UNCERTAINTY APPROACH TO THE INFILL OF NAVIGATION CHANNELS AND TRENCHES

WITH TELEMAC2D

University of Twente

Faculty of Engineering Technology

Civil Engineering

BSc Thesis
Cynthia Wertwijn

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HR Wallingford
Working with water

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Supervisors:
Dr. Ir. P. C. Roos
Dr. Ir. M.A.F. Knaapen

PREFACE

Preface

This document is for the thesis of the Bachelor Civil Engineering at the University of Twente. In this bachelor thesis, a study of the uncertainty on sediment infill is shown. The research conducted for this thesis report is done at HR Wallingford under supervision of Michiel Knaapen, from HR Wallingford, and Pieter Roos, from the University.

First of all I want to thank my supervisors. I would like to thank Michiel Knaapen for his help with the problems in the programme and support during my placement period. I want to thank Pieter Roos for the effort and help with my progression in the research and report. Furthermore, I want to thank Pieter for his support during my placement period.

Secondly I want to thank the HR Wallingford for giving me the opportunity to do my research. I especially want to thank the Coast and Estuaries department of HR Wallingford for making me feel at home at the company. I also want to thank David Wyncoll for helping with special problems that arose in the program. During my placement period I met some amazing peers, whom I would like to thank for the pleasant time at the office, diners, lunches and sightseeing.

At last I would like to thank my family and friends for their help, love and support during this research period. Even when I was too far away to see them, they made me feel close to home and loved.

I hope you enjoy reading this report.

Cynthia Wertwijn

ABSTRACT

Abstract

Trenches and navigation channels are designed according to precise research in each area where they are placed. In this research the quantification of the uncertainties in the infill of these channels and trenches is studied. For studying this area the following goal is set:

Quantifying the uncertainties of a deterministic morphodynamic model for sandy beds by a sensitivity and probabilistic analysis with taken into account the input parameters and their underlying relationships.

The infill used to find the uncertainties needed to accomplish the goal is the amount of sediment that is placed in the trench after a time period. This infill is found by using the program SISYPHE and the by HR Wallingford recommended formulae for a flume. This goal can be split into 3 analyses, the sensitivity analysis, research of underlying relationships and probabilistic analysis. The sensitivity analysis will investigate the effect of each input parameter on the infill prediction. The settling velocity has the most influence on the infill prediction and the number of sediment classes does not have any influence on the infill prediction on its own. The influence of each input parameter on the infill prediction is shown in the table below.

Input parameter	Range	Infill rate uncertainty	Effect
Settling velocity (w_s)	$0.002 - 0.4\ ms^{-1}$	163%	Positive effect
Median diameter$(D_{50,n})$	$0.00006 - 0.00476\ m$	120%	Negative effect
Porosity(P)	$0.41 - 0.46$	37%	Positive effect
90% grain diameter(D_{90})	$0.00006 - 0.00476\ m$	37%	Positive effect
Sediment density(ρ_s)	$2597 - 2703\ kgm^{-3}$	9%	Negative effect
Nikuradse parameter(k_s)	$0.009 - 0.18\ m$	4%	Negative effect
Number of sediment classes(n)	$1 - 7$	0%	No effect

The research of underlying relationships between the input parameters resulted in simplified formulations. To create the simplified formulae a range is found by conducting a range for each found formula en combining these ranges to make the range that fits all the ranges for each formula.

With these relations and the sensitivity analysis the probabilistic analysis is done. In this research, the Monte Carlo method is used. In the Monte Carlo approach, a model prediction will be computed multiple times, each time with different values for the input parameters. For every run, the Monte Carlo analysis chooses a value randomly for each input parameter within their ranges and uses these values to predict the sand bed infill. The different results together give a normal distribution for the sediment infill. With this normal distribution the average infill value and the uncertainty of the infill can be found.

The average channel and trench infill is $0.1\ m$. Approximately 98% of the channels and trenches with sandy beds will have a sand infill lower than 0.35m. This $0.35m$ infill can be taken into account with designing a channel to keep the trench depth below a needed depth, which can save time and effort in researching the sediment characteristics of the site.

For the trench and channel width on trench depth 0.75m the average narrowing of the width for sandy beds is $11m$. 98% of the trenches and channel will lie between 14 and 34m. This result can also be taken into account with designing a channel to keep the trench width above a certain wide.

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Notation

Symbol	Definition	Dimension
A_{sb}	empirical bed transport coefficient in the flume	[$s^{2.4}$ $m^{-1.4}$]
$A_{sb,n}$	empirical bed transport coefficient for each sediment class n	[$s^{2.4}$ $m^{-1.4}$]
A_{ss}	empirical suspended transport coefficient at in the flume	[$s^{2.4}$ $m^{-1.4}$]
$A_{ss,n}$	empirical suspended transport coefficient for each sediment class n	[$s^{2.4}$ $m^{-1.4}$]
B	flume width	[m]
C	concentration of sediment in the flume	[m^3m^{-3}]
C_D	drag coefficient at point x,y in the flume	[–]
C_e	equilibrium concentration at point x,y in the flume	[m^3m^{-3}]
C_t	concentration at time -1	[m^3m^{-3}]
D	deposition of suspended load	[ms^{-1}]
$D_{50,n}$	median grain diameter for each sediment class n	[m]
D_{50}	median grain diameter for each sediment class n	[m]
D_{90}	grain diameter for which 90% of the grains by mass is finer	[m]
E	erosion of suspended load	[ms^{-1}]
g	gravity acceleration	[ms^{-2}]
h	water depth at point x,y in the flume	[m]
H_s	significant wave height	[m]
k	wave number	[m^{-1}]
k_s	Nikuradse roughness parameter	[m]
K_k	Von Karman constant	[–]
n	Number of sediment classes	[–]
P	porosity of the bed	[–]
$\overrightarrow{Q_b}$	volumetric bed-load flux at point x,y in the flume	[m^2s^{-1}]
$\overrightarrow{Q_s}$	suspended load flux at point x,y in the flume	[m^2s^{-1}]
$\overrightarrow{Q_{sr}}$	sediment transport rate	[m^2s^{-1}]
s	relative density of sediment $\left(=\frac{\rho_s}{\rho}\right)$	[–]

NOTATION

S_{fi}	slope friction in direction i	[ms^{-2}]
S_i	slope of the waterway in direction i	[mm^{-1}]
t	time	[s]
$\bar{u}$	depth average flow velocity in direction x	[ms^{-1}]
$\vec{U} = (\bar{u}, \bar{v})$	depth average flow velocity	[ms^{-1}]
$U_{cr,n}$	critical velocity for each sediment class n	[ms^{-1}]
U_{cr}	total critical velocity at point x,y in the flume	[ms^{-1}]
U_o	wave velocity at point x,y in the flume	[ms^{-1}]
$\bar{v}$	depth average flow velocity in y direction	[ms^{-1}]
w_s	average settling velocity	[ms^{-1}]
x	horizontal coordinate in the along-flume direction	[m]
y	horizontal coordinate orthogonal to x	[m]
z	vertical coordinate	[m]
z_b	trench/channel depth (bottom elevation)	[m]
Z_{ref}	reference bottom elevation	[m^{-1}]
β	coefficient for sloping bed effect	[–]
$\varepsilon_{s,x}$	dispersion coefficient in x direction for suspended load	[m^{2}s^{-1}]
$\varepsilon_{s,y}$	dispersion coefficient in y direction for suspended load	[m^{2}s^{-1}]
ζ	change in bed level	[m]
ρ	fluid density	[kgm^{-3}]
ρ_s	sediment density	[kgm^{-3}]
$\rho_{s,dry}$	dry sediment density	[kgm^{-3}]
τ_{ij}	shear stress in direction $[i, j]$	[kgms^{-2}]
υ	kinematic viscosity	[m^{2}s^{-1}]
ω	orbital frequency	[s^{-1}]

INTRODUCTION

1 Introduction

Trenches and channels are chosen according to precise research in each area where they are placed. In this research the quantification of the uncertainties in the infill of the channels and trenches is researched. A general explanation of this research and the external organisation is given in this chapter. This chapter starts with a description of the external organisation. It is followed by the description of the project itself in section 1.2. With this general description of the project, the problem is defined. This is followed by the main objective, section 1.4, for solving the problem described in section 1.3. Section 1.3 and 1.4 are used to create the questions which will be studied in this research, shown in section 1.5. The objective and questions studied in this research are used to create a plan for this research. The used methods in used order are described in section 1.6. This research works with some limitations which are described in section 1.7. The last section of this chapter gives an outline of this report.

1.1. External organisation

About 66 years ago HR Wallingford was founded by the British government (Members of FLOODsite, 2009). Nowadays HR Wallingford is an independent non-profit organisation that works in the field of civil engineering and environmental hydraulics (About HR Wallingford, 2013). In this field, particularly the areas of rivers catchments, estuaries, coast and offshore, HR Wallingford is seen as a European leader with their knowledge and research (Members of FLOODsite, 2009). The company's reputation is kept by re-investing their profit into research and development. Through this research and development HR Wallingford creates solutions for complicated problems and obstacles. The organisation has a global network of clients and partners from governmental organisations to universities (About HR Wallingford, 2013). The organisation invests in creating more knowledge and improving the knowledge they and others already have. HR Wallingford also helps others, by handing out information to universities and hosting students or young researchers on-site for collaborative projects (Members of FLOODsite, 2009).

The company consists of more than 280 employees all over the world (Members of FLOODsite, 2009). HR Wallingford has offices in among others India, China and United Arab Emirates. The head-quarter is situated at Wallingford in the United Kingdom. The park is 76 acres and placed on the banks of the Thames in the region South Oxfordshire (British Council for Offices, 2011). On these 76 acres there are facilities from physical modelling to ship simulation centre and flood product testing. At the moment HR Wallingford is working on a project that is creating a cleaner, healthier tideway tunnel for the Thames by means of physical modelling the river and its engineering work (HR Wallingford, 2013).

This research project has been performed at the Coasts and Estuaries Group. The Coasts and Estuaries Group offers knowledge about environments and processes in coasts and estuaries. Research in this field provides information about managing water and sediment from erosion, sediment transport to flooding and the protection of the coastal environments.

1.2. Project description

This research is a part of a bigger project within HR Wallingford, called Application of uncertainty analysis. This research is about analysing the uncertainty, range in which the parameters can vary, of the infill of channels and trenches. Because of the uncertainties in the infill prediction, channel design is a risk in projects about for example building harbours or installing pipelines. To decrease the uncertainty for each input parameter the ranges need to be narrowed or confirmed. As a result the calculated trench and channel infill are among others more precise or certain for the use in harbour and pipeline installation design (DPW, 2012) (Wilkens & Chesher, 2011).

