor influence.

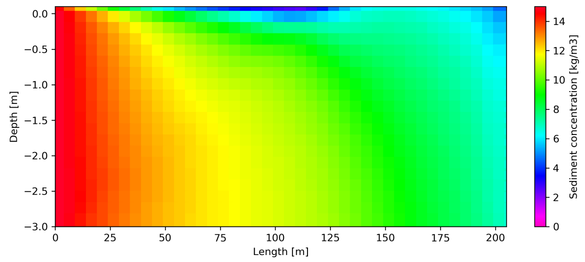
Note, the influence of density differences are not implemented in this scenario. The results of the scenario with combined effects are shown in Section 3.5.

3.4.1. Sediment dispersion: additional mixing of sediments

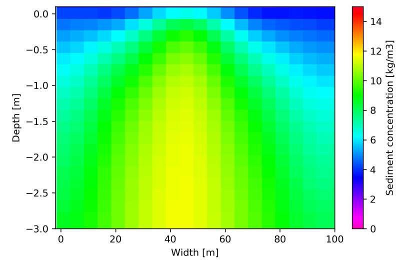
Wind causes additional mixing in the settling basins. This can be seen in Figure 3.16. The sediment concentration over cross-sections of the base case are compared. In the first two plots, the base case without wind is used. In the other plots wind is from different directions: 0 °, 90 ° and 180 °. The left plots show the length cross-sections, the right plots show width cross-sections.

Additional mixing due to the wind can be seen. When no wind is present, the sediment concentration decreases over the length of the basin. When wind is present, the sediment is dispersed throughout the entire basin and over the water column. The sediment concentration is nearly uniform over the width cross-sections for all cases with wind.

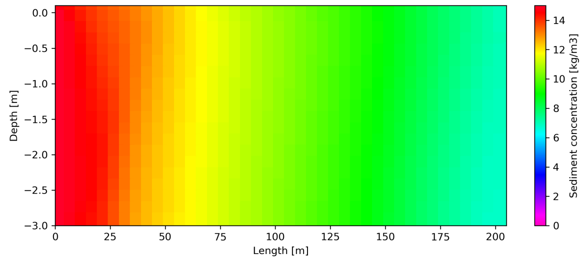
These results do not only confirm the additional mixing due to wind. It also does show the direction of the wind is not important for the mixing of sediments. Additionally, the direction of wind does not create local differences in sediment concentration (due to secondary flow).



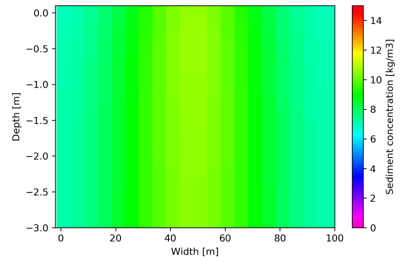
(a) Dir = 00, Vel = 00: Length



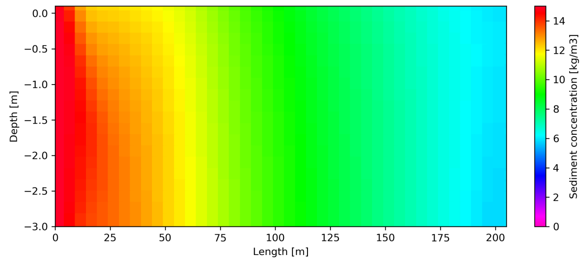
(b) Dir = 00, Vel = 00: Width



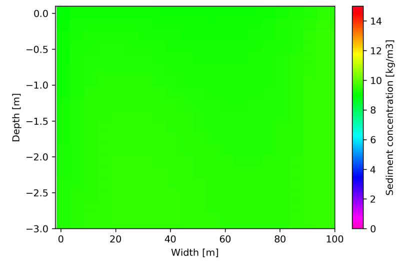
(c) Dir = 00, Vel = 10: Length



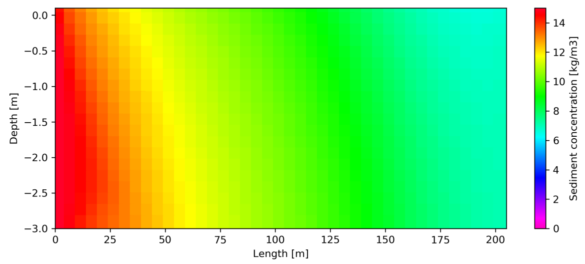
(d) Dir = 00, Vel = 10: Width

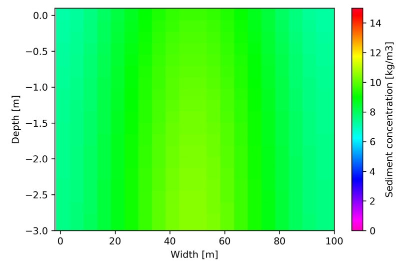


(e) Dir = 90, Vel = 10: Length



(f) Dir = 90, Vel = 10: Width





(g) Dir = 180, Vel = 10: Length (h) Dir = 180, Vel = 10: Width

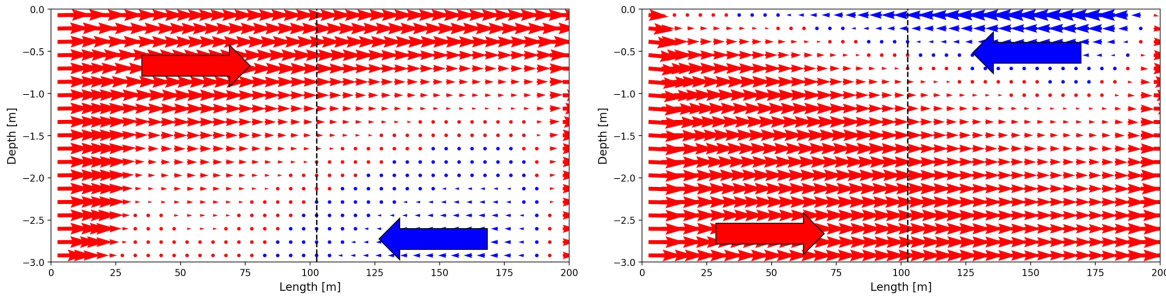
Figure 3.16: Additional mixing due to wind from all directions.

3.4.2. Flow profile: secondary circulations

Secondary flow originates in a settling basin when the wind blows over the basin. Figure 3.17 shows secondary flow for wind from 0 ° and wind from 180 ° (with respect to the flow direction).

The secondary flow is induced due to the increased shear stress by the wind. The shear stress moves water towards one side of the basin, where it is piled up. A return current under water will be formed in the other direction. The return current is formed due to increased hydrostatic pressure that is formed by the water piled up. Secondary flow can be in the same direction as the general flow (Figure 3.17a) or in the opposite direction (Figure 3.17b).

Local currents of high concentrated sediment straight towards the outflow could not be observed. The sediment is completely mixed throughout the basin such that no large gradients in the concentration exists. No clear relation could be found when comparing the flow pattern (Figure 3.17) with the concentration pattern (Figure 3.16).



(a) dir = 0 °, vel = 10 m/s

(b) dir = 180 °, vel = 10 m/s

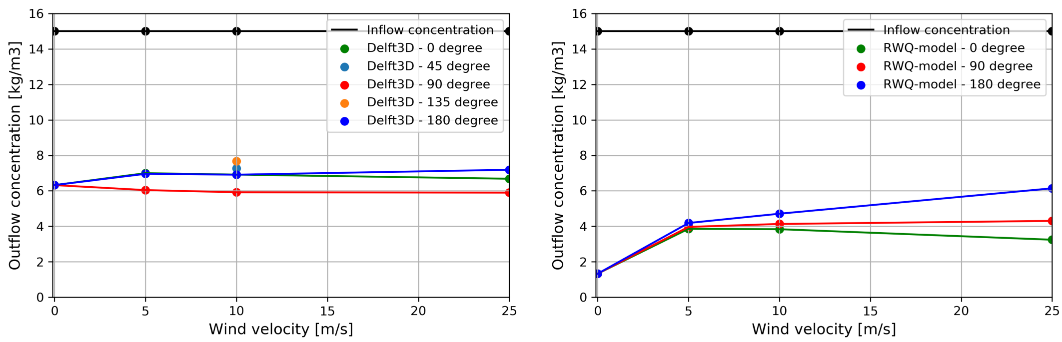
Figure 3.17: Velocity profile over the middle cross-section

3.4.3. Effect on outflow concentration

The outflow concentration is shown in Figure 3.18. Left: the estimated outflow concentration by Delft3D. Right: the estimated outflow concentration by the RWQ model.

The following differences on the outflow concentration are recognized:

- The scenarios in absence of wind differ significantly. This might show differences in the calculated mixing between both models.
- Due to this difference, the relation for increasing wind velocity is different as well. The increase for Delft3D is much smaller than the increase for the RWQ model.
- The direction of the wind has more influence for the RWQ model than for the Delft3D model. This could possibly be explained by the difference in outflow boundary. For the RWQ model the outflow boundary is present over the complete width, while for the Delft3D model this is much narrower.



(a) Delft3D

(b) RWQ model

Figure 3.18: Outflow concentration affected by wind.

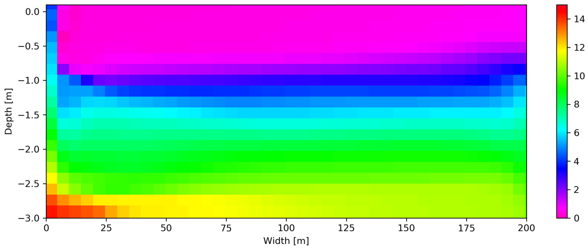
3.5. Density & wind

Wind induces additional mixing while density differences suppresses mixing. The dispersion of sediment throughout the basin will be governed by either of these mechanisms. Density is the governing mechanism for regular wind velocities up to 10 m/s (for the used settings). For stormy conditions (wind velocity > 10 m/s), wind will be the governing mechanism. Density dominated cases show highly concentrated mixture near the bottom and lower outflow concentrations. Wind dominated cases show sediment mixed over the full water column and higher outflow concentrations.

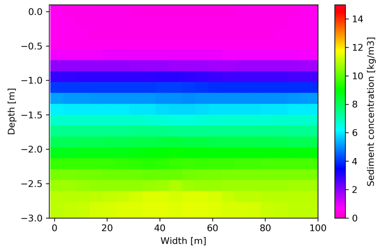
3.5.1. Dispersion of sediment: governed by wind or density differences

The distribution of sediment concentration shows which mechanism is leading. For density governed cases the sediment concentration will form horizontal layers over the bottom of the basin. When wind conditions are determining, the sediment is mixed over the full water column. In other words, for density dominated cases vertical gradients in the sediment concentration can be observed. For wind dominated cases no gradients in sediment concentration can be observed.

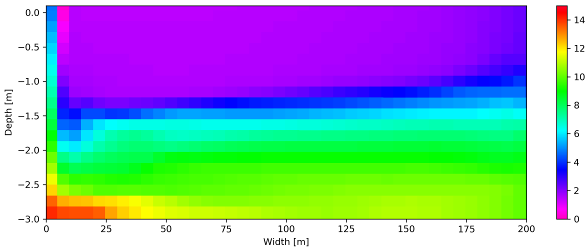
The difference in either wind or density governed cases is shown in Figure 3.19. Up to vel=10 m/s the dispersion of sediment is governed by density differences. When the wind is strong enough, the wind will govern the sediment dispersion. Then, additional mixing can be observed. Only the case with wind from 180 ° is shown. The wind velocity is set to 5, 10, 15, 20 and 25 m/s. The resulting sediment dispersion in length and width direction along the middle cross-section are shown.