The infill prediction can be modelled with SISYPHE by using HR Wallingford's standard deterministic model for calculating trench infill in sandy beds (Wilkens & Chesher, 2011). SISYPHE is a numerical transport model that belongs with the TELEMAC flow model. This model calculates the morphological changes with various flow and sediment conditions. The calculations are functions of time-varying flow conditions, like wave height and flow velocity, and sediment characteristics. SISYPHE uses among others the formulae of Soulsby and Chezy to compute the change bed levels over time. The variables taken into account by the SISYPHE are among others the effect of waves and currents and cohesive and non-cohesive sediment characteristic. It can be used for a large variety of hydrodynamic situations and sediment mixtures from rivers to harbours. In this research SISYPHE will be run on an idealised geometry to keep the simulation time short allowing for the number of runs required to assess the uncertainties in the predictions (Villaret & El Kadi, 2010).

1.3. Problem definition

The previous section explained that channel design is a risk in projects about for example building harbours or installing pipelines. In recent research there are models created to calculate the morphological changes of channels and trenches over time with the use of SISYPHE. However, these deterministic models still have uncertainties in the calculation of migration and infill. By generating a tool that quantifies the uncertainties, the best channel or trench design can be modelled more accurately. This will optimise the design for each trench of channel on maintenance and dredging. This will save costs in these kinds of projects and supply more knowledge about uncertainties in the whole coastal area (Wilkens & Chesher, 2011).

1.4. Objective

The main objective of this research is:
Quantifying uncertainties of the deterministic model for sandy sea beds by a sensitivity and probabilistic analysis with taken into account the input parameters and their underlying relationships.

1.5. Researched questions

The main question put up for this study can be deduced from the problem definition in section 1.3 and objective in section 1.4. The mean question is as followed:
What is the magnitude of uncertainties in channel and trench infill?

This main question can be divided into 4 sub-questions listed below:

- How works the deterministic model used by HR Wallingford for trench and channel infill calculations?
- What is the influence of the input parameters on the infill prediction model?
- What are the underlying relationships that will have influence on the values of the input parameters?
- How should uncertainty in channel and trench infill be quantified?

1.6. Methodology

Figure 1.1 shows the sequence of analysis according to Bakker, Uijttewaal, Winterwerp, Jonkman and Veale (2009) that will be followed. The starting values of the input parameters are the values used in the flume experiment, shown in model geometry in section 2.1 and table 2.1.

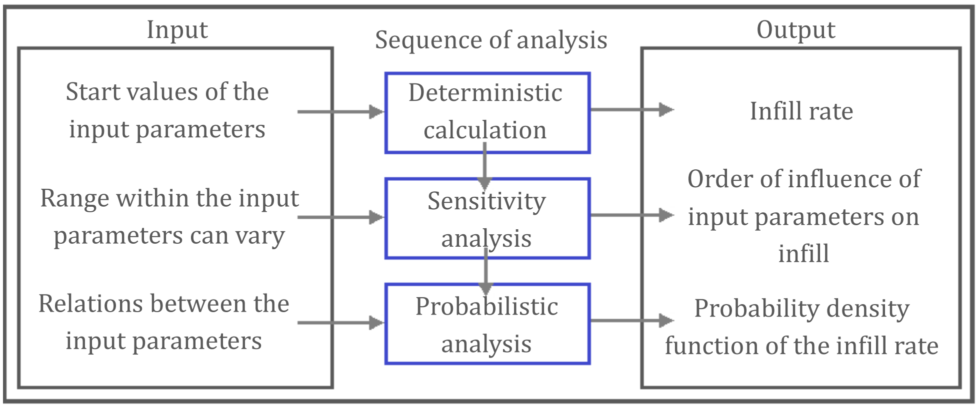

Figure 1.1: Sequence of analysis with the in- and output according to Bakker, et al. (2009)

This research starts with identifying the deterministic model and its input parameters. The input parameters are the parameters that hold the input for the deterministic model. The other parameters, that describe for example the relation between input parameters, will be called parameters. With these input parameters the infill rate can be found. The infill rate is the percentage ratio between the sediment infill at time t in the trench and the initial trench depth.

The uncertainty analysis starts with investigating the effect is of each input parameter on the deterministic model. For each input parameter the value is multiplied by a half and two. With these values the model is run multiple times. The variations in results show the effect of an input parameter on the model. Afterwards the range for each input parameter is found. This is just done by doing some literature research about how much they can vary within the limitations of this research. A comparison between these ranges and the temporary ranges given by multiplying by 0,5 and 2 is conducted to find the effect of each input parameter on the infill rate. The conclusion that is drawn from this comparison is checked by running the deterministic model for each input parameter's range edges and a few values within the range. The amount in which the infill predictions varies by changing an input parameter within its range, shows how the sensitivity of the deterministic model is on each input parameter. Afterwards the change in infill rate for each input parameter is compared with each other. This shows the order of influence of input parameters on the infill (Booij, 2012).

Before the probabilistic analysis starts, the relationship between the input parameters needs to be identified. By identifying the relation and the causal connections, the sequence of important and influential input parameters can change. An input parameter that is not influential on its own can have an immense impact on the infill in combination with a change of another input parameter. This would make this input parameter due to its relation to the other input parameter more important in the infill prediction than expected from the sensitivity analysis (Van Gelder, 2000). Furthermore, relation is researched to narrow the ranges for each input parameter. To find out the relations, formulae which link the input parameters will be searched. For each found formula a range is conducted by changing all the parameters in the formula and the input parameters within given ranges. These ranges can be combined to make a range for each input parameter that fits all the ranges for each formula.

Bakker, et al. used the Monte Carlo analysis for analysing the mud infill prediction, because it is an easy applicable approach that works with ranges. In this research, which is similar, the Monte Carlo would suit the best as well. In the Monte Carlo approach, a model prediction will be computed multiple times, each time with different values for the input parameters. For every run, the Monte Carlo analysis randomly chooses a value to each input parameter within their ranges and uses these values to predict the bed infill. The different results together can be put in a probabilistic distribution to find the most likely value and the uncertainty of the infill.

1.7. Limitations

For this research some variables are fixed, which are explained in section 1.7.1. Furthermore, this research is only done for sandy beds. The explanation of this limitation is explained in section 1.7.2. In the last section the researched conditions will be defined.

1.7.1. Fixed variables

The wave effects are also fixed variables. At the moment these variables cannot be changed in the Monte Carlo tool for SISYPHE. When these variables can be changed the uncertainty, analysis should be done with these input parameters, because for example storm and wind will change the wave effects which can have a big effect on the infill prediction (Landry & Garcia, 2011).

Furthermore, the empirical slope factor, which is a factor that included the diffusion in the bed evolution to make the bed evolution more in line with the actual bed load transport, will be seen as a fixed variable (Villaret & El Kadi, 2010). This empirical factor can vary between 0 and infinity. To get the best possible value for this factor, real-life measurements need to be done (Wilkens & Chesher, 2011). Next to this, studying the empirical factor can be investigated on its own due to the big range and especially the little amount of knowledge about reasons for choosing a value. In this research the empirical slope factor will be kept at the recommended rate for TELEMAC, which is 1.3 (Villaret & El Kadi, 2010).

1.7.2. Sediment limitation

This research only uses bed material that is sand for two reasons. First of all estuaries are dominated by sand (McNally & Mehta, 2002). Secondly most of the harbours are placed in sandy sites (Van Rijn, Harbour siltation and control measures, 2012) (Leys & Mulligan, 2012).

1.7.3. Researched conditions

Sediment conditions changes within each place on the bed and changes over time in water systems. This means that the precise sediment characteristics are uncertain even after expensive testing. To find and narrow the uncertainty ranges it is important to see this group as unknown input parameters. Because of these reasons the sediment conditions will be researched in this research (Ongley, 1996).

The fluid conditions contains among others the wave forces, the water depth and flow velocity. The average values needed for these input parameters can be obtained with SeaZone (SeaZone Solutions division of HR Wallingford Ltd.) According to Soulsby (1997) these input parameters except the water depth have an uncertainty of 10% and the water depth has an uncertainty of 5%. By researching the fluid conditions, the wave forces will change the velocities and other fluid conditions. Because of this the uncertainty cannot be narrowed that much till none, so these conditions are not researched.

1.8. Thesis outline

Model description	In chapter 2, the main physical processes underlying the deterministic model used in this research.
Sensitivity analysis	In chapter 3, the input parameters for sandy beds will be quantified by a sensitivity analysis.
Input relationships	Chapter 4 will explain the relations between the input parameters
Probabilistic analysis	Chapter 5 will show the uncertainty by doing a probabilistic analysis
Discussion	Chapter 6 discusses in which extent the objectives are achieved and gives an evaluation on the methodology and results.
Conclusion	Chapter 7 gives the conclusion form this research
Further research	Chapter 8 gives recommendations and a set-up for further research.

2 Description of the deterministic model

In this chapter the main processes of the deterministic model are described to answer 'How works the deterministic model used by HR Wallingford for trench and channel infill calculations?' which is the first sub-question. The deterministic model, HR-SISYPHE, can run a variety of sediment transport formulae. The formulae used in this research and described in this part, are the by HR-Wallingford recommended settings (Wilkens & Chesher, 2011) (Villaret & El Kadi, 2010). The model geometry is defined in section 2.1. The calculations are divided into processes which will be explained in different sections. Section 2.2 explains how the morphological changes in the flume are calculated. To calculate morphological changes the bed load (section 2.3) and suspended load transport (section 2.4) need to be calculated. These transport processes are driven by a hydrodynamic model, which is explained in section 2.5. The chapter ends with a section, in which the settings and results of an example run are described.

2.1 Model geometry

This research works with a flume, the top view of which is shown in figure 2.1. This figure shows the 4 boundaries of the model which are red and blue. At the left blue boundary a uniform discharge of water and sediment flows into the flume. The water with sediment will flow out of the flume at the right blue boundary with a uniform water depth. This water flow direction is subject to the currents. The two red boundaries are closed-off, this means that no water or sediment flows in or out through these boundaries. The figure shows that the geometry of this model is smaller than 1 meter. Because the Soulsby-Van Rijn formulae are not valid for water depths smaller than 1 meter, the flume will be scaled up by multiplying the laboratory dimension by 10 and the time by $\sqrt{10}$ to obtain the researched dimensions (Van Rijn, 1984) (Wilkens & Chesher, 2011).

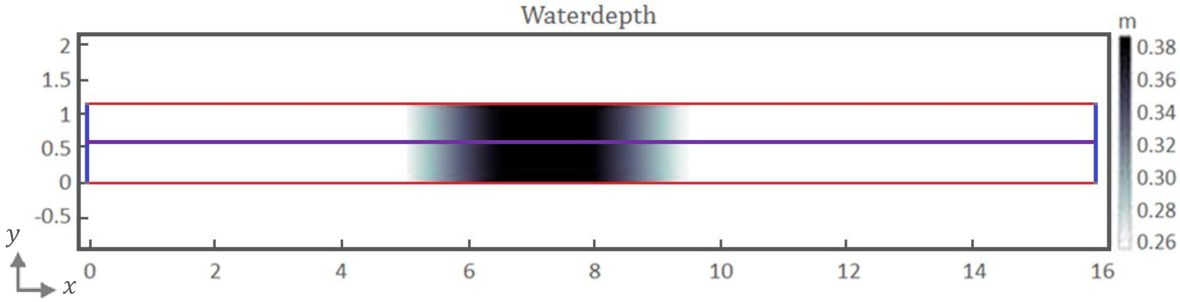

Figure 2.1: Top view of flume for deterministic model [m]

Furthermore figure 2.2 gives a side impression of the flume. In this figure the velocity U in the direction x at height z is shown. In this research the depth averaged shallow water equations are applied. These equations assume that a logarithmic velocity profile at the start of the flume stays in the same shape, at every point in the flume, which will be stretched out when the water depth increases. The velocity profile changes due to vegetation, which is not included in the research, and a high slope gradient. When the slope gradient is high the velocity profile in the trench will differ from the velocity profile outside the trench, and there might even be flow reversal in the trench. The trench is in figure 2.2 the isosceles trapezium with the maximum depth z_b which is 0.125m in this research. In this research the slope gradient S_x, formula is shown in equation 2.1, is 0.125 depth change from 5 to 6.25m and 8.25 to 9.5 m in direction x. This is much smaller than $\frac{1}{5}$ which still gives the logarithmic velocity profile according to Berger, Teeter and Pankow (1993).

$$S_x = \frac{\partial z_b}{\partial x} \qquad (2.1)$$

$$S_y = \frac{\partial z_b}{\partial y} \tag{2.2}$$

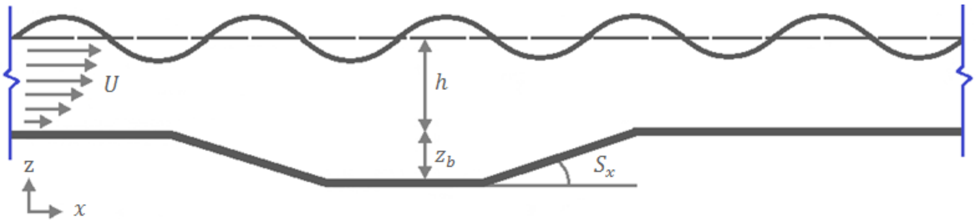

Figure 2.2: Side view of flume for deterministic model [m]

This justifies the use of a depth averaged velocity in this deterministic model. So the model will be run according to a 2D horizontal approach.

2.2 Morphological change

When water flows over a granular bed, it causes a shear stress on that bed. If the flow velocity is high enough, this bed shear stress can exceed the threshold value. The threshold value marks the point from which the sediment will start moving. When the bed shear stress exceeds the threshold value, the sediment will start to move. This movement is called transport, because the sediment is transported to another place (Fox, McDonald, & Prichard, 2011).

Sediment can be transported through suspension or by rolling, hopping and sliding alongside the bed (Snellink & de Korte, 2010). The transport of suspended sediment particles is known as suspended load. The transport of sediment by rolling, hopping and sliding is called bed load transport. The bed load flux $\overrightarrow{Q_b}$ and the suspended load flux $\overrightarrow{Q_s}$ together is the total sediment load. This total load at place x, y on the bed for a time period t is needed for calculating the change in bed shape. The change in bed-level ζ is calculated with the porosity P, which is a value for the percentage of space in the soil (Soulsby, 1997).

$$\frac{\partial \zeta}{\partial t} = -\frac{1}{1-P}\left(\frac{\partial Q_b}{\partial x} + \frac{\partial Q_b}{\partial y} + \frac{\partial Q_s}{\partial x} + \frac{\partial Q_s}{\partial y}\right) \tag{2.3}$$

2.3 Bed load transport

The bed load transport can occur over a flat bed by the fluid velocity and over a slope by gravity and fluid velocity. The velocity differs at different heights above the bed. The velocity near the bed will be lower than the velocity near the surface. This change in velocity is due to the bed friction. The friction rate changes by changes in the bed roughness. The bed roughness impacts, as explained in section 2.3.2, the velocity near the bed and the bed load transport. Next to this, the velocity depends on currents and waves. The effects that currents and waves have on the bed load transport, is explained in section 2.3.3. All these effects together give the bed load transport, defined in section 2.3.1.

2.3.1 General bed-load transport formulae

The bed load transport $\overrightarrow{Q_b}$ is calculated according to Soulsby and Van Rijn (Soulsby, 1997) :

$$\overrightarrow{Q_b} = A_{sb}\vec{U}\left[\sqrt{\left|\vec{U}\right|^2 + \frac{0.018}{C_D}U_o^2} - U_{cr}\right]^{2.4}\left(1 - \beta \tan\frac{\partial z_b}{\partial x}\right) \qquad for \sqrt{\overrightarrow{U^2} + \frac{0.018}{C_D}U_o^2} \geq U_{cr} \tag{2.4}$$

$$\overrightarrow{Q_b} = 0 \qquad for \sqrt{\overrightarrow{U^2} + \frac{0.018}{C_D}U_o^2} < U_{cr} \tag{2.5}$$

The bed load transport $\overrightarrow{Q_b}$ is calculated with a correction method. This correction method takes in account the bottom elevation z_d over length x in the fluid flow direction and an empirical factor β. The empirical factor β ensures that a diffusion factor is included in the bed evolution (Villaret & El Kadi, 2010). With this correction method the bed evolution is more realistic.

The critical velocity U_{cr} also needs to be specified for the bed-load transport. This parameter shows from which velocity the sediment start moving on the bed and is explained in section 2.3.4. The depth-averaged velocity $\vec{U}$ is a vector with x-component $\bar{u}$ and y-component $\bar{v}$. This velocity expresses the current effects in the bed transport formula by changing its sign. The wave effects are included in the equation 2.4 by the wave velocity U_o. This wave effect is explained in section 2.3.3. Furthermore, the bed roughness affects the bed evolution. This effect is implemented by the drag coefficient C_D, to be explained in section 2.3.2. Next to this, the bed evolution is calculated with an empirical bed transport factor A_{sb} with each median diameter for sediment class n by Soulsby and Van Rijn (Soulsby, 1997):

$$A_{sb,n} = \frac{0.005h\left(\frac{D_{50,n}}{h}\right)^{1.2}}{\left((s-1)gD_{50,n}\right)^{1.2}} \tag{2.6}$$

$$A_{sb} = \frac{1}{n}\sum_{1}^{n} A_{sb,n} \tag{2.7}$$

These equations need the median grain diameter D_{50} for each sediment class n, the water depth h, acceleration due to gravity g and the relative density s. The gravitational acceleration is 9.81 ms^{-2} (Fox, McDonald, & Prichard, 2011). The relative density of sediment is given by dividing the sediment ρ_s by the fluid density ρ (Soulsby, 1997):

$$s = \frac{\rho_s}{\rho} \tag{2.8}$$

2.3.2 Bed roughness effects

The drag coefficient, also known als bottom friction is calculated according to Nikuradse's law (1933):

$$C_D = 2\left(\frac{K_k}{log\left(\frac{h12}{k_s}\right)}\right)^2 \tag{2.9}$$

The value of the bottom friction is determined by the water depth, Van Karman constant K_k, which is 0.4 according to Fox, McDonald and Prichard (2011), and the Nikuradse roughness parameter k_s.The Nikuradse parameter is a parameter that introduces the bed roughness to the transport processes and is related to the different bottom types.

The fixed variables are among others the gravity acceleration g (9.81 ms^{-2}) and Von Karman constant K_k (0.4) are by definition the shown value.

2.3.3 Wave effects

The wave effects can be expressed in terms of the orbital velocity. The orbital velocity can be calculated in different ways. In this research orbital velocity is generated from the linear wave theory with the orbital (wave) frequency ω and significant wave height H_s (Villaret & El Kadi, 2010):

$$U_o = \frac{H_s\omega}{2\sinh(kh)} \tag{2.10}$$

This formula depends on the wave frequency and wave number k. The orbital frequency is the frequency in which waves arrive. The wave number k is a function of the orbital frequency ω, water depth h and the gravity acceleration g, shown in equation 2.11 (Soulsby, 1997):

$$\omega^2 = gktanh\,(kh) \tag{2.11}$$

2.3.4 Critical velocity

The critical velocity is the depth-averaged speed required to move the sediment on the bed and is according to Van Rijn (1984)[1] given by:

$$U_{cr,n} = 0.19\left(D_{50,n}\right)^{0.1}\log_{10}\left(\frac{4h}{D_{90}}\right) \qquad \text{for } 0.1 \leq D_{50,n} \leq 0.5\ mm \tag{2.12}$$

$$U_{cr,n} = 8.5\left(D_{50,n}\right)^{0.6}\log_{10}\left(\frac{4h}{D_{90}}\right) \qquad \text{for } 0.5 \leq D_{50,n} \leq 2.0\ mm \tag{2.13}$$

$$U_{cr} = \frac{1}{n}\sum_{1}^{n} U_{cr,n} \tag{2.14}$$

In these formulae the median diameter has a range within which formula is the most suitable. Next to the median diameter, the grain diameter for which 90% of the grains by mass are finer D_{90} and the water depth are key elements to compute the critical current velocity.

2.4 Suspended load transport

The suspended load transport is the sediment that is carried into suspension by currents, waves and flow velocities. The general suspension discharge formulae, defined in section 2.4.1, use the net sediment flux. The net sediment flux is the net difference between the sand picked up and positioned at the same place (section 2.4.2).

2.4.1 General suspended transport formulae

The suspend transport can be described as the depth integrated concentration of sediment in the water C multiplied by the flow velocity (Fox, McDonald, & Prichard, 2011):

$$\overrightarrow{Q_s} = \vec{U}C \tag{2.15}$$

The concentration of suspended sediment in a place is the amount in dispersion with the net sediment flux minus the concentration that is moved away from this place by the velocities. Suspended sediment concentration is calculated with the following formula (Huybrechts, Villaret, & Hervouet, 2010):

$$\frac{\partial \mathrm{C}}{\partial \mathrm{t}} = \left[\frac{\partial}{\partial \mathrm{x}}\left(\varepsilon_{\mathrm{s,x}} * \frac{\partial \mathrm{C}}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{y}}\left(\varepsilon_{\mathrm{s,y}} * \frac{\partial \mathrm{C}}{\partial \mathrm{y}}\right)\right] - \bar{\mathrm{u}}\frac{\partial \mathrm{C}}{\partial x} - \bar{\mathrm{v}}\frac{\partial \mathrm{C}}{\partial \mathrm{y}} + \frac{(\mathrm{E}-\mathrm{D})_{\mathrm{z=z_{ref}}}}{\mathrm{h}} \tag{2.16}$$

The formula works with the dispersion coefficient ε_s, depth averaged velocities $\bar{u}$ and $\bar{v}$, which are described with the hydrodynamic model in section 2.5, and net sediment flux $(\mathrm{E}-\mathrm{D})_{\mathrm{z=z_{ref}}}$.