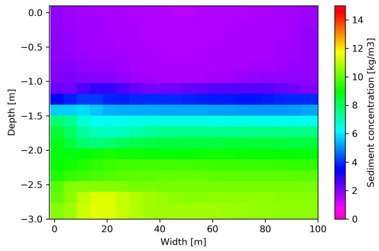
(a) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 5 m/s



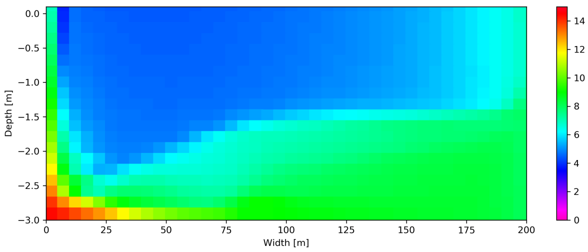
(b) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 5 m/s



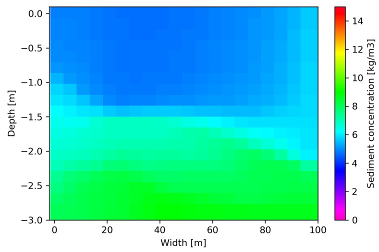
(c) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 10 m/s



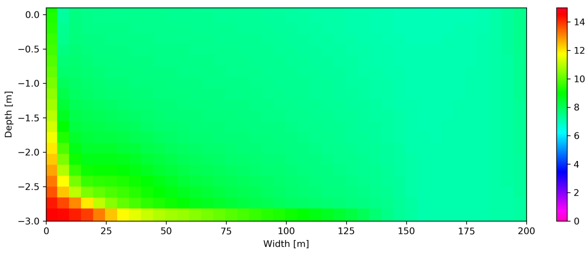
(d) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 10 m/s



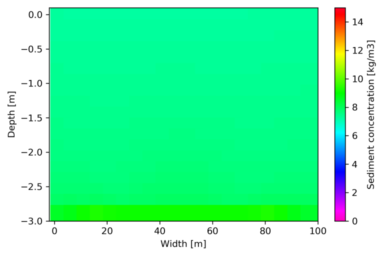
(e) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 15 m/s



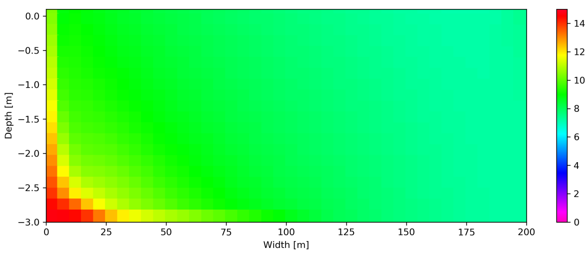
(f) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 15 m/s



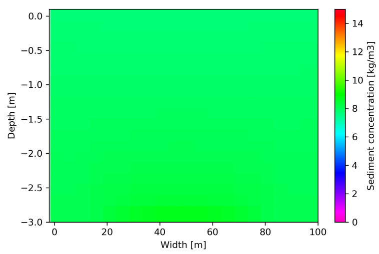
(g) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 20 m/s



(h) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 20 m/s



(i) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 25 m/s



(j) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 25 m/s

Figure 3.19: Dominance by either wind or density differences

3.5.2. Outflow concentration

Dominance by wind increases mixing and therefore reduces the settling of fine sediments. Results of the outflow concentration support this finding. The wind needs to overcome a certain threshold before it increases the outflow concentration. Figure 3.20 shows this threshold is dependent on the direction, and lies between 5 and 15 m/s, around 10 m/s. The outflow concentration for stormy conditions (wind velocity > 25 m/s) shows the same increase in outflow concentration.

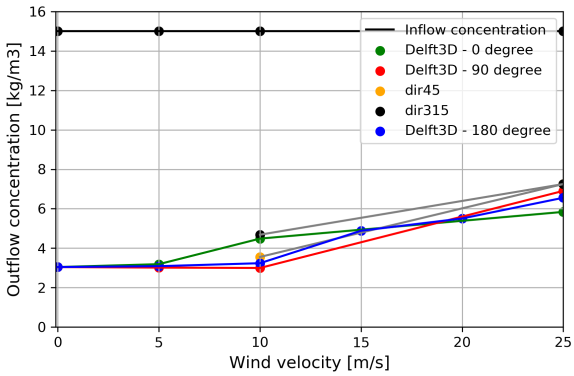


Figure 3.20: Outflow concentration for the scenario with density and wind combined. The dots are results from cases. The lines are interpolations between the results.

In the considered cases the transition from density-dominated to wind-dominated is around 10 m/s. However, this will be different for other cases. The strength of the density driven current is dependent on the sediment characteristics. Larger particles will sustain longer from being (re)suspended by wind. However, one should keep in mind that the outflow concentration will always increase when wind is dominant. Thus, storm conditions could increase the outflow concentration (here: times 2).

3.5.3. Geometry cases

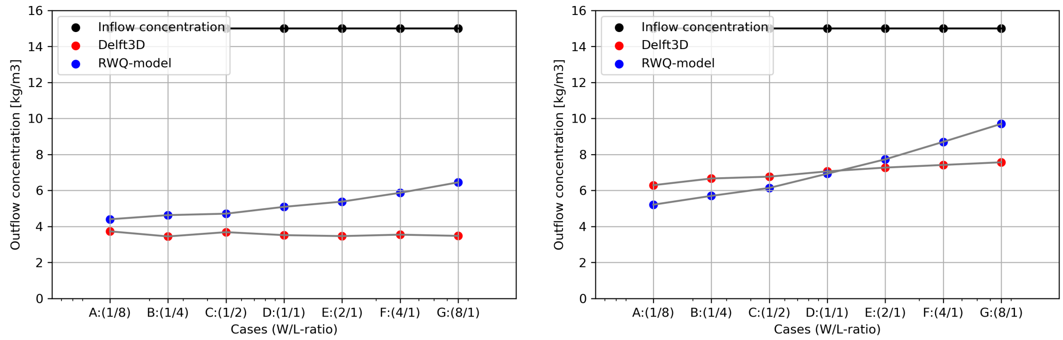
The model comparison results are described with different geometry cases. The results can be found in Figure 3.21, 3.22 and 3.23.

- The influence of the different shapes (W/L-ratio) is very low. All different geometry cases in a set show nearly the same result. In all cases the strength of the wind (10 m/s vs 25 m/s) has a large influence on the outflow concentration. All sets support this statement.

- The direction of the wind does influence the outflow concentration, but the changes in outflow concentration are minor. This is supported by comparing the results of set 1 and set 2.

- The settling velocity has a major influence on the outflow concentration. The increase in outflow concentration between set 1 and set 3 is a factor of 2. This is the same order of magnitude as regular conditions (10 m/s) vs storm conditions (25 m/s). When wind is increased to 25 m/s and settling velocity decreased, the total increase in outflow concentration can be 4 times higher.

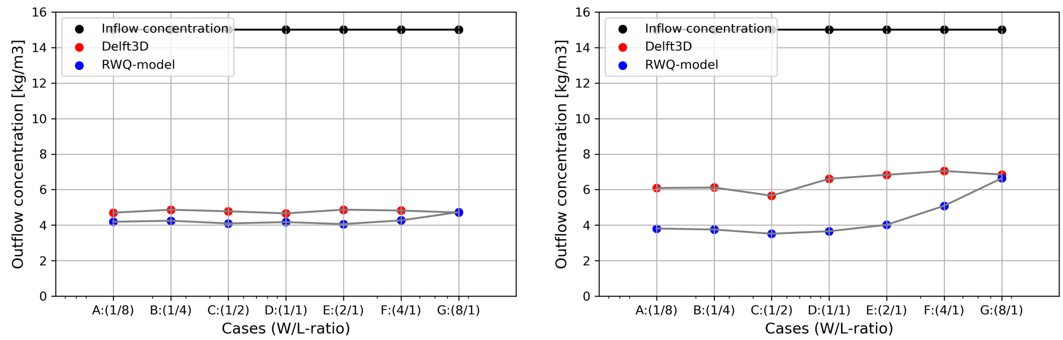
Set 1



(a) Wind velocity = 10 m/s (b) Wind velocity = 25 m/s

Figure 3.21: Outflow concentration set 1.

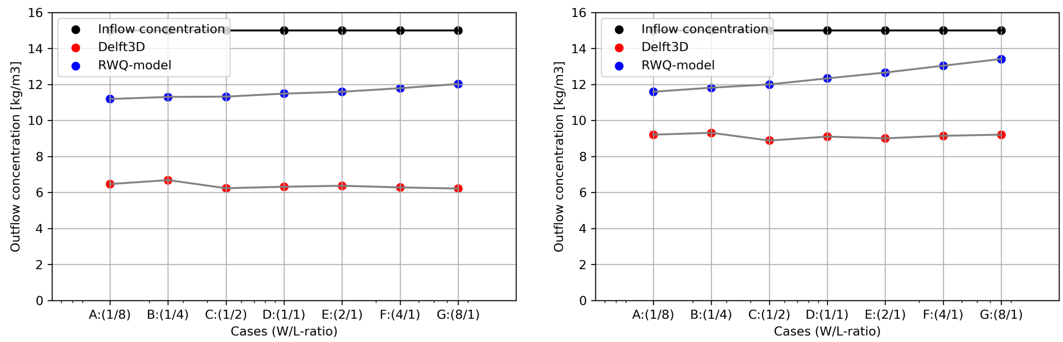
Set 2



(a) Wind velocity = 10 m/s (b) Wind velocity = 25 m/s

Figure 3.22: Outflow concentration set 2.

Set 3



(a) Wind velocity = 10 m/s (b) Wind velocity = 25 m/s

Figure 3.23: Outflow concentration set 3.

3.5.4. Richardson number

The Richardson number, *Ri*, is a measure of the relative strength of the density gradient compared to the strength of the flow of water. The Richardson number is described in (amongst others) Galperin et al. [2007] as:

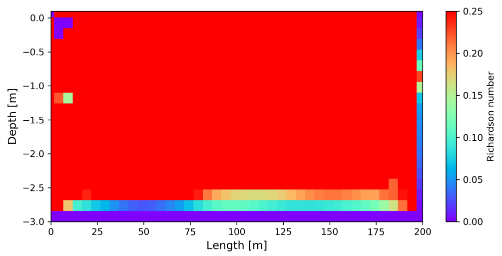
$$Ri = \frac{N^2}{S^2} \tag{3.4}$$

Where N^2 is the square of the buoyancy (here: $N^2 = -g(\delta\rho/\delta z)/\rho_0$) and S is the vertical shear of the horizontal velocity (here: $S^2 = \left[(\frac{\delta u}{\delta z})^2 + (\frac{\delta v}{\delta z})^2\right]$).