2.4.2 Bed evolution due to suspension

The difference in erosion and deposition will be calculated for the length above the bed equal to z_{ref} which is zero (Knaapen & Kelly, 2011). The bed evolution can be put down according to Miles' equation 2.17 (1981) with the use of the settling velocity w_S and the two concentrations.

$$D - E = w_s(C_e - C_{t-1}) \tag{2.17}$$

The concentration C_{t-1} is the concentration in the previous time step. In the first time step the value is set to zero. The other concentration, equilibrium concentration, is calculated with Soulsby-Van Rijn (Soulsby, 1997):

$$C_e = \overrightarrow{Q_{sr}}\left(h\vec{U}\right)^{-1} \tag{2.18}$$

The sediment transport rate Q_{sr} can be calculated in the same way as the bed evolution at equation 2.4 and 2.5 with an empirical suspended transport factor A_{ss} (Soulsby, 1997):

[1] Keep attention, because the dimensions do not match

$$\overrightarrow{Q_{sr}} = A_{ss}\vec{U}\left[\sqrt{\overrightarrow{U^2} + \frac{0.018}{C_D}U_o^2} - U_{cr}\right]^{2.4}\left(1 - \beta\, tan\frac{\partial z_b}{\partial x}\right) \qquad for\ \sqrt{\overrightarrow{U^2} + \frac{0.018}{C_D}U_o^2} \geq U_{cr} \tag{2.19}$$

$$\overrightarrow{Q_{sr}} = 0 \qquad for\ \sqrt{\overrightarrow{U^2} + \frac{0.018}{C_D}U_o^2} < U_{cr} \tag{2.20}$$

The depth-averaged current velocity $\vec{U}$, threshold current velocity U_{cr}, orbital velocity U_o, drag coefficient C_D and bed slop factor β are already defined in section 2.3 Bed load transport. This sediment transport rate is calculated with empirical suspended transport factor A_{ss} for each median diameter n by Soulsby and Van Rijn (Soulsby, 1997):

$$A_{ss,n} = \frac{0.012hD_{50,n}\left(\left(\frac{g(s-1)}{\upsilon^2}\right)^{\frac{1}{3}}D_{50}\right)^{-0.6}}{\left((s-1)gD_{50,n}\right)^{1.2}} \tag{2.21}$$

$$A_{ss} = \frac{1}{n}\sum\nolimits_1^n A_{ss,n} \tag{2.22}$$

2.5 Hydrodynamic model

The 2D hydrodynamic model solves the basic mass and momentum conservation of the horizontal components x and y. In this section among others the mass conservation equation and the momentum conservation equations are given in section 2.5.1. These equations need the stresses on the fluid, shown in section 2.5.2 and the slope effects, shown in section 2.5.3.

2.5.1 General equations

The mass conservation law states that the amount of change in volume the fluid is the same as the amount fluid and sediment added and removed to the volume (Fox, McDonald, & Prichard, 2011). With this law the mass conservation equation has been composed with the scalars for the depth-averaged velocity in the x and y direction, $\bar{u}$ and $\bar{v}$, in equation 2.23.

$$\frac{\partial h}{\partial t} + \frac{\partial(h\bar{u})}{\partial x} + \frac{\partial(h\bar{v})}{\partial y} = 0 \tag{2.23}$$

The momentum law states that the change in momentum in a time period is the same as the change in rate of momentum added to the sum of forces acting on the volume. With this law the momentum conservation equations have been composed.

$$\frac{\partial(h\bar{u})}{\partial t} + \frac{\partial(h\bar{u})}{\partial x} + \frac{\partial(h\bar{v})}{\partial y} + \frac{1}{2}g\frac{\partial h^2}{\partial x} = \frac{1}{\rho}\left(\frac{\partial(h\tau_{xx})}{\partial x} + \frac{\partial(h\tau_{xy})}{\partial y}\right) + gh\left(S_x - S_{fx}\right) \tag{2.24}$$

$$\frac{\partial(h\bar{v})}{\partial t} + \frac{\partial(h\bar{u})}{\partial x} + \frac{\partial(h\bar{v})}{\partial y} + \frac{1}{2}g\frac{\partial h^2}{\partial y} = \frac{1}{\rho}\left(\frac{\partial(h\tau_{yy})}{\partial y} + \frac{\partial(h\tau_{yx})}{\partial x}\right) + gh\left(S_y - S_{fy}\right) \tag{2.25}$$

2.5.2 Stresses on the fluid

The stresses on the fluid are the bed shear stress and the transverse shear stresses. According to Villaret and El Kadi (2010) in x and y direction is:

$$\tau_{xx} = \frac{1}{2}\rho C_D\bar{u}\left|\vec{U}\right| \tag{2.26}$$

$$\tau_{yy} = \frac{1}{2}\rho C_D\bar{v}\left|\vec{U}\right| \tag{2.27}$$

The transverse shear stresses are described with the kinematic viscosity υ (Steffler & Blackburn, 2002):

$$\tau_{xy} = \tau_{yx} = \upsilon\rho\left(\frac{\partial\bar{u}}{\partial x} + \frac{\partial\bar{v}}{\partial y}\right) \tag{2.28}$$

2.5.3 Slope friction

According to Steffler and Blackburn (2002) and Villaret and El Kadi (2010) the friction slope in direction x S_{fx} and in direction y S_{fy} can be defined as:

$$S_{fx} = \frac{\bar{u}|\vec{U}|}{2g^2h} C_D \tag{2.29}$$

$$S_{fy} = \frac{\bar{v}|\vec{U}|}{2g^2h} C_D \tag{2.30}$$

2.6 Example run

In the previous section is shown that the model needs a lot of data. The geometry shown in section 2.1 gives the slope, bed shape and width of the model. The width and other needed parameters for the run are shown in table 2.1.

Table 2.1: Input parameters for running deterministic model with their reference values

Parameter	Value	Parameter	Value
Median diameter for sediment class 1 ($D_{50,1}$)	0.0001 m	Sediment discharge at start of flume (Q_s)	*0.528* $kgm^{-1}s^{-1}$
Median diameter for sediment class 2 ($D_{50,2}$)	0.0001 m	Depth averaged velocity ($\bar{U}$)	0.57 ms^{-1}
		Coefficient for sloping bed effect (β)	1.3
90% grain diameter (D_{90})	0.0003 m	Settling velocity (w_s)	0.0221 ms^{-1}
Water depth (h)	*2.55 m*	Dispersion coefficient ($\varepsilon_{s,x}$ and $\varepsilon_{s,y}$)	0.01 m^2s^{-1}
Significant wave height (H_s)	0.8 m	Fluid density (ρ)	1000 kgm^{-3}
Nikuradse parameter (k_s)	*0.015 m*	Sediment density (ρ_s)	2650 kgm^{-3}
Number of sediment classes (n)	*2*	Kinematic viscosity (υ)	10^{-6} $kg(ms)^{-1}$
Porosity of bed (P)	*0.4*	Orbital frequency (ω)	0.21 s^{-1}
Von Karman constant (K_k)	*0.4*	Gravity acceleration (g)	9.81 ms^{-1}

The run is done with time steps of 1 second for a time period of 113841 seconds which is in real-life 36000 seconds $\left(\frac{113841}{\sqrt{10}}\right)$ which is 10 hours. The result of this run, shown in figure Figure 2.3, with the initial bed-level and the measured bed level after 10 hours in real-life have been put together to present the difference between the modelled infill and the measured infill after 10 hours in real-life. The figure that shows the results is taken in the middle width of the flume over the length from 6 till 14 meter. It appears that the model has a slight difference in the infill to the measured bed level. The infill rate of this run is 52% of the trench infill at point 84,5.5.

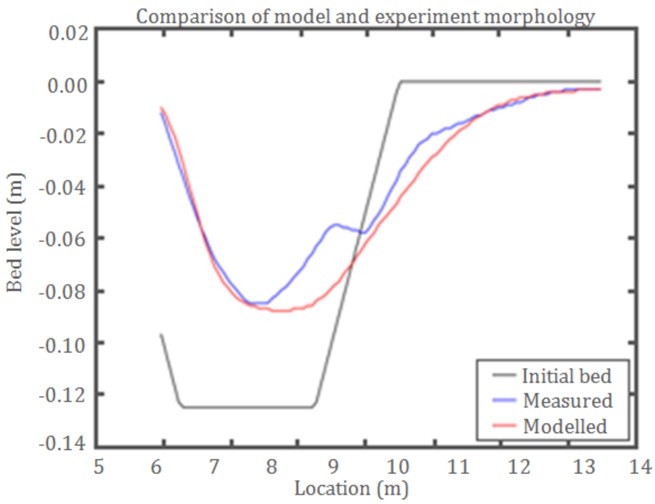

Figure 2.3: Comparison of modelled and experimented infill

3 Sensitivity analysis

In this section the second sub-question 'What is the influence of the input parameters on the infill prediction model?' by conducting a sensitivity analysis with each input parameter. This analysis starts with finding out the effect of the input parameter on the deterministic model in section 3.1. This is followed by section 3.2 which determines the range for each input parameter can vary. With this range and the effect on the model, the effect on the bed prediction can be defined in section 3.3.

3.1 Effect of input parameters on the deterministic model

The effect of each input parameter on the deterministic model is done by multiplying the start value and dividing the start value by two. These two values define a range in which each input parameter varies. The model is run for values within these ranges. Afterwards, the differences between the infill rates for the start values and the boundaries are calculated. This difference is measured in the middle of the flume width (5.5 m in y direction in the deterministic model) and on the whole of the flume length. The place where the measurement is taken, is shown by the purple line in Figure 2.1. The list of input parameters is shown in Table 3.1 with the infill rate. The infill rate is calculated at the deepest point of the modelled reference bed level from chapter 2 at the end of the run period (84 m in the x direction in the deterministic model). This point is chosen to keep into account that the trench will migrate over time. A positive effect implies that increasing the value for the input parameter gives an increased infill rate. A negative effect of an input parameter on the infill rate gives a decreased infill rate with an increased value for the input parameter.

Table 3.1: Input parameters with influence on the bed infill prediction multiplying with 0.5 and 2

Input Parameter	Infill rate		Effect
	For $0.5 * $ value	For $2 *$ value	
ρ_s	80%	12%	Negative effect
P	39%	97%	Positive effect
D_{50}	82%	25%	Negative effect
k_s	52%	52%	No effect
w_s	30%	75%	Positive effect
D_{90}	48%	55%	Positive effect
n	52%	52%	No effect

3.2 Range of input parameters

Sediment conditions change within each place on the bed and change over time in water systems. This means that the precise sediment characteristics are uncertain even after extensive testing. To find and narrow the range of uncertainty it is important to see the input parameters in this group as unknown. This means that the input parameters will not vary around a measured value (Ongley, 1996). The sediment density actually varies around 2650 kgm^{-3} with a variation percentage of 2% according to Soulsby (1997). The ranges for the density of sandy beds given by Hillel (1980b) and Atkinson (Atkinson)are approximately the same as the range given by Soulsby (1997). This means that the range for the sediment density will be from 2597 to 2703 kgm^{-3}.

As this research only covers sandy beds, the sediment characteristics have to work for a grain size diameter between 0.06 and 4.76 mm to cover the ranges given for sand by among others The Dutch Normalisation Institution (Commissie Geotechnics, 1989), American Society for Testing and Materials (ASTM, 2000) and Wentworth's grain size scale (Soulsby, 1997). These edges in grain sizes are the edges for the median diameter and the 90% grain diameter. Within these grain sizes the porosity of the bed can vary from 0.25 to 0.46 (Environmental Science Division, 2013) (Soulsby, 1997).

The restrictions in sediment diameter also create a range for the settling velocity. The settling velocity can be calculated in multiple ways. Sadat-Helbar, Amiri-Tokaldany, Darby and Shafaie (2009) defined the settling velocity for each diameter according to, among others, Stokes (Graf, 1971) and Van Rijn (Van Rijn, 1989). The settling velocity for sand lies approximately between 0.002 and 0.4 ms^{-1}(Sadat-Helbar, Amiri-Tokaldany, Darby, & Shafaie, 2009). This range is bigger than the range, from 0.004 till 0.3 ms^{-1}, Soulsby (1997) would give for sediment particles within these grain size edges and sediment densities. To get the largest uncertainty the range for the settling velocity will be from 0.002 and 0.4 ms^{-1}.

Furthermore, the ranges for the Nikuradse roughness coefficient and the number of sediment classes need to be specified. The number of sediment classes is minimal 1. For the upper boundary 7 classes are chosen, because sand can be divided into 7 groups according to Folk (1954). And the Nikuradse roughness coefficient will vary between 0.009 and 0.18 m. This range results from the range for the bed roughness length z_0, shown in equation 3.1 (Nikuradse, 1933).

$$\mathrm{k}_s = 30 * z_0 \qquad (3.1)$$

The bed roughness length varies between 0.3 mm and 6.0 mm for sandy beds. This will give a range from 0.009 till 0.18 m for the Nikuradse roughness parameter (Soulsby, 1997).

3.3 Effect of input parameters on the bed infill prediction

With the ranges given in the previous section, the infill prediction is calculated by varying each input parameter separately within its ranges. The differences between the infill for the start values and the edges are calculated on the same place as section 3.1. The order of influence with percentage of change on the infill at point (84, 5.5) for each input parameter is shown in Table 3.2. In the order of influence number 1 is the most influential and number 7 is the least influential. A positive difference in infill rate between the upper and bottom edge shows that the input parameter has a positive effect, explained in section 3.1.

Table 3.2: Input parameters with influence on the bed infill prediction within the ranges

Order of influence	Input Parameter	Range	Infill rate		Infill uncertainty percentage*
			For lowest parameter value	For highest parameter value	
1	w_s	$0.002 - 0.4\ ms^{-1}$	8%	93%	85%
2	D_{50}	$0.00006 - 0.00476\ m$	62%	0%	62%
3	P	$0.25 - 0.46$	45%	71%	26%
4	D_{90}	$0.00006 - 0.00476\ m$	44%	63%	19%
5	ρ_s	$2597 - 2703\ kgm^{-3}$	54%	50%	3%
6	k_s	$0.009 - 0.18\ m$	52%	50%	1%
7	n	$1 - 7$	52%	52%	0%

4 Relations

In this chapter the third sub-question 'What are the underlying relationships that will have influence on the values of the input parameters?' will be studied by finding underlying relations between the input parameters. In section 4.1 the different kind of relations are explained. In section 4.2 the found relations between the input parameters are described. The last section will give the additional ranges for doing the Monte Carlo analysis. For more information is referred to appendix A.

4.1 Different relations

Parameters can have different relations to each other. Examining if there is a relation between the parameters can be done by exploring the correlation between two or more parameter. When the parameters do not have a correlation, it will be associated with not having any effect on each other's value (Shenoy, Srivastava, & Sharma, 2002).

According to the Business Dictionary, correlation is a relationship between any two or more variable in which they vary together over a period (Luthra & BusinessDictionary.com, 2011). In other words, a correlation exists when the value of one parameter is associated with the value of another (Gerstman, 2013). A correlation can be positive or negative. When parameters X and Y have a positive correlation with each other, parameter X increases when parameter Y increases. When parameter X increases and this results in a decrease of parameter Y, than parameter X and Y have a negative correlation. For a further explanation of correlations is referred to appendix A.

When parameters have a correlation, they can have causation as well. Causation only appears when the change in value of parameter X is the only parameter that has an effect on parameter Y.

4.2 Relations between input parameters

In this section the direct relations are described. The direct relations are relations between input parameters that not have been created by combining relations between these input parameters with other input parameters. This is not defined in this section, because the relations are already taken into account by applying both relations separately without combining them. The first relation is between the median diameter, sediment density and settling velocity. These input parameters have a relation according to Van Rijn (1993), Hallermeier (1981) and Soulsby (1997). Their relation formulae have been used to create a formula for these three parameters, shown in equation 4.1. This formula has a range that is given by constant a in this formula.

$$\rho_s = a\frac{w_s}{D_{50}} \qquad 17\ kgsm^{-5} < a < 7476\ kgsm^{-5} \qquad (4.1)$$

Because the additional range given by formula 4.1 has a larger range than the range for the sediment density found in chapter 3, this range is not included in the Monte Carlo analysis. Next to this relation the sediment density also has a relation to the porosity (Depeweg & Mendez, 2007). In the same way as equation 4.1, equation 4.2 is created. Due to the small range for the sediment density, the range for the porosity needs to be changed to get a value for the sediment density that is within its range. This range is an additional range for the Monte Carlo analysis for which the dry sediment density $\rho_{s,dry}$ will be found randomly and independently for calculating the sediment density. The new range for the porosity will be $0.41 - 0.46$. For this new range for the porosity the infill rate uncertainty is 19%.

$$\rho_s = \frac{\rho_{s,dry}}{1-P} \qquad 504\ kgm^{-3} < \rho_{s,dry} < 1313\ kgm^{-3} \qquad (4.2)$$

Furthermore the porosity has a relation to the median diameter. Wu and Wang (2009) researched the different relation formulae by other authors and found out that Komura's formula with a 30% error, shown in equation 4.3, has all the measured data within its range. The 30% error is included in the formula by constant b, which also creates an additional range for the porosity in relation to the median diameter (Komura, 1963).

$$P = b\left(0.245 + \frac{0.0864}{(100D_{50})^{0.21}}\right) \qquad 0.7 \leq b \leq 1.3 \qquad (4.3)$$

The median diameter also has a relation with the 90% grain diameter. The only found formula of the relation between these two input parameters, is that the median diameter always is smaller than the 90% grain diameter. The grain diameter and the median diameter both have a relation with the Nikuradse parameter. According to Yen (1992) the Nikuradse can be defined as followed:

$$k_s = c * D_{50} \qquad 1 \leq c \leq 7 \qquad (4.4)$$

$$k_s = d * D_{90} \qquad 1 \leq d \leq 5 \qquad (4.5)$$

The constants c and d are randomly found dependently. Because the median diameter needs to be smaller than the 90% grain diameter, constant c needs to be bigger than constant d.

4.3 Additional ranges

The relations between the input parameters can be transformed into ranges that have to be used next to the ranges given by the sensitivity analysis from chapter 3 for the Monte Carlo analysis. The ranges are listed below.

$$\frac{504}{1-P} < \rho_s < \frac{1313}{1-P}$$

$$0.7\left(0.245 + \frac{0.0864}{(100D_{50})^{0.21}}\right) < P < 1.3\left(0.245 + \frac{0.0864}{(100D_{50})^{0.21}}\right)$$

$$D_{50} < k_s < 7D_{50}$$

$$D_{90} < k_s < 5D_{90}$$

$$D_{50} < D_{90}$$

$$0.41 < P < 0.46$$

5 Probabilistic analysis

In this chapter the last sub-question 'How should uncertainty in channel and trench infill be quantified?' will be defined through a probabilistic analysis. The first section will explain how the input for the probabilistic analysis is generated. This is followed by the probabilistic infill, section 5.2. Furthermore this section explains how the probabilistic infill will be changed to create an infill quantity and uncertainty. The last section will give a conclusion of the infill quantity and uncertainty found by the probabilistic analysis.

5.1 Generating input for the probabilistic infill

The Monte Carlo input is generated randomly in Excel with the given ranges and relational ranges from the previous chapters. The other input parameters which are not studied in this research have a fixed value. The fixed values for these input parameters are given in table 2.1. In chapter 3 the order of influence is given. Due to the relationships between input parameters the order in which the input will be generated is changed. The median diameter has causation with the number of sediment classes. Because the number of sediment classes is needed to generate the number of values for the median diameter, the number of sediment classes will be placed after the settling velocity and before the median diameter. Furthermore, the porosity range changed due to the relation with the sediment density. This means that the influence of this input parameter changed. However, the influence of this input parameter becomes the same as the influence of the 90% grain diameter, so this does not change the order of influence. The order for generating the input parameters with their ranges and the relational ranges are given in table 5.1.

Table 5.1: Order for generating the input parameters and the ranges for each input parameters.