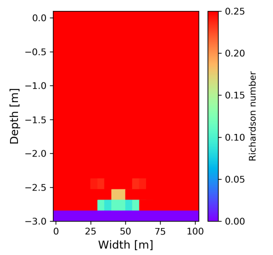
For high Richardson numbers ($Ri > Ri_c$) the system is stratified and layers with different levels of density are formed. When the Richardson number is low ($Ri << Ri_c$), the system is mixed and no layers can be identified. Here, Ri_c is the critical Richardson number. Ri_c is between 0.25 and 1. The exact value of Ri_c depends on the velocity ratio, $\zeta = \frac{U}{W}$ with U = average flow velocity in basin and W = inflow velocity [Winterwerp, 2002]. As the velocity ratio is very low in settling basins, the lower boundary of Ri_c is assumed to be applicable for this case.

The Richardson number is calculated for the cases with density differences applied. Without any density differences, $\delta\rho = 0$ and therefore $Ri = 0$ (Equation 3.4).

The Richardson number is calculated for the base case with density differences (Figure 3.24). This case does not contain any wind. As one can see, the Richardson number of the system is mostly >0.25. Therefore, the system is highly stratified. This is in agreement with the found concentration distribution from Section 3.3. Near the bottom the Richardson number decreases. This can be explained by looking at the previous plots of concentration and flow velocity (Figure 3.10 and Figure 3.13). The $\frac{\delta\rho}{\delta z}$ decreases over the lowest row. The flow velocity is still relatively high. Looking at Equation 3.4 shows the Richardson number will decrease. This behaviour could occur due to the settings used in the Delft3D model; settling does occur but the bathymetry is not updated.



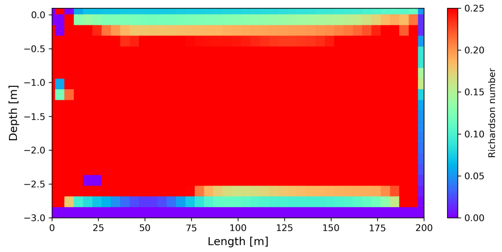
(a) Cross-section: (y=1/2W, x=0 to x=L)



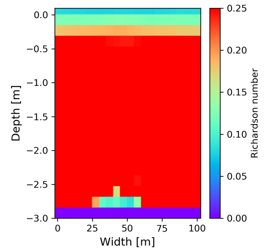
(b) Cross-section: (x=1/2L, y=0 to y=W)

Figure 3.24: Richardson number in the base case with density differences.

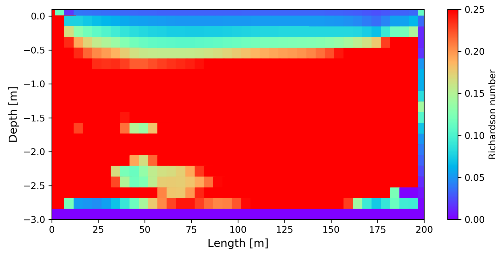
Figure 3.25 shows the transition from a stratified system to a mixed system. The same cases as Figure 3.19 are used. The Richardson number decreases as the wind increases. The system gets more mixed and the influence of the density driven currents decreases. In this example, the transition from a stratified system to a mixed system is around 15 m/s. Comparing the Richardson number with the outflow concentration of the exemplary cases (Figure 3.20), it can be concluded that more mixed systems experience higher outflow concentrations.



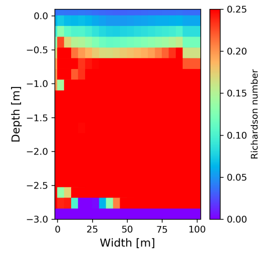
(a) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 5 m/s



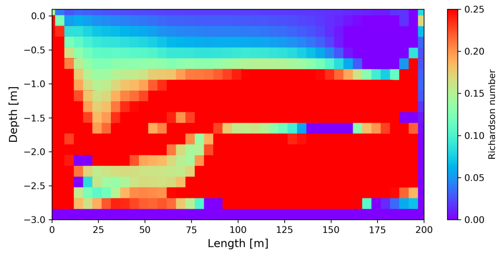
(b) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 5 m/s



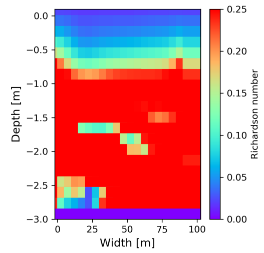
(c) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 10 m/s



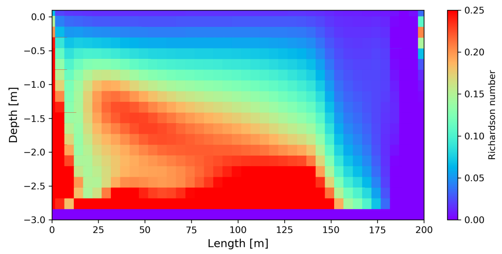
(d) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 10 m/s



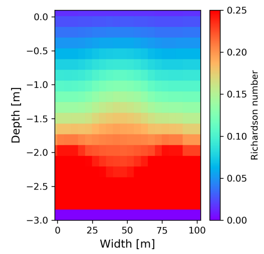
(e) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 15 m/s



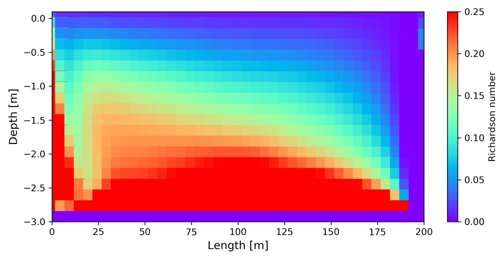
(f) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 15 m/s



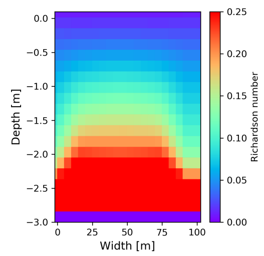
(g) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 20 m/s



(h) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 20 m/s



(i) Cross-section: (y=1/2W, x=0 to x=L)
Wind dir = 180 °, vel = 25 m/s



(j) Cross-section: (x=1/2L, y=0 to y=W)
Wind dir = 180 °, vel = 25 m/s

Figure 3.25: Richardson number for cases with dominance by either wind or density differences

3.6. Sensitivity analysis

3.6.1. Sensitivity to physical effects

An overview of the model sensitivity to different physical effects is given in Table 3.1. The base case is used with a number of influencing effects. The sensitivity analysis is not generally applicable. The goal of the analysis is to give an indication of the increase of outflow concentration. Three different models/settings are used: Delft3D without density differences, Delft3D with density differences and the RWQ model (without density differences).

The shown outflow concentration corresponds to the used input value as **minimum** and **maximum**. The **factor** is the factor between the minimum and maximum outflow concentration ($\frac{max}{min}$). The factor indicate the relative increase of the effect on the outflow concentration. As an example the settling velocity is described. The outflow concentration shows to be highly influenced by the settling velocity. The factor is therefore around 6 for Delft3D (for both settings) and >700 for the RWQ model.

Conclusions that can be drawn from the results of the sensitivity analysis are:

- The largest influencing factor is the influence of the settling velocity. However, the expected influence by the RWQ model seems to be overestimating the effect. Delft3D (both with and without density differences) shows the influence is much smaller.

- The effect of the density differences can be seen from the influence by the wind velocity, inflow concentration and W/L-ratio. Low wind velocities do not influence the outflow concentration. The outflow concentration by minimum wind velocity is therefore significantly lower when density differences are taken into account. The inflow concentration is increased by a factor 9, while the outflow concentration for Delft3D-density is only a factor 4.7. This shows that the effect of hindered settling is less present when density differences are taken into account. Lastly, the conclusion of the independence of a W/L-ratio is shown here again.

- Delft3D estimates the difference in outflow concentration between different wind directions lower. As the maximum and minimum outflow concentration have different directions, no directions are shown.

Some remarks must be made on this sensitivity analysis. As no combinations of effects are taken into account, some influencing factors strengthen each other when combining them. Example: the effect of the wind velocity could be increased and smaller particles used (lower settling velocity). One should take this (and other, non described combinations) into account when using this overview.

The scenarios for different settling velocities and inflow concentrations can be found in Appendix A.1.

Influencing effect		Delft3D-Uniform $[kg/m^3]$	Delft3D-Density $[kg/m^3]$	RWQ model $[kg/m^3]$
Wind direction				
Min	[°]	5.90	6.55	3.24
Max	[°]	7.19	6.90	6.14
Factor	[-]	1.2	1.1	1.9
Wind velocity				
Min	5 $[m/s]$	6.32	3.01	3.86
Max	25 $[m/s]$	7.19	6.90	6.14
Factor	[-]	1.1	2.3	1.6
Settling velocity				
Min	$2.5x10^{-6}[m/s]$	14.64	7.49	14.23
Max	$2.5x10^{-4}[m/s]$	2.32	1.23	0.02
Factor	[-]	6.3	6.1	711.5
Inflow concentration				
Min	$5[kg/m^3]$	2.09	1.56	0.51
Max	$45[kg/m^3]$	19.79	7.40	4.55
Factor	[-]	9.5(/9=1.1)	4.7(/9=0.5)	8.9(/9=1.0)
(W/L)-ratio				
Min	1/8	4.86	3.20	2.55
Max	8/1	10.77	3.30	0.17
Factor	[-]	2.2	1.0	15

Table 3.1: Overview table of sensitivity analysis on outflow concentrations

3.6.2. Sensitivity to model parameters

Apart from the sensitivity to physical parameters, the model also uses a number of model parameters. These model parameters could be used to validate a model, when comparing to measurements for instance. As the models used are not calibrated and the used model parameters are estimated values, the sensitivity to these model parameters are qualitatively described.

Delft3D uses the k-ϵ turbulence model. For this turbulence model the input of background eddy viscosity and diffusivity are required. The sensitivity analysis shows the processes inside the basin are highly dependent on the given input. The background eddy viscosity shows determining for the originating flow pattern and the influence of the jet flow (by the inflow pipe). The background eddy diffusivity is responsible for density driven transport. Therefore, the diffusivity-input is determining for the influence of density driven currents. When the background diffusion coefficient is smaller, the influence of the density difference is (relatively) larger, and the density driven currents are formed.

The wind drag coefficient determines the influence of the wind on the water surface. Here, different definitions are possible, determined by the climate on the location of the project (air temperature and pressure). The conclusion is drawn that for all commonly used wind drag coefficients the influence is minor. Especially when one compares the influence of the wind drag coefficient to the uncertainty in wind velocity or wind direction. The used wind drag coefficients are based on the used values in Lange [2011] and Deltares [2011a].

3.7. Summary and conclusion

Width uniform conditions:
The ”width uniform conditions”-scenario shows the current approach of uniform conditions over the width in the RWQ model are only valid for very narrow cases. Both flow velocity and sediment concentration are only width uniform for narrow cases (W/L-ratio ≤1/4). The influence of the in- and outflow is observable throughout the whole basin and can not be neglected (as neglecting this influence is part of the assumptions). The outflow concentration differs a lot; in Delft3D the geometry has an high influence while not in the RWQ model.

Density differences conditions:
Density differences throughout the basin have a large influence on the dispersion of sediment. Driven by diffusive transport, the distribution of sediment concentration is uniformly spread over the basin. The sediment disperses evenly as an highly concentrated layer over the bottom of the basin. The sediment distribution seems approachable as width uniform, like is done by a 2DV model. The flow profile is complex and not suitable to approximate with a 2DV approach.