Order	Input Parameter	Range	Relational ranges
1	w_s	$0.002 - 0.4\ ms^{-1}$	-
2	n	$1 - 7$	-
3	D_{50}	$0.00006 - 0.00476\ m$	-
4	P	$0.41 - 0.46$	$0.1715 + \frac{0.6048}{(100D_{50})^{0.21}} < P < 0.3185 + \frac{0.11232}{(100D_{50})^{0.21}}$
5	D_{90}	$0.00006 - 0.00476\ m$	$D_{50} < D_{90}$
6	ρ_s	$2597 - 2703\ kgm^{-3}$	$\frac{504}{1-P} < \rho_s < \frac{1313}{1-P}$
7	k_s	$0.009 - 0.18\ m$	$D_{50} < k_s < 7D_{50}$; $D_{90} < k_s < 5D_{90}$

The number of runs needed for the Monte Carlo analysis MC_r can be calculated as followed (Burns & Bush, 2006):

$$MC_r = \frac{s_a^2 p(100 - p)}{s_a} \tag{5.1}$$

This formula works with the percentage in which the sampling fits the criteria p. The Monte Carlo sample will fit the found criteria from chapters 3 and 4, but it is possible that there are criteria to the input parameters which were not found. According to Burns and Bush (2006) the worst case scenario is a 50 per cent sampling fit. Because it is unknown how many underlying relations have been missed, the worst case scenario is used. The better the sampling fit all the criteria the less runs need to be done, so the amount of runs needed, will be lower than the actual calculated runs.

Furthermore, the acceptable sampling error s_a needs to be defined. According to Burns and Bush (2006) a confidence interval of 95 per cent is acceptable in research. This percentage is chosen due to keeping the running time feasible. It is also acceptable in sediment transport issues, which suffers from large ranges of uncertainty and model errors that change in magnitude (Van Rijn, 1993). With a confidence interval percentage of 95, the acceptable sampling error is 5. With this confidence interval the standard deviation s_a according to Burns and Bush (2006) is 1.96. This makes the needed runs for this research approximately 400.

5.2 Probabilistic infill

With the input parameters for 400 rounds SISYPHE is run. The result of the runs is shown in figure 5.1.

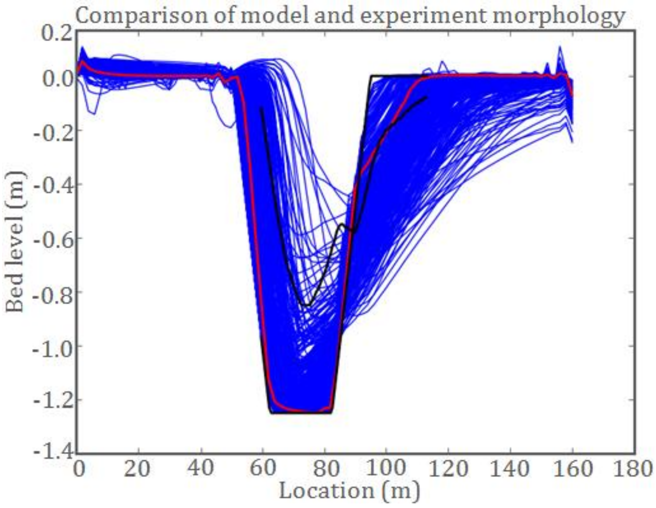

Figure 5.1: Infill predictions of the 400 runs

At the same point (84,5.5) defined in section 3.1 the depth of the trench for each run is found. Furthermore the width of the trench at 75% of the total trench depth is calculated. With these numbers for each run a probabilistic distribution can be set-up. Figure 5.2 and 5.3 show that the trench depth and width have a normal distribution Right side the distribution line stops at the initial trench depth (1.25m), because the trenches do not increase in trench depth by sediment infill.

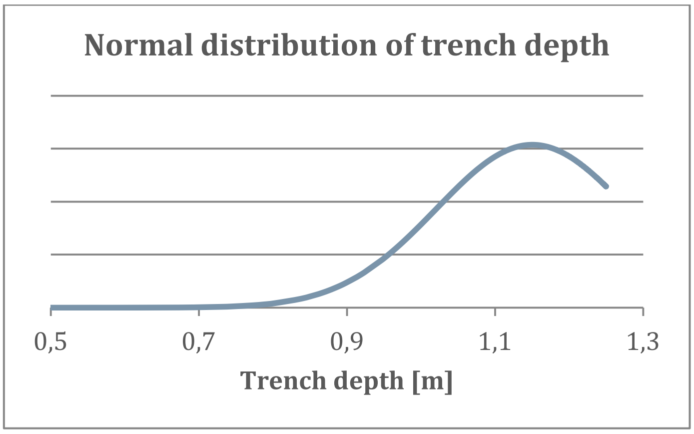

Figure 5.2: Normal distribution of trench depth

The normal distribution for the trench width also stops directly. This shows that there is a relation between the trench depth and the trench width. Because the trench depth did not increase, the trench width did not do that as well. Furthermore, figure 5.1. shows that the trench width decreases on the side where the water flows from and increases on the other side.

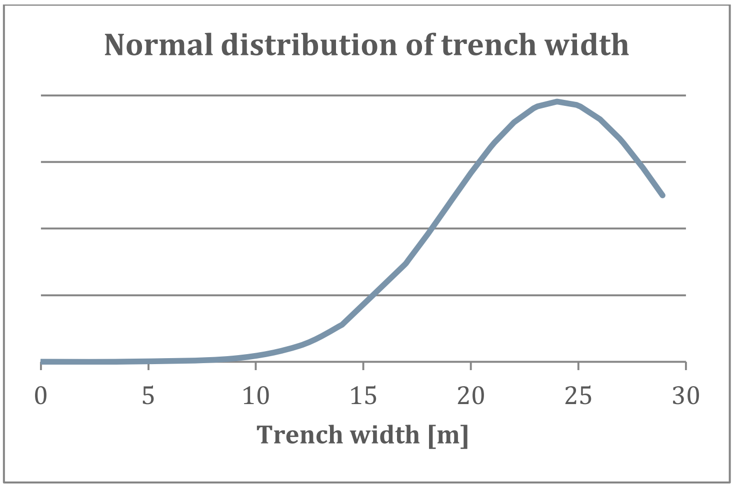

Figure 5.3: Normal distribution of trench width

These probabilistic distributions will be used to calculate the infill quantities and uncertainties. The infill quantity will be seen as the mean of all infill prediction runs. With this mean the distribution of the uncertainty can be found by a standard deviation. This standard deviation is the average amount that the infill varies from the median diameter, shown in equation 5.2 (McClave, Sincich, & Benson, 2007).

$$s = \sqrt{\frac{1}{m}\sum_{0}^{m}(\bar{\zeta} - \zeta_m)^2} \tag{5.2}$$

5.3 Conclusion of the infill quantities and uncertainties

With the infill distribution the mean infill and standard deviation can be calculated. The result of these calculations is shown in table 5.2 and table 5.3. These values are also shown in percentage of the initial trench depth and trench width at 75% of the original trench depth of 1.25m, which makes the reference level to be 0.75m.

Table 5.2: Mean and standard deviation for trench depth at end of run

	Trench depth at end of run period
Mean	1.15 m
Mean in percentage of initial trench depth	92%
Standard deviation	0.13 m
Standard deviation in percentage of initial trench depth	10%

68% of the run lies in the interval $[\bar{\zeta} - s, \bar{\zeta} + s]$. To get a 95% interval the standard deviation has to be multiplied by 1.96. In this 95% interval 2.5% lies below the bottom boarder which is 0.9 m. This means that 97.5% of the trench infill is lower than 0.35m, which is 35% of the initial trench depth (Fidler, 2012).

Table 5.3: Mean and standard deviation for trench width at end of run

	Trench width at end of run period
Mean	24.08 m
Mean in percentage of initial trench width (35 m)	69%
Standard deviation	5.10 m
Standard deviation in percentage of initial trench width	15%

The 95% of the runs fits between a trench width of 14 and 34m. This means that approximately 98% has a trench width bigger than 14m at an initial trench depth of 0.75m, which is bigger than the initial bottom width of the trench.

6 Discussion

The discussion of this research can be divided into three groups, the input, methods and results. First the input will be discussed. The input is followed by the chosen methods, in section 6.2. Finally the results will be discussed in section 6.3.

6.1 Discussion on input

With this research the uncertainty in the infill was studied. For the infill prediction the deterministic model is run. This deterministic model can vary by changing the formulae used in this model. Changes in the model can also change the infill prediction. This model is used, because it is one of the few models that use a non-equilibrium sediment transport formulation. As a result, the infill prediction with this model reproduces the measured infill better than other models (Knaapen & Kelly, 2011).

Some input parameters in this deterministic model have not been researched, as is explained in the introduction. However these input parameters have influence on the infill prediction and can vary from one situation to the other. This means that these input parameters can change the uncertainty and quantification of the infill which have not been taken into account in this research.

6.2 Discussion on methods

This research sequence starts with the sensitivity analysis. This is followed by the study of underlying relations between the input parameters. The research ended with a probabilistic analysis. The discussion on the methodology will be done in this sequence.

To find the influence of each input parameter on the infill prediction a sensitivity analysis is done for each input parameter separately. This analysis gives uncertainties given by changing every input parameter. However, this research is not sufficient to find the uncertainty on and quantification of the infill. The effect of several of the input parameters on the infill prediction is not researched in this part, because the underlying relations were not studied yet. These input parameters will have a different influence on the total infill at the end of the run period.

The influence of the input parameters was researched after the influence of each input parameter on the infill prediction. The underlying relations were studied by searching previous research on these input parameters which gives values of the parameters that actually fit together in real-life situations. This part of the research can have inaccuracy or miss important relations. Some relations were not formulated in previous research or found in this searching period. These relations have not been taken into account in this research, but can have a result in real-life trench or channel infill.

The last part of this research is the probabilistic analysis. This analysis is a strong method to obtain an uncertainty distribution in this research. However, this analysis needs more runs in this research for a higher confidence interval which was not possible within the time constraint. This can result in different uncertainties and quantifications.

6.3 Discussion on results

The result of this research is only conducted from one trench shape. Different shapes can change the infill prediction and uncertainty in infill. Due to changes in shapes and in water flow directions on the trench, sediment infill can change.

Furthermore, the results can differ when the infill is analysed at other points in the trench, due to migration of the trench in each run. Each run can have a different migration length. To keep in mind the migration the deepest point of the initial run in chapter 3 is used.

7 Conclusion

The objective of this research is quantifying the uncertainties of the deterministic model for sandy beds by an uncertainty analysis. Quantifying these uncertainties is done by answering the sub-questions shown in section 1.5. The first question 'How works the deterministic model used by HR Wallingford for trench and channel infill calculations?' is answered by studying the deterministic model and reading literature about sand infill predictions. The second sub-question 'What is the influence of the input parameters on the infill prediction model?' is answered by studying each sediment characteristics input parameter separately. This gives the amount in which the change in input parameter value changes the infill prediction of the deterministic model. Table 7.1 shows the influence of each input parameter on the infill prediction model. Below the table the additional ranges are given that show relationships between the input parameters. These relationships are a result of researching sub-question two 'What are the underlying relationships that will have influence on the values of the input parameters?'.

Table 7.1: Input parameters with influence on the bed infill prediction within the ranges

Input parameter	Range	Infill uncertainty
Settling velocity (w_s)	$0.002 - 0.4\ ms^{-1}$	85%
Median diameter($D_{50,n}$)	$0.00006 - 0.00476\ m$	62%
Porosity(P)	$0.41 - 0.46$	19%
90% grain diameter(D_{90})	$0.00006 - 0.00476\ m$	19%
Sediment density(ρ_s)	$2597 - 2703\ kgm^{-3}$	3%
Nikuradse parameter(k_s)	$0.009 - 0.18\ m$	1%
Number of sediment classes(n)	$1 - 7$	0%

$$\frac{504}{1-P} < \rho_s < \frac{1313}{1-P}$$

$$0.7\left(0.245 + \frac{0.0864}{(100D_{50})^{0.21}}\right) < P < 1.3\left(0.245 + \frac{0.0864}{(100D_{50})^{0.21}}\right)$$

$$D_{50} < k_s < 7D_{50}$$

$$D_{90} < k_s < 5D_{90}$$

$$D_{50} < D_{90}$$

With the relations between the input parameters, which give the input parameters additional ranges, and the influences of these parameters on the infill prediction, the probabilistic analysis can be deducted. This probabilistic analysis is the answer on the last sub-question 'How should the uncertainty in channel and trench infill be quantified?' With this analysis the infill and uncertainty in infill are quantified. At the end of this sub-question the main question of this research 'What is the size of uncertainties in channel and trench infill?' can be answered.

The average channel and trench infill is $0.1\ m$ (8%). Approximately 98% of the channels and trenches with sandy beds will have a sand infill lower than 0.35m, which is 35% of the initial trench depth. This 35% infill can be taken into account with designing a channel to keep the trench depth below a needed depth, which can save time and effort in researching the sediment characteristics of the site.

For the trench and channel width on trench depth 0.75m the average narrowing of the width for sandy beds is $11\ m$ ($31\%\ of\ the\ initial\ trench\ width$). 98% of the trenches and channel will lie between 14 and 34m. This result can also be taken into account with designing a channel to keep the trench width above a certain wide.

8 Further research

By conducting this research an interesting topic for further research arose. The relation between the median diameter and the 90% grain diameter is not formulated and it is interesting to find out if it is possible to formulate a relationship in another way than that the D_{50} needs to be smaller than D_{90}. It would be interesting to find out if the distribution of grain has a particular range in which the distribution width varies or if there is no pattern found between the median diameter and the 90% grain diameter.

Additionally, two topics for further research in this area are recommended. First of all, the fluid conditions were not included in this research, explained in section 1.7. When this research can be conducted, it would give a more complete uncertainty analysis to analyse the fluid conditions alone and together with the sediment conditions. By analysing the uncertainty due to fluid conditions first alone, it gives an indication of the influence on the infill. When afterwards doing the research with both conditions together, it can be researched if the uncertainty changes from the infill with the conditions separately and if this is conform the expectation due to the separate research.

Secondly, it is recommended to find out if changes in the shape, slope gradient and navigation will change the sediment infill. The navigation is the angle at which the water flows over the trench. The used trench profile based on contractors past data for pipeline installation has a bottom width of 1.5 m and a trench depth of 2.1 m (Lowe, 2010). For the trenches the slope and navigation can be researched with this profile. For the trench design is it wise to research if the studied slopes do not change the water velocity profile. When the velocity profile stays the same, this research can be done with a 2D model, like the model used in this research.

The researched channel slopes should not exceed $\frac{1}{5}$ given in section 2.1, thus this research can be done with a 2D approach and this deterministic model (Waterways Development Division of Canadian Coast Guards, 2002). For channel design all aspects of the shape, like depth, width and slope, should be studied. The bottom width of channels for one- way traffic lies between 5 and 8 and for two-way traffic lies between 9 and 10m according to Bray (1979) and the Waterways Development Division of the Canadian Coast Guards (2002). Furthermore Bray (1979) and the Waterways Development Division of the Canadian Coast Guards (2002) also explain that the water and trench depth together lie usually between 16 and 26m. With this information the best orientation and shape of a trench and channel in each situation can be researched. To research this, the dredging costs and effects need to be taken into account. The dredging costs have already been set up with the use of Bray (2002), Vlasblom (2003) and Farnham (2010).

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Appendix

APPENDIX

Appendix A: Relations between the input parameters

In chapter 4 is explained that parameters can have different relations to each other like correlations and causation. It also expressed that a correlation exists when the value of one parameter is associated with the value of another (Gerstman, 2013). For example when a woman thinks certain jewellery bring luck, the woman will wear this jewellery to important meetings and job interviews.

Chapter 4 explained that there are positive and negative correlations. These different correlations can best be explained with an example. For example when the owner of an ice-cream shop thinks that sun increase the ice-cream sale. A high sale is for the ice-cream shop owner a very positive result, high value. Next to this sun is a parameter for which a lot of sun is the high value. When the owner hears it will be a sunny day, the owner will think it is going to be good day to sell ice-cream. So the owner associates a high value for sun with a high value for sales. When there will be little to no sun, the owner will associate this with a low value for sales. In other words the owner associates the value of the sun with the value for sales. This example explains the positive correlation. It can also be the other way around. If the owner looks at the rain instead the sun, he will associate a positive value for rain with low sales. So he associates a value of rain with an opposite value for sales. This phenomenon is called negative correlation. When a correlation between the parameters is not positive or negative, it is no correlation at al. In this case the owner does not associate for example the wind with the ice-cream sales. The correlations are shown in figure A.1 (Shenoy, Srivastava, & Sharma, 2002).

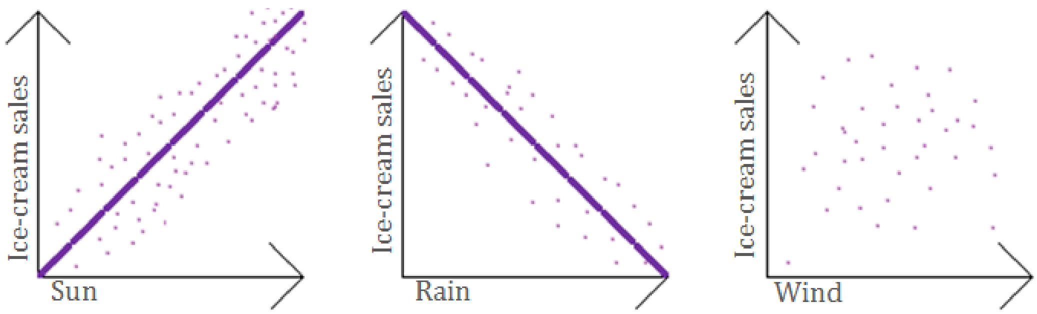

Figure A.1: Positive correlation (left), Negative correlation (middle), No correlation (right)

In this appendix the relations between each input parameter are studied. Each section describes the relation between one parameter and the other parameters. Due to the high amount of relations with the median diameter, the first section will describe these relations. Afterwards the parameters are described in their order of influence shown in table 3.2.

A1. Relation between the median diameter and other input parameters

In this section relations between the median diameter and other input parameters are researched. In section A1.1 the relation between the median diameter, settling velocity and sediment density will be described. This is followed by the relation with the porosity. Afterwards in section A1.3 the relation with the 90% grain diameter will be explained. Later on in section A1.4 the relation between the median diameter and Nikuradse parameter. Finally the relation with the number of sediment classes is presented.

APPENDIX

A1.1. Relation between median diameter, settling velocity and sediment density

The settling velocity can be estimated in multiple ways with the median diameter. For example the settling velocity according to Van Rijn (1993) is:

$$w_s(Van\ Rijn) = \frac{\left(\frac{\rho_s}{\rho}-1\right)gD_{50}^2}{18\upsilon} \qquad if\ D_{50} \leq 10^{-4}\ m \tag{A1.1}$$

$$w_s(Van\ Rijn) = \frac{10\upsilon}{D_{50}}\sqrt{1 - 0.01\frac{\left(\frac{\rho_s}{\rho}-1\right)gD_{50}^3}{18\upsilon^2}} - 1 \qquad if\ 10^{-4}m < D_{50} < 10^{-3}m \tag{A1.2}$$

$$w_s(Van\ Rijn) = 1.1\sqrt{\left(\frac{\rho_s}{\rho} - 1\right)gD_{50}} \qquad if\ D_{50} \geq 10^{-3}m \tag{A1.3}$$

These formulae show that the settling velocity in theory has a positive correlation with the median diameter. If the median diameter increases it is associated with the increase of the settling velocity. This correlation also works the other way around. When the settling velocity increases it can be associated with the increase of the median diameter. In other words, the median diameter and the settling velocity have a positive correlation in both ways. The settling velocity also has a positive relation with the settling velocity and the median diameter. In this research the gravity acceleration g is a fixed variable. So next to the median diameter the kinematic viscosity and fluid density can change. To make a simplified version that includes results of different formulae for calculating the settling velocity, 3 formulae have been calculated. The first formulae are that of Van Rijn, shown in the equations above. The other two formulae are stated in equation A1.7 (SeaZone Solutions division of HR Wallingford Ltd.) and A1.4-6 (Hallermeier, 1981). The Gibbs' formula is not used, because this has a very low percentage of prediction in which the observations lie according to Soulsby (1997).

$$w_s(Hallermeier) = \frac{\left(\frac{\rho_s}{\rho}-1\right)gD_{50}^2}{18\upsilon} \qquad if\ D_{50} \leq 10^{-4}\ m \tag{A1.4}$$

$$w_s(Hallermeier) = \upsilon\frac{\left(\left(\frac{g\left(\frac{\rho_s}{\rho}-1\right)}{\upsilon^2}\right)^{\frac{1}{3}}D_{50}\right)^{2.1}}{6D_{50}} \qquad if\ 10^{-4}m < D_{50} < 10^{-3}m \tag{A1.5}$$

$$w_s(Hallermeier) = 1.05\sqrt{\left(\frac{\rho_s}{\rho} - 1\right)gD_{50}} \qquad if\ D_{50} \geq 10^{-3}m \tag{A1.6}$$

$$w_s(Soulsby) = \frac{\upsilon}{D_{50}}\left(\sqrt{\left(10.36^2 + 1.049\left(\left(\frac{g\left(\frac{\rho_s}{\rho}-1\right)^{\frac{1}{3}}}{\upsilon^2}\right)^{\frac{1}{3}}D_{50}\right)\right)^3} - 10.36\right) \tag{A1.7}$$