The highly concentrated layer is also formed for mixtures with a lower concentration. Sediment with high settling velocity induces a stronger density current, but due to fast settling sediments the density driven currents die out quickly. Slow settling sediment stays longer in the upper part of the water column and the high concentrated layer is not formed on the bottom of the basin. These statements are further supported in Appendix A.1.

Wind conditions:
Wind induces additional mixing and therefore higher outflow concentration. The additional mixing increases with higher wind velocities. The direction of the wind seems to be less important. Based on this observation, the conclusion is drawn that secondary circulation has a minor influence on the outflow concentration.

Combined conditions:
When wind and density differences are combined, density differences suppress the additional mixing induced by the wind. However, when the wind gains in strength (wind velocity > 10 m/s), the influence of the wind will increase and the additional mixing due to wind will dominate over the suppressing effect of density differences.

Sensitivity analysis:
The RWQ model is more sensitive to the settling velocity of the particles. The geometry (W/L-ratio) of a basin is less important. The dense, concentrated layer near the bottom diffuses over the whole basin. The difference between the RWQ model and Delft3D model are dependent on the wind (direction and velocity) and the settling velocity of the individual particles.

4

Filling behaviour in settling basins

This chapter shows the filling behaviour over time in settling basins. While filling a settling basin with dredged slurry (mixture), the storage capacity decreases. This results in a shorter retention time for the mixture. The effect of decreasing storage capacity on the outflow concentration is not clear. A shorter retention time could mean less settling of sediment, and therefore an increase of outflow concentration for a fuller basin. However, less depth could also result in less mixing (by the wind).

This chapter first identifies the physical effects influencing the filling behaviour. Cases are modelled with Delft3D to show how basins are filled. The outflow concentration is plotted over the time. The effect of filling (and the resulting decrease of storage capacity) on the outflow concentration can be seen.

4.1. Approach

The filling of a settling basin is a cumulative process on a relatively large time scale. Small fluctuations are unimportant and therefore neglected. An estimate of the formed bathymetry needs to be made on the basis of representative parameters.

Three different settling velocities (grain sizes) are used. First, the settling velocities are used separately. Second, a combined case is shown. This means first the individual influence of the settling velocity can be seen, and next the effect of combined settling velocities.

As small fluctuations are neglected, the assumption is made wind has no influence. Only long, consecutive wind is expected to influence the formed bathymetry. However, this seems unlikely and making this case unnecessarily complex. In Appendix B.1 the results of wind cases are shown. These results support the assumption made here.

Chapter 3 stresses the importance of density differences and density driven currents in settling basins. Density driven currents are taken into account here. To see the influence on the formed bathymetry, additional scenarios without density driven currents are shown in Appendix B.3.

Further variables of influence on the settling behaviour could be the inflow concentration, inflow rate, density of settled material and erosion rates. For all these considerations representative values are chosen. Again, a very precise estimation for one particular project would not be effective as only an indicative answer is useful. The dependency of the settling behaviour is low for the representative values and their fluctuations.

4.1.1. Modelled cases

For the filling behaviour scenario, four cases are set-up (A, B, C and D). The grid of the base case is used. In the cases the morphology is updated according to the settled sediments. The cases are all similar, only the particle fall velocity is changed. The key input values for the cases can be found in Table 4.1. Case A to C all consist of one sediment fraction. Case D consists of a combination of case A, B and C. The total inflow concentration is for all cases 15 kg/m^3. A morphological scale factor has been applied to accelerate settling.

Filling behaviour cases	Input
Length	200 m
Width	100 m
Depth	3 m
Inflow rate	2 m^3/s
Inflow concentration	15 kg/m^3
Density differences	on
Morphologic scale factor	5
Simulation time	96 hrs
Settling velocity	
Case A	1.0 mm/s
Case B	0.1 mm/s
Case C	0.025 mm/s
Case D	combination

Table 4.1: Input values for the filling behaviour cases

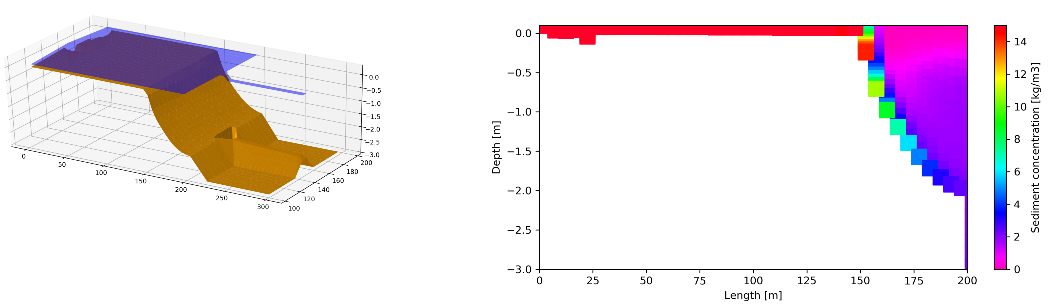
4.2. Three forms of settling

Three different forms of settling are distinguished. A bathymetry plot and cross-section of sediment concentration are shown (Figures 4.1 to 4.3). Per case a small description of the settling behaviour is given.

Case A: high settling velocity

Case A has sediment with high settling velocity (1 mm/s). The sediment settles directly when entering the basin. The bottom fills up to the level where the flow velocity becomes too high for the particles to settle (up to -0.1 to -0.2 m). The sediment concentration is almost zero for the rest of the basin. The basin fills fast and controlled: starting at the inflow and moving towards the outflow.

For most cases this kind of settling is perfect; almost no outflow of suspended sediment matter and very local settling of sediment. Local settling of sediment makes it easy to quickly empty the basin when required to do so.



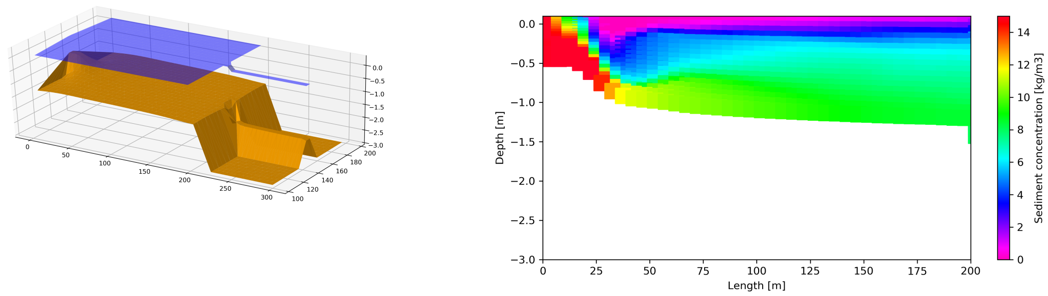
(a) 3D plot case A

(b) Spread plot case A

Figure 4.1: Filling behaviour case A

Case B: medium settling velocity

Case B has sediment with a settling velocity of 0.1 mm/s. This is the same settling velocity as the default for the cases of Chapter 3. Settling of the particles mainly happens near the inflow, but some sediment stays in suspension for a longer duration. The suspended sediment forms a layer with high sediment concentration over the bottom of the basin. Therefore, sediment settles throughout the whole basin.



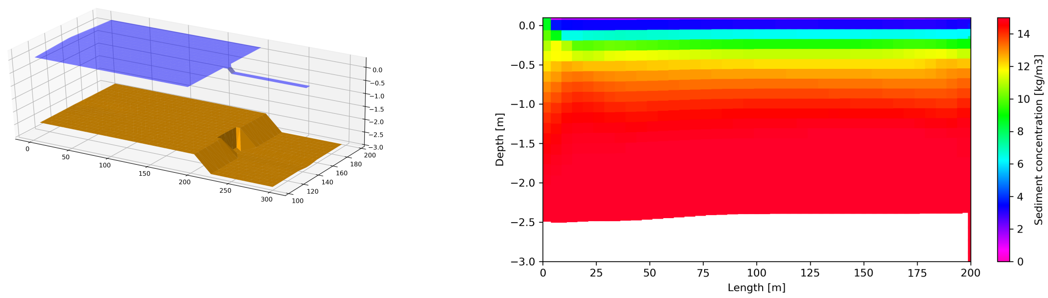
(a) 3D plot case B

(b) Spread plot case B

Figure 4.2: Filling behaviour case B

Case C: low settling velocity

Case C consists of sediment with low settling velocity (0.025 mm/s). The sediment stays in suspension over the complete basin and everywhere in the basin is the same amount of settling. The outflow concentration is still very high. This can also be seen from the bathymetry that has only changed with 0.5 m compared to the original situation. This case is the least favourable. This settling basin does not seem very effective for this case.



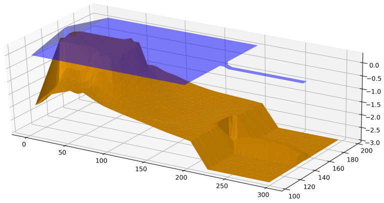
(a) 3D plot case C

(b) Spread plot case C

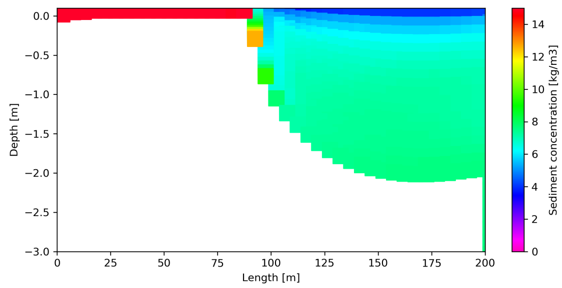
Figure 4.3: Filling behaviour case C

Case D: combined

The combined case shows a combination of settling patterns. Figure 4.4(a) shows the sediment front is starting at the inflow and spreading in all directions. In the rest of the basin there is some settling. The sediment concentration is nearly constant throughout the rest of the basin, although one is still able to see the vertical gradient. As visible on the 3D plot, the settling is not uniform over the width of the basin.



(a) 3D plot case D



(b) Spread plot case D

Figure 4.4: Filling behaviour case D

4.3. Influence on outflow concentration

The outflow concentration has been plotted over the time of the simulation. The material of case B and C stays longer in suspension, as could be expected from the previous section. Before their outflow concentration becomes stable, the water in the basin is first saturated with mixture. Up to this point the outflow concentration increases. The finer the material is, the longer takes (settling velocity of case B vs settling velocity of case C). Case A has too coarse material which settles directly: the water in the basin does not get saturated with mixture.

As almost all sediments settle in Case A, the storage capacity of the basin decreases rapidly and the outflow concentration starts to increase. Case B and Case C stay constant. This means that from the starting point (empty basin, depth is at -3 m everywhere) to the end of the simulation (Figure 4.2, 4.1, 4.3) there is no effect on the outflow concentration. This shows the outflow concentration is not very sensitive to the depth.

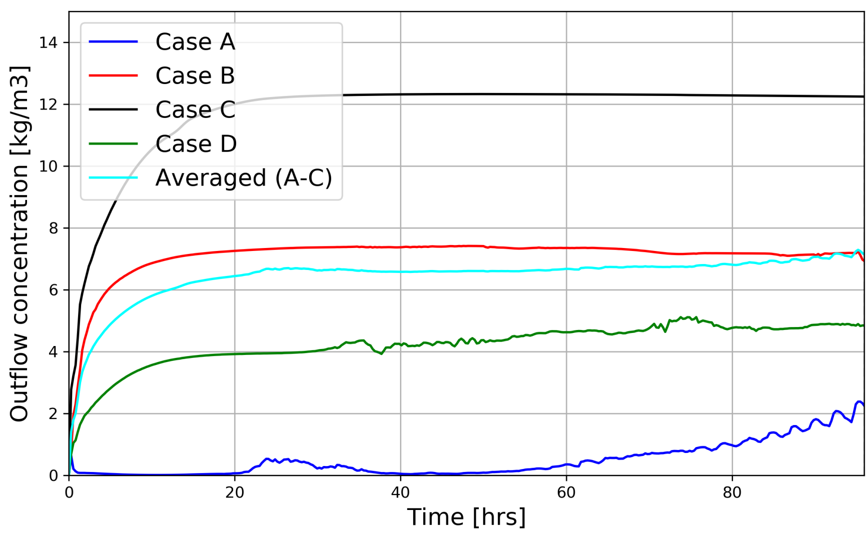


Figure 4.5: Outflow concentration over time

4.4. Concluding remarks

The filling behaviour is dependent on the settling velocity of the particles. High settling velocity (Case A: 1.0 mm/s) will cause settling in the vicinity of the inflow. Spreading from the inflow, moving like a front towards the outflow. When the settling velocity is lower (Case B: 0.1 mm/s), sediment is spread further over the basin. Still, most settling is in the vicinity of the inflow. For sediment with a very low settling velocity (Case C: 0.025 mm/s), settling occurs throughout the whole basin nearly uniform. Most sediment does not settle and flows out of the basin again. In all cases the inflow concentration is constant at 15 kg/m^3. The combined case, Case D, shows a combination of all the three independent settling patterns. Here, no width uniform settling occurs, which can be seen in the separate cases.

In Appendix B.1 the results of adding wind conditions (10 and 25 m/s, 0 °) are shown. There is almost no difference in formed bathymetry between no wind and wind with a speed of 10 m/s. Wind of 25 m/s has significant influence as less material settles.

Appendix B.3 goes into the effect of density driven currents on the filling behaviour. Due to settling the depth decreases and therefore the conveying part of the basin decreases. This causes an increase in the flow velocity and a decrease in the settling. This means less settling in areas where material has already settled, and therefore the sediment spreads more uniform over the basin (than the concentration when settling is not taken into account). However, density driven currents result in a more uniform spread and less bumps. The difference in distribution of sediment concentration throughout the basin is significant; as described earlier the density differences cause a vertical gradient instead of a horizontal gradient.

5

Evaluation of RWQ assessment methodology

5.1. Validity of the current assessment

The current assessment on return water quality problems consists of designing possible settling basin configurations and testing the outflow concentration with the RWQ model. Based on the outcome of the RWQ model an advise for a suitable design is given.

The RWQ model is a good first indicator. The model is quick and easy to use. The input parameters are easy to derive from the design and the intermediate results (plotted on the screen) increase the process insight. As the model is quick and easy, different configurations can be tested and the sensitivity of different cases can be derived. For some (realistic) configurations, the predicted outflow concentration was nearly the same for the RWQ model and the Delft3D model.

However, this research shows not all processes are implemented in the RWQ model. The sediment dispersion by density differences is currently neglected, while Delft3D shows this is the leading transport mechanism. The flow (velocity) is averaged over the width of the basin, while Delft3D shows large eddies over the width and length of the basin will be formed. As the eddies get the overhand in wide basins, the width-uniformity assumption of the RWQ model is only valid for narrow basins or only for sediment dispersion. Next, in the current assessment (RWQ model) the sensitivity to (extremely) fine sediments is too large. The estimated outflow concentration for (extremely) fine sediments is too high when comparing the results with the Delft3D model. Lastly, the plots between each calculation show in high detail the spreading of sediment. As the leading mechanism of dispersing sediment is different, these plots of the sediment concentration throughout the basin might create an unrealistic sense of the processes.

There is not such as an validity domain for the RWQ model. When using the model, one should keep the following rules of thumb in mind:

- **Settling velocity:** The RWQ model is too sensitive for low settling velocities. The comparison with Delft3D (with density differences) shows the sensitivity was significantly lower. Density driven transport decreases this sensitivity.

- **Dimensions:** The real width and length of the basin should be used. In the current RWQ model an approximation of the flow pattern is used, but this is not in correspondence with flow patterns found in Delft3D. As the density differences (not implemented in the current version of the RWQ model) spread the sediment concentration through the complete basin, the full size of the basin will be used for settling.

- **Wind:** Three wind velocity conditions are determining for the outflow concentration: 5, 10 and 25 m/s. The result for the case without wind deviates between Delft3D and RWQ model (there might be not enough mixing in the RWQ model, resulting in a too low outflow concentration), therefore 5 m/s should be used for this representation. Wind velocity of 10 m/s should be used for moderate conditions. Wind velocity of 25 m/s should be used for extreme conditions. The wind directions leading to the highest outflow concentration should be used.

- **Configurations:** It is advised to neglect the morphological update function to determine the outflow concentration. The morphological update function could be used when determining the storage capacity of the basin. The flocculation add-on does not seem to function correctly.

- All other input values (sediment concentration, inflow rate, temperature etc.) should use representative values for the modelled case.

Disclaimer
These rules of thumb are drafted with a very practical view. When looking in a more theoretical way, one will conclude the RWQ model uses (too) many simplifications and the validity is uncertain. However, the resulting outflow concentration is in the same order of magnitude when using the rules of thumb. As there is not an easy alternative at this moment, these rules of thumb will increase the reliability of the RWQ model and the assessment in general.

Although the improvements in the prediction will lower the probability of a violation, conditions will always stay variable. The strategy should therefore contain more mitigating measures to lower the outflow concentration. As the costs of dredging equipment are high (and leading in general), mitigating measures that prevent a delay due to exceeding outflow concentration limits . This is further elaborated in Section 5.2: *Design considerations of settling basins*.

In conclusion, the RWQ model is good tool for a first estimator. However, with caution and knowledge of this report as not all processes are implemented correctly. For better results one should consider to use a 3D model, like Delft3D. Still, the result will stay questionable/uncertain without more information or validation possibilities.

But, due to all uncertainties by the inflowing sediment and weather conditions, one should also come up with a strategy to mitigate these risks. One could consider to use a worst-case scenario and/or use a representative scenario for most conditions and include extra mitigating measures.

5.2. Design considerations of settling basins

In the current assessment on settling basins the only parameter describing the effectiveness is the outflow concentration. However, recent experiences on project Grensmaas showed in practise this is not the only consideration when designing, using and optimizing a settling basin. In practice the optimization was based on the use of equipment (which could be stopped due to too high outflow concentrations), which are the highest costs on a project most of the time.

5.2.1. Experiences

The Grensmaas is a project that has been in execution for 12 years, where gravel is washed and sorted. During this project a lot of fine material is released which needs to settle before the used water can be returned to the nearby canal. The basins (three basins parallel to each other) need to be emptied every six weeks, one at a time. Emptying a basin is done by a combination of two excavators and four dump trucks. When clearing of the basin takes more time, more equipment is needed as the basins rotate on a tight schedule.

Coagulants are added to the mixture to increase settling velocity. Coagulants therefore ensure the outflow concentration is below the prescribed limits. However, more coagulants are added (overdosed) to further increase the settling velocity. By doing so, all settling is concentrated near the inflow and moving like a front towards the outflow. The equipment used for clearing the basin can work more efficiently and no extra equipment is necessary. This saves more money than the extra costs of the coagulants. Referring to the different settling forms as identified in Chapter 4: without coagulants form C would be present, when only meeting the outflow concentration form B would be present, but by adding more coagulants and therefore overdosing, form A is present.

The design optimization that is made in this case, is based on costs for extra equipment and costs for coagulants. The costs are based on indications given by the project team:

- **Coagulants:** Overdosing costs around 1500 euro/week (Variable, depending on the mixture). Coagulants will always be necessary (to fulfil outflow concentration limit) and here is therefore assumed that the minimum costs are 1000 euro/week. This means the extra costs for overdosing are 500 euro/week.

- **Equipment:** Costs for a combination of one excavator and two dump-trucks is estimated at 4000 euro/week (666,67 euro/day). The project uses two combinations that need two weeks for clearing an overdosed basin.

- **Comparison:** For the comparison three examples are calculated. High coagulant, medium coagulant and low coagulant dose. For the high coagulant dose 12 working days are counted, as the current operations use. Medium coagulant dose is assumed to require one extra day of work and for a low coagulant dose, two extra days of work are estimated. The comparison is visualized by three cases in Figure 5.1. The results show overdosing the coagulant is the cheapest method.

This optimization is possible on the Grensmaas as this is a long lasting project which already needs coagulants. Therefore, the effective coagulant type was already known. As sediment types are different they require different types and doses of coagulants. To find the optimal type and dose is therefore only worth the effort when a project already uses coagulants and/or is long lasting.

An optimization strategy as used on the Grensmaas could also be implemented for similar projects. Required for such an optimisation of the design is the use of coagulants and the need to remove or use the residual of the settling basin. This could be required when the settling basin is not large enough for the complete operation or when the basin itself will be reclaimed as well.

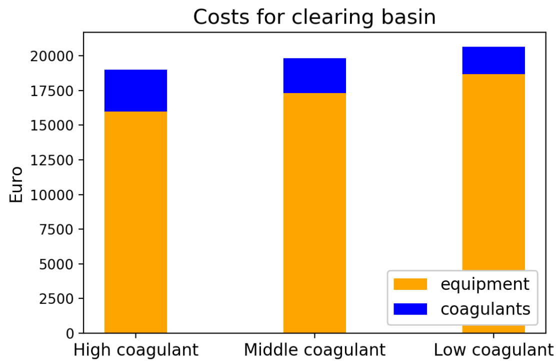


Figure 5.1: Costs for clearing basin at the Grensmaas. This visualization shows the (increase in) equipment costs is much larger than the (decrease in) costs for coagulants.

5.2.2. CSD exemplary project

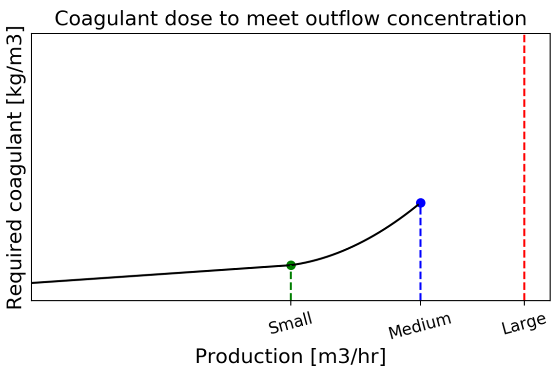
An imaginary project is used to show different optimization possibilities. Realistic trends and relations are used, but no numbers are given. In this imaginary project the team needs to decide to use a small dredge, medium dredge or large dredge. All three dredgers are available and only the production and outflow concentration is considered. For the production by all dredgers additional coagulants are required to fulfil to the outflow concentration limits.

The relation between the required coagulant dose and the production is visualized in Figure 5.2a. The small dredge is very efficient in the use of coagulant for the given production. The medium dredge is not efficient in coagulant usage, but with a maximum amount of coagulant the outflow concentration is still reached. The large dredge has such a large production the coagulant is not able to keep the outflow concentration below the prescribed limit. The only solution for the large dredge is to pause the dredger when the outflow concentration reaches the limit.

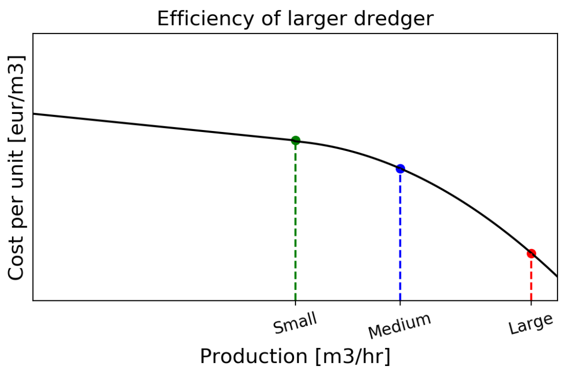
The efficiency curve of the dredgers is shown in Figure 5.2b. The production (in m^3/hr) is plotted against the cost per unit (in eur/m^3. Larger dredgers result in a lower price per unit as larger dredgers are more efficient.

The expected outflow concentration is plotted against the project duration. The small and medium dredge both stay under the prescribed limit. The large dredge needs to stop the production every now and then to keep the outflow concentration below the prescribed limit (Figure 5.2c). The progress of the project is shown in Figure 5.2d. When in operation, the large dredge is the fastest. Due to the required stops to keep below the outflow concentration limit the average production of the dredger is decreased. The medium dredge finishes the job just in time. The small dredge will not meet the deadline and therefore a fine has to be paid.

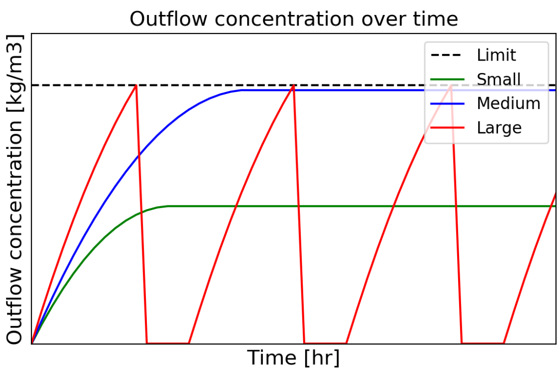
Combining these relations with each other, an optimum for the production is found. The small dredger is too slow to finish the project in time, resulting in additional costs. The large dredge is too expensive as the production needs to be stopped (and might be more useful on another project). The medium dredge is optimal. Although the coagulants are not used in optimal dose (overdosed), the costs for the equipment (dredge) are an order of magnitude higher and therefore more important to optimize.



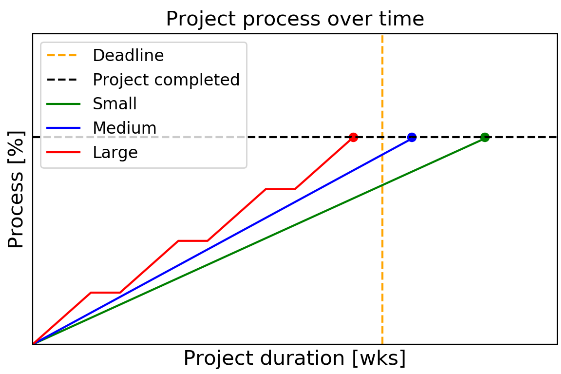
(a) Coagulant efficiency



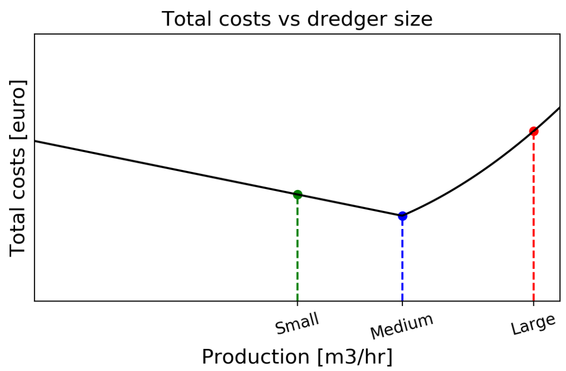
(b) Dredger efficiency



(c) Emission of suspended sediment for different cases



(d) Project process with different dredgers



(e) Total costs for different dredgers

Figure 5.2: Optimization for CSD exemplary project

This optimization is based on relations as found at project Grensmaas and at Van Oord. The described case could be used as an example for future optimizations. The optimization could not only be used when using coagulants as mitigating measures, different mitigating measures are possible to implement. The main message is that often the price of the equipment is much higher than the price of mitigating measures. Therefore mitigating measures should not necessarily be used in their most efficient form, as each cost reduction of equipment is possibly larger than the price of the inefficient, however effective, mitigating measure.

5.3. Measurements supporting the assessment

The original plan for this research was to validate the model findings by a measurement campaign. Validation of the models would increase the reliability. The measurement campaign was to be held at project Grensmaas in Limburg, but due to the overdosed coagulants validation of the models was not possible. The question arises to what extend a validation campaign is helpful to validate the model for general use.
This section shows the additive value of measurements during different phases of projects including settling basins. The different phases are the tender and execution phase. Measurements during a tender should make the estimation more accurate. Measurements during the execution of a project should help predicting any exceedance in the near future. This should enable to take mitigating measures, to prevent downtime.

The most essential parameters for the process in the basin and the resulting outflow concentration are the settling velocity (particle size), wind velocity and the overall area of the basin. The measurements should help predict and validate parameters for these most important processes. The overall area of the basin is left out, as this can easily be determined and does not change.

To start, measurements at the inflow and outflow on sediment concentration and inflow rate are required. On a project these are possibly very variable and accurate data is therefore necessary.

5.3.1. Settling velocity

During a tender the settling velocity of the particles is determined based on the grain size distribution. This information is provided by the production estimators.

During the execution of a project, measurements on the settling velocity can be performed by:

- **Size of sediment**
  With equipment as a LISST (*Laser In-Situ Scattering and Transmissometery*) the particle size distribution of the suspended sediment on multiple locations in the basin could be measured. With known particle size the fall velocity could be calculated.

- **Fall velocity in laboratory**
  Samples could be taken to measure the particle fall velocity in a laboratory. This could be used as an input for the models.

- **Decrease of sediment concentration (over a profile) through the basin**
  By measuring sediment concentration profiles in the basin the influence of density could be proven and additional mixing could be measured. The decrease of sediment concentration over the length or width is expected to be minor as density driven transport creates a layer of uniform sediment concentration.

- **Formed bathymetry**
  The formed bathymetry shows where the sediment settles and the amount of sediment that settles.

5.3.2. Wind

During a tender the order of magnitude of wind gusts and storms is required. These could be assessed from various meteorological institutes. Measurements could be used for more accurate and more site specific data. However, historical sources are likely to contain more data over a longer period of time and therefore better estimates could be made.

During the execution phase the wind could be monitored by measurements on site (near the settling basin) and by keeping a close eye on the prediction done by the local services (if available).

6
Discussion, conclusion and recommendations

6.1. Discussion

The (comparative) modelling study shows the complexity of predicting the outflow concentration of settling basins. Some case properties (like sediment particle size, wind velocity and dpeth of the basin) can strengthen each other or cancel each other out. It is not always clear what the effect of combinations will be and what combinations lead to extreme outflow concentrations, as different theories are possible and not all combinations could be modelled. An example of such a combined effect is the combination of finer sediment (lower settling velocity), strong wind (15-25 m/s) and a reduction or increase of the water depth. It is still unknown what effect the change of water depth will have.

In the comparative modelling study the different assumptions are validated individually. These assumptions are width uniform flow and neglecting the effect of density differences. Based on the individual results, both the assumptions did not seem correct. However, differences in density do make the distribution of sediment concentration (more) uniform over the width. A 2DV approach seems therefore justifiable again. In other words; although in the design of the RWQ model density differences are neglected, the model does take the most important effect of density differences, the distribution of sediment concentration over the entire width of the basin, into account by the 2DV approach.

This research is completely based on theory and theoretical models. Since the validation campaign did not go as planned, validation of the models was not possible. Although a modelling program like Delft3D is validated for general usage, the specific purpose of settling basins is not validated. This uncertainty is present with for example the weir element in Delft3D. In a settling basin the small scale sediment transport around the weir could be of influence, while Delft3D is not certain to represent this correctly. Next, calibration of the turbulence closure models is required. The sensitivity analysis shows that a different input of the turbulence closure models could change the complete system.

The assessment is also a balance between complexity and accuracy. One needs to strive to keep the model as simple as possible without too many input values, but a certain level of accuracy and reliability is essential. There is a large step in complexity between a first indicator (RWQ model) and a detailed model (validated Delft3D model). Questionable is the added value of an unvalidated Delft3D model when comparing to the RWQ model (with the proposed rules of thumb of Section 5.1) or a 'back-of-the-envelope' calculation (Section 3.1). Especially during a tender phase, when the extra input values (as required for Delft3D or different complex models) are not available and assumptions have to be made.

Lastly, the research showed the results of the assessments are very dependent on the settling velocity of the smallest particles. The uncertainty of the model goes hand in hand with this uncertainty.

6.2. Conclusion

6.2.1. Process insight

The model study shows that density differences are the main dispersing mechanism of sediment concentration throughout the basin. The density driven currents spread the sediment concentration over the complete basin, with a vertical gradient in sediment concentration. Currently, density differences are neglected in the assessment done by Van Oord (RWQ model) and it would therefore be improved when implemented. Wind may cause additional mixing and therefore a horizontal gradient in sediment concentration. This only occurs if the wind is stronger than a certain threshold value, depending on the project/basin (for this research was found: $v_{wind} > 10m/s$). The filling behaviour (and formed bathymetry) are mostly determined by the grain size distribution (settling velocity) of the inflowing sediment.

6.2.2. Assessment

The RWQ model is suitable for a first estimate of the outflow concentration, although one should keep the simplifications in mind. An assessment done by Delft3D (or similar) could provide more insight with better process understanding (implementation of density driven currents). However, when assumptions are required (and no further validation is possible), the extra accuracy of the Delft3D model will reduce significantly.

Therefore, the assessment should (also) be focussed on improving mitigating measures rather than only improve the predictive capabilities. This could be used in combination with representative scenarios and/or extreme scenarios. Due to the site specific sediment characteristics, assessments on settling basins will always stay difficult to predict during tender phases without additional measurements. Uncertainties in the assessment are further found in the sediment properties, production and wind conditions.

6.2.3. Research questions

– What are the governing physical processes that cause suspended sediment concentrations and particle size distributions to change along a settling basin and over time?

  In general, density driven transport is the main dispersion mechanism. When the wind gains in power the dispersion of sediment could be driven by the additional mixing by wind.

– For what geometries of a settling basin is a 2DV-model (RWQ-model) applicable, and when is a 3D-model (Delft3D) more appropriate to use for modelling?

  Different than expected, the W/L-ratio (geometry) is not of influence on the outflow concentration. Since the (main) sediment dispersion mechanism is the difference in density throughout the basin, the sediment concentration is equally distributed everywhere. The size of the basin (total area) is important. Although the 2DV RWQ model does not take all processes into account, the RWQ model is good to use as a first estimator.

– What is the effect of different influences on the flow pattern (like wind, density driven currents and fill rate of the basin) and how does this affect the outflow concentration of suspended sediment concentration?

  Wind causes additional mixing throughout the basin. Secondary flow does not show much influence. Density driven currents enable a fluid mud layer to form over the bottom of the basin. This density driven current distributes the sediment over the entire basin. The fill rate does not increase the outflow concentration. Only when nearly full the outflow concentration increases.

– What (measurable and predictable) conditions are most decisive for the processes in the basin and the resulting outflow concentration?

  The models show the settling velocity of the sediment is most decisive for the outflow concentration. Next, the overall available area for a basin is important in the prediction of the outflow concentration. Lastly, the weather conditions are necessary to know. Especially storm events with (longer, consecutive) periods of high wind velocities are important.

– What is the validity of the current return water quality assessment and how could this be improved?

The current assessment uses the RWQ model. The RWQ model does not implement all relevant processes. However, the outflow concentration could be used as a first indicator. For increased accuracy a 3D model (Delft3D or similar) is recommended. The 3D model represents the processes more correctly. However, the 3D model requires more input which will be based on assumptions during a tender phase. The accuracy of the model will be dependent on the accuracy of these assumptions.

The current assessment could further be improved by cost-benefit analysis by comparing the costs of mitigating measures with the costs of a violation (delay of equipment, project duration, fines). Here, most of the time the conclusion can be drawn that the use of equipment is (far) more expensive than mitigating measures on a settling basin. Inefficient but effective use of mitigating measures to ensure continuity of dredgers are therefore justified.

With some small measurements on the settling velocity and the wind the estimate could be made more accurate. When the relation between inflowing particle size, wind and outflow concentration could be proved, violations could be prevented by acting on accurate predictions.

6.3. Recommendations

The recommendations for future assessments, improvements on the assessment and better process understanding are divided over the different readers. [redacted]
Future research should focus on sediment transport around a weir and in-situ effects compared to the models (validation of the models).

[redacted]

- [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
- [redacted]
- [redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

Research in the following subjects can improve the assessment:

- The performance (difference in inflow concentration and outflow concentration) of settling basins at projects. The results could be used as a reference for the Delft3D and RWQ model results.
- The effect of the weir on sediment transport is difficult to assess with 3D modelling software. Lab experiments or in-situ measurements could improve the understanding of sediment transport over a weir.

- The effect of the use of coagulants on settling basins. What are the long term effects of adding coagulants and how does the settling behaviour got influenced?

Bibliography

CEDA. Underwater sound in relation to dredging. Technical report, 2011. URL `https://dredging.org/media/ceda/org/documents/resources/cedaonline/2011-11{_}ceda{_}positionpaper{_}underwatersound{_}v2.pdf`.

Deltares. Delft3D-FLOW Manual. Technical report, Deltares, Delft, 2011a. URL `https://content.oss.deltares.nl/delft3d/manuals/Delft3D-FLOW{_}User{_}Manual.pdf`.

Deltares. *Delft3D-RGFGRID*. 2011b.

Paul L.A. Erftemeijer, Bernhard Riegl, Bert W. Hoeksema, and Peter A. Todde. Environmental impacts of dredging and other sediment disturbances on corals: A review. *Mar. Pollut. Bull.*, 64(9):1737–1765, 2012. URL `https://doi.org/10.1016/j.marpolbul.2012.05.008`.

Boris Galperin, Semion Anderson, and Philip S. Sukoriansky. On the critical Richardson number in stably stratified turbulence. *Atmos. Sci. Lett.*, 8:65–69, 2007.

Carlo Gualtieri, Athanasios Angeloudis, Fabian Bombardelli, Sanjeev Jha, and Thorsten Stoesser. On the Values for the Turbulent Schmidt Number in Environmental Flows. *Fluids*, 2(2), 2017. URL `https://doi.org/10.3390/fluids2020017`.

K. Hutter, Y. Wang, and I. P. Chubarenko. *Physics of Lakes*. 2011.

KNMI. Windschaal van Beaufort, 2020. URL `https://www.knmi.nl/kennis-en-datacentrum/uitleg/windschaal-van-beaufort`.

Debora Koller, Ana Luiza de Oliveira Borges, Eduardo Phul, and Rafael Manica. Prediction of the bedforms generated by density currents based on fluvial phase diagrams. *RBRH*, 22, 2017. URL `https://www.researchgate.net/publication/319948620{_}Prediction{_}of{_}the{_}bedforms{_}generated{_}by{_}density{_}currents{_}bas`

A.N Kolmogorov. Equations of turbulent motion in incompressible fluid. In *Izv. Akad. Nauk. SSR, Ser. zicheska Vi*, volume 1, pages 56–58. English tr edition, 1942.

William De Lange. Probabilistic design of settling basins for environmental compliance. Technical Report April, Delft University of Technology, 2011. URL `https://repository.tudelft.nl/islandora/object/uuid{%}3A0fe4643f-d868-4849-90af-579fb543a8b2?collection=education`.

Johan G. S. Pennekamp and Marinus P. Quaack. Impact on the environment of turbidity caused by dredging. *Terra Aqua*, 42(April):10–20, 1990. URL `https://www.researchgate.net/publication/294556844{_}Impact{_}on{_}the{_}environment{_}of{_}turbidity{_}caused{_}by{_}dredging`.

L Prandtl. Über ein neues Formelsystem für die ausgebildete Turbulenz. In *Nachrichten von der Akad. der Wissenschaften Gottingen. Math. Phys. Klasse*, pages 6–19. 1945.

Caroline S. Rogers. Responses of coral reefs and reef organisms to sedimentation. *Mar. Ecol. Prog. Ser.*, 62:185–202, 1990. URL `http://www.int-res.com/articles/meps/62/m062p185.pdf`.

Leo C. van Rijn. *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Aqua Publications, Amsterdam, 1993.

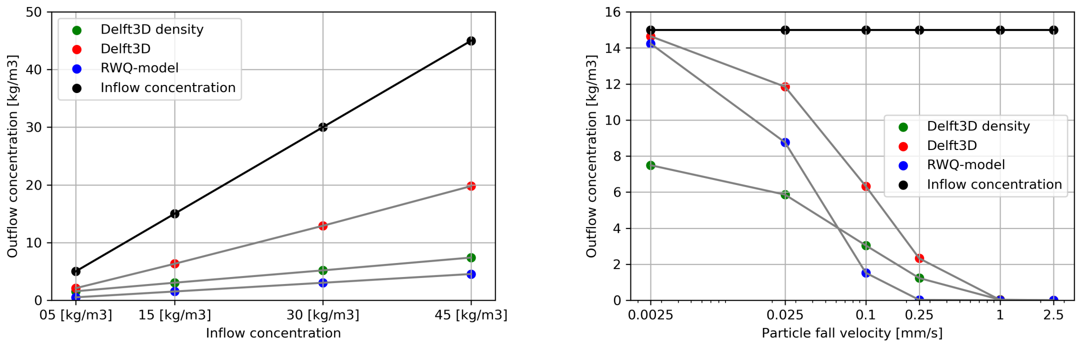
Vincent Vuik. Numerical modeling of sediment transport over hydraulic structures. Technical report, 2010.

J.C. Winterwerp. Near-Field Behavior of Dredging Spill in Shallow Water. *J. Waterw. Port, Coastal, Ocean Eng*, 128(2):96–98, 2002.

A Sensitivity analysis

A.1. Sensitivity to sediment inflow

The determined outflow concentration is influenced by the inflow concentration and the settling velocity of the particles. The relative and absolute reduction is higher for high inflow concentrations. The influence of the settling velocities of the particles is substantial. Delft3D-Density estimates the influence lower than the RWQ model and Delft3D with uniform density. This is concluded from the difference in outflow concentration for settling velocities of $2.5x10^{-4}$ and $2.5x10^{-6}$ m/s.



(a) Sediment concentration

(b) Settling velocity

Figure A.1: Influence of sediment inflow conditions on the outflow concentration.

B

Additional cases on filling behaviour

B.1. Filling behaviour under wind circumstances

In this section the three cases of Chapter 4 are extended with wind. Per case three wind conditions are modelled:

- no wind (used as reference, same as used in 4)
- wind of 10 m/s and 180 ° ; density driven transport
- wind of 25 m/s and 180 ° ; wind driven transport

Conclusions: The difference in settling behaviour between the case without wind and with wind of 10 m/s is minor. The outflow concentrations are close to each other and the formed bathymetry are similar to the case without wind.

For wind of 25 m/s there is in all cases significant less settled material at the end of the simulation.

Remarkably, the influence of the wind was most significant for the particles with the largest settling velocity. This is different from the expectation.

B.1.1. Outflow concentration

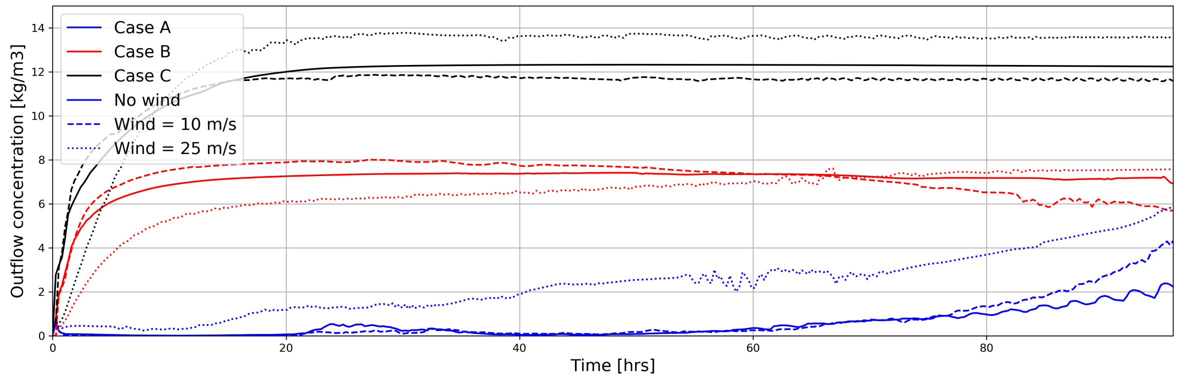
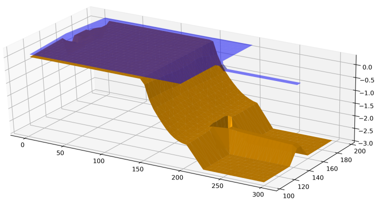
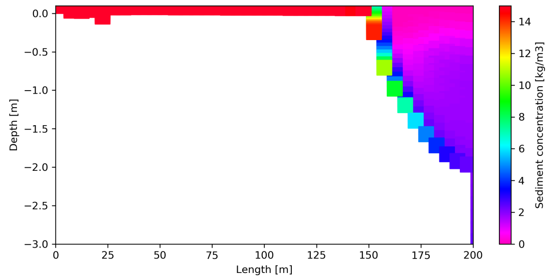


Figure B.1: Outflow concentration over time for different wind velocities

B.2. Case A

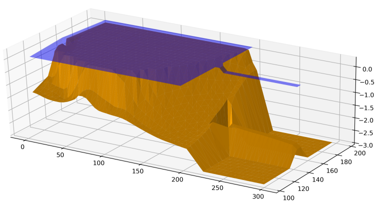


(a) 3D plot case A

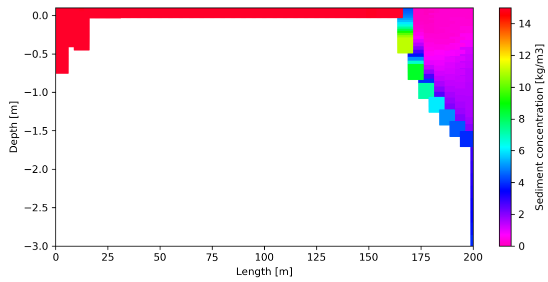


(b) Spread plot case A: wind = 0 m/s

Figure B.2: Filling behaviour case A: wind = 0 m/s

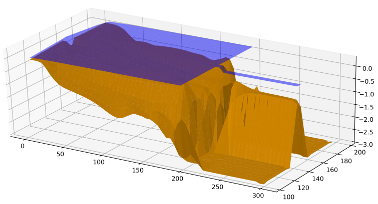


(a) 3D plot case A

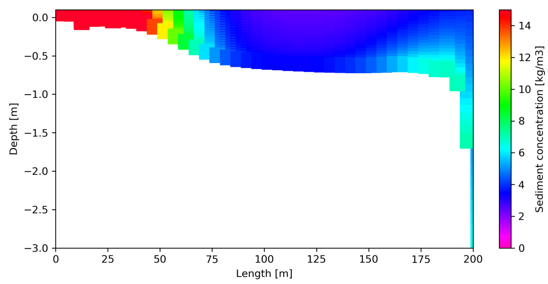


(b) Spread plot case A: wind = 10 m/s

Figure B.3: Filling behaviour case A: wind = 10 m/s



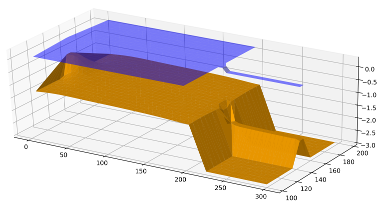
(a) 3D plot case A



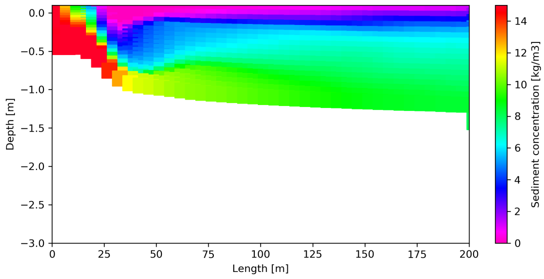
(b) Spread plot case A: wind = 25 m/s

Figure B.4: Filling behaviour case A: wind = 25 m/s

B.2.1. Case B

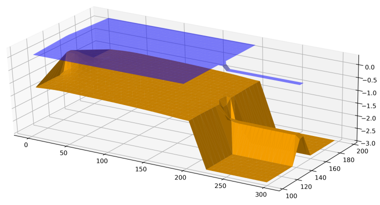


(a) 3D plot case B

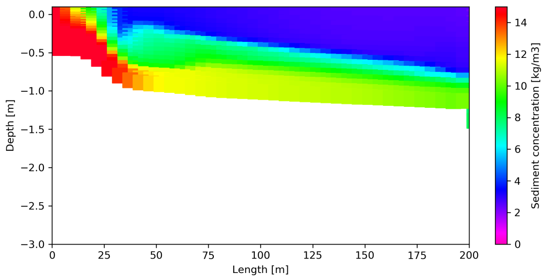


(b) Spread plot case B: wind = 0 m/s

Figure B.5: Filling behaviour case B: wind = 0 m/s

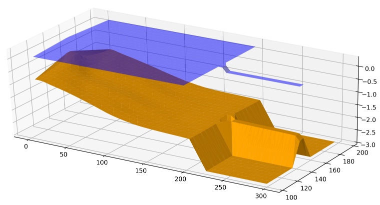


(a) 3D plot case B

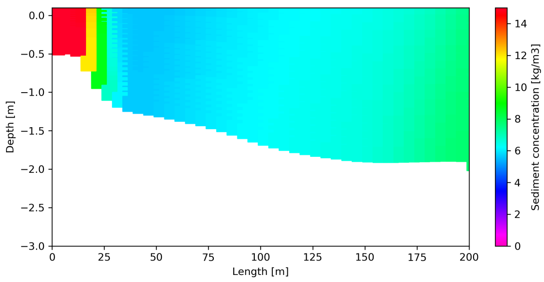


(b) Spread plot case B: wind = 10 m/s

Figure B.6: Filling behaviour case B: wind = 10 m/s



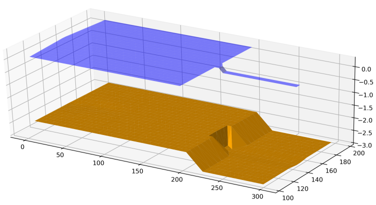
(a) 3D plot case B



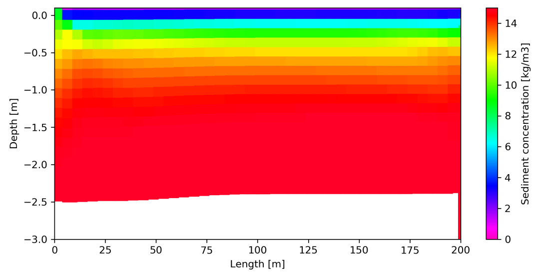
(b) Spread plot case B: wind = 25 m/s

Figure B.7: Filling behaviour case B: wind = 25 m/s

B.2.2. Case C

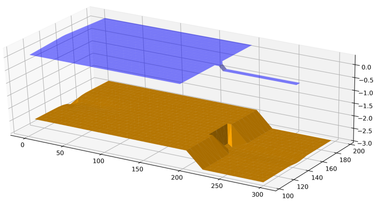


(a) 3D plot case C

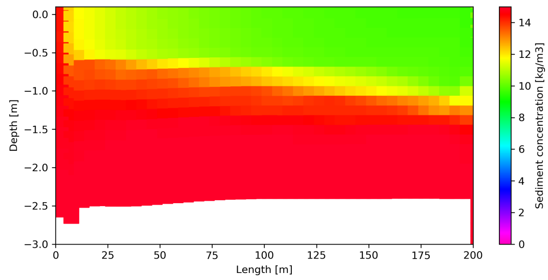


(b) Spread plot case C: wind = 0 m/s

Figure B.8: Filling behaviour case C: wind = 0 m/s

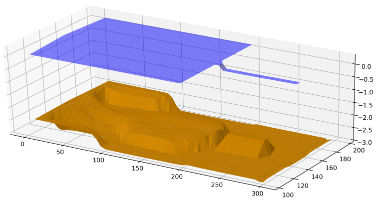


(a) 3D plot case C

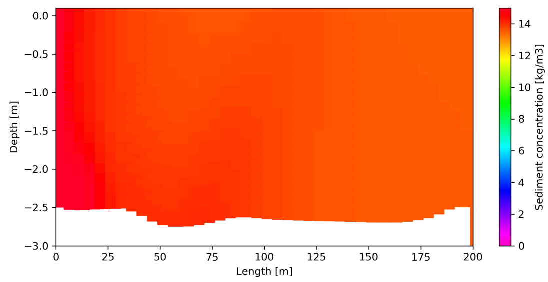


(b) Spread plot case C: wind = 10 m/s

Figure B.9: Filling behaviour case C: wind = 10 m/s



(a) 3D plot case C



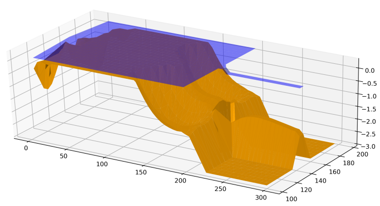
(b) Spread plot case C: wind = 25 m/s

Figure B.10: Filling behaviour case C: wind = 25 m/s

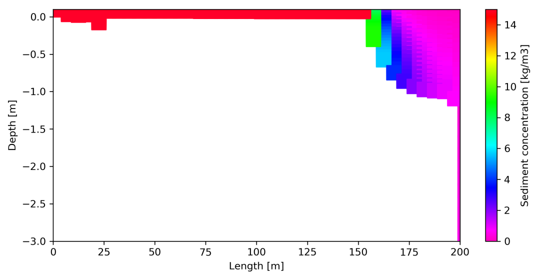
B.3. Filling behaviour with uniform density

The results of the cases without density differences implemented is shown in Figures B.11 to B.13. Compare this to the results of cases with density differences (Chapter 4).

Case A, high settling velocity, stays near the same. Still, all sediment settles quickly in the vicinity of the inflow. The moving front can still be recognized. The resulting distribution of concentration throughout the basin stays the same.
For low settling velocities, Case C, the distribution of sediment concentration is different. This is in line with the conclusions drawn in Chapter 3. Different is the location of settling. Without density differences a gradually decrease of settled material can be seen, as with density differences more influence of the inflow is observed (less settling in the vicinity of the inflow).
The intermediate case B is most different. Although the same trend in the bathymetry can be seen (moving front, settling through the rest of the basin), the amount of settling is different. The concentration distribution is in correspondence with the conclusions drawn in Chapter 3.

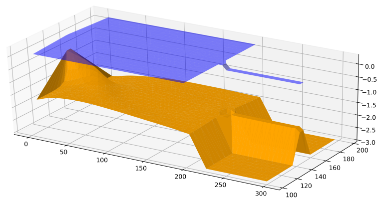


(a) 3D plot case A: No density

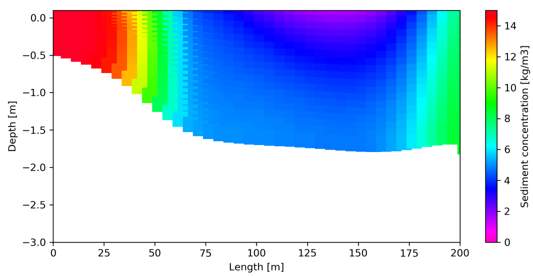


(b) Spread plot case A: No density

Figure B.11: Filling behaviour case A: No density

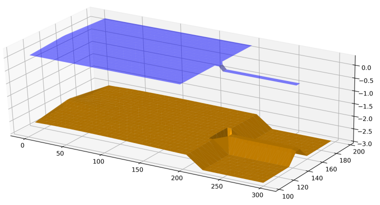


(a) 3D plot case B: No density

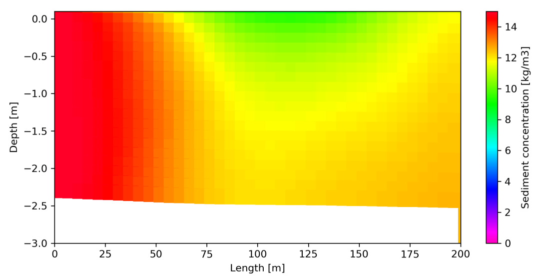


(b) Spread plot case B: No density

Figure B.12: Filling behaviour case B: No density



(a) 3D plot case C: No density



(b) Spread plot case C: No density

Figure B.13: Filling behaviour case C: No density