For each formulae random median diameters and sediment density within their range, random kinematic viscosities between $1.79 * 10^{-6}$ and $6.58 * 10^{-7} m^2 s^{-1}$ and random fluid densities between 1020 till 1050 kgm^{-3} are used to calculated the settling velocities (Talley, Pickard, Emery, & Swift, 2011). The different calculated settling velocities are divided by the median diameters, this result in formula A1.8 which is an approximation of the relation between the median diameter, settling velocity and the sediment density. Constant a in this formula is the parameter that includes the range in difference between the three input parameters.

$$\rho_s = a\frac{w_s}{D_{50}} \qquad 17kgsm^{-5} < a < 7476\ kgsm^{-5} \tag{A1.8}$$

A1.2. Relation between median diameter and porosity

The relation between the median diameter and porosity in waterways has been studied by among others Komura (1963), Colby (1963) and HAN, Wang and Xiang (1981). In these researches the porosity of sediment deposition is related to among other the median diameter. The porosity in this research is used as the porosity of repositioned sediment. Wu and Wang (2009) researched the formulae and found out that Komura's formula has a better coverage than the other formulae with a 30% error in the measured data. Komura's formula is shown in equation A1.9 (Komura, 1963). This 30% error is included in equation A1.10 by constant b (Wu & Wang, 2009).

$$P = 0.245 + \frac{0.0864}{(100D_{50})^{0.21}} \qquad \textbf{(A1.9)}$$

$$P = b\left(0.245 + \frac{0.0864}{(100D_{50})^{0.21}}\right) \qquad 0.7 \leq b \leq 1.3 \qquad \textbf{(A1.10)}$$

A1.3. Relation between median diameter and 90% grain diameter

Because the grain diameter for which 90% of the grains by mass is finer than the grain diameter for which 50% is finer, the median diameter and D_{90} depend partially on each other. When the D_{90} will decrease at one point the D_{50} also needs to decrease to stay below the 90% grain diameter boundary. These parameters also affect each other when the mean grain diameter increases. When the D_{50} increases the D_{90} needs to increase at a point as well to stay above the median diameter.

$$D_{50} < D_{90} \qquad \textbf{(A1.11)}$$

The relation shown above only works when D_{50} increases or D_{90} decreases to such a point that the one parameter will pass the other parameter. The correlation between the median diameter and the 90% grain diameter can be seen as a partial correlation that only works when the one passes the other parameter. This correlation can be larger, because the grain diameter has a distribution which can create an additional relation. This relation with distribution widths has not been researched, so this possible relation cannot be included in this research.

A1.4. Relation between median diameter and Nikuradse parameter

The Nikuradse roughness coefficient can be estimated in multiple ways. According to Wilson k_s is a formula of the shields parameter and the median diameter (Wilson, 1989), shown in equation A1.12. However authors only use the diameter like Van Rijn, equation A1.14, or Soulsby and Humphrey, equation A1.13 to calculate the Nikuradse parameter (Van Rijn, 1993) (Soulsby & Humphry, Field observations of wave-current interaction at the sea bed, 1990). The formulae show that k_s has a positive correlation with the D_{50}.

$$k_s(Wilson) = 70 * \sqrt{\theta} * D_{50} \qquad \textbf{(A1.12)}$$

$$k_s(Soulby \,\&\, Humphery) = 2.4 * D_{50} \qquad \textbf{(A1.13)}$$

$$k_s(Van\ Rijn) = 2.5 * D_{50} \qquad \textbf{(A1.14)}$$

The Nikuradse coefficient can depend on the median diameter and shields parameter or on the median diameter and the degree of ripples on the bed, so the correlation cannot be called causation (Soulsby, 1997). With these different formulae one formula can be formulated (Camenen, Larson, & Bayram, 2008):

$$k_s = c * D_{50} \qquad \textbf{(A1.15)}$$

According to Yen (1992) the constant c varies between 1 and 7 based on other authors like Van Rijn.

A1.5. Relation between median diameter and number of sediment classes

The D_{50} and n have a relation with each other. When the number of sediment classes increases the number of median diameters increases with the same value. This also works in the other way, for example when the number of median diameters change the number of sediment classes change. Because this connection is directly related, it can be seen as causality. Due to this causality the number of sediment classes need to be defined before the median diameter values for each class can be found.

A2. Relation between the settling velocity and other input parameters

In this section relations between the settling velocity and other input parameters are researched. In section A1.4 that relation between the settling velocity and the median diameter is already defined. Furthermore the relation between the sediment density and the settling velocity has already been defined in section A1.4. In other words, these relations are not defined in this section. This sections start with defining the relation between the settling velocity and the porosity. Afterwards in section A2.2 the relation with the 90% grain diameter will be explained. The next section characterizes the relation with the Nikuradse parameter. At last the relation with the number of sediment classes is presented.

A2.1. Relation between settling velocity and porosity

Due to the relation between the settling velocity and median diameter and the relation between the porosity and the median diameter, the settling velocity and porosity also have a relation. This relation can be created by combining equation A1.10 and A1.15.

A2.2. Relation between settling velocity and 90% grain diameter

The settling velocity and the 90% grain size value are related to each other through the mean grain diameter. De median diameter has a positive correlation with the D_{90} and the other way around which is explained in section A1.3. Next to this, the median diameter has a positive correlation with the settling velocity. So when the 90% grain diameter changes, this can change the median diameter. This change in the median diameter will then change the settling velocity. In other words, D_{90} and w_s can have a positive correlation. To research if this is correct, the same estimation technique is conducted as in section A1.1 with the same ranges for the parameters and implementing D_{90} by formula A1.11. The scatterplot visualized in figure A.2, shows that there is indeed a positive correlation between the settling velocity and the 90% grain diameter.

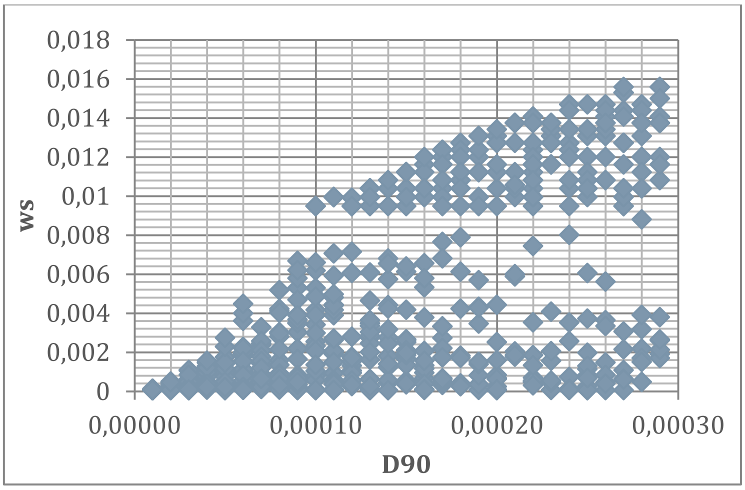

Figure A.2: Scatterplot of relation between settling velocity and 90% grain diameter

A2.3. Relation between settling velocity and Nikuradse parameter

The settling velocity is estimated with the median diameter. Next to this, the median diameter has a positive relation with the Nikuradse parameter. This means that when the Nikuradse parameter changes, the median diameter can change, which on its turn can change the settling velocity. So these parameters have a correlation with each other. This correlation will be less strong than the correlation between these parameters and the median diameter, because with every formula more parameters can be included in the relation between the input parameters. To show this, the settling velocity estimation formula is shown with Wilsons' formula for the Nikuradse parameter and equation A2.1.

$$\left.\begin{aligned} k_s = 70 * \sqrt{\theta} * D_{50} \rightarrow D_{50} = \frac{k_s}{70 * \sqrt{\theta}} \\ w_s = \frac{(s-1) * g * D_{50}^2}{18 * v} \end{aligned}\right\} w_s = \frac{(s-1) * g * \left(\frac{k_s}{70 * \sqrt{\theta}}\right)^2}{18 * v} \qquad \text{(A2.1)}$$

Because the Shield parameter also has an influence on this relationship and this parameter was not included in the relation between the D_{50} and thew_s, the relation between k_s and w_s will be less influential than the relation between the median diameter and the settling velocity.

A2.4. Relation between settling velocity and number of sediment classes

The settling velocity and number of sediment classes do not have a relation, because it only changes the number classes for sediment. It does not change the settling velocity and the other way around.

A3. Relation between the porosity and other input parameters

Some of the relations between the porosity and other input parameters have already been defined in the previous sections. From the other relations two work through the relation with the median diameter. By combining equation A1.10 and A1.11 the only found relation between the porosity and the 90% grain diameter can be conducted. Furthermore the found relation between the Nikuradse parameter and porosity is by combining equation A1.10 and A1.15. Next to these relations, there are two relations that need to be defined in this section. The relation between the porosity and sediment density will be characterized first. Afterwards, the relation with the number of sediment classes will be defined.

A3.1. Relation between porosity and sediment density

The sediment density, also called the wet sediment density, can be calculated with the dry sediment density and porosity, shown in equation A3.1 (Depeweg & Mendez, 2007).

$$\rho_s = \frac{\rho_{s,dry}}{1-P} \qquad \text{(A3.1)}$$

The dry sediment density varies between 1500 and 1550 kgm^{-3} for sand (Depeweg & Mendez, 2007). With this relation a range for the sediment density in relation to the porosity can be conducted and is shown in equation A3.2.

$$\frac{1500}{1-P} < \rho_s < \frac{1550}{1-P} \qquad \text{(A3.2)}$$

Due to this small range for the sediment density, the range for the porosity needs to be changed to get a value for the sediment density that is within its range. For example with a porosity value of 0.3 and the highest dry sediment density of 1550 kgm^{-3} the sediment density will be 2155 kgm^{-3} which is lower than the minimum range for this parameter given in chapter 3. The new range for the porosity that makes sure that the sediment density can fit within its range due to the relation between these parameters will be from 0.41 till 0.46.

A3.2. Relation between porosity and number of sediment classes

The porosity and number of sediment classes do not have a relation, because it only changes the number classes for sediment. It does not change the value of these classes which then can change the porosity.

A4. Relation between the 90% grain diameter and other input parameters

In previous sections the relations between the 90% grain diameter and some of the other input parameters have already been defined. The undefined relations with the 90% grain diameter are between the D_{90} and sediment density, Nikuradse parameter and number of sediment classes. The relation between the sediment density and 90% grain diameter can be found by combining equation A1.11 with A1.12. This relation is not described further, because the relation is already included by using the equations separately. The other two input parameters will be described below. This section will describe the relation between the D_{90} and Nikuradse parameter in section A4.1. In section A4.2 the relation between the number of sediment classes and the 90% grain diameter will be defined

A4.1. Relation between 90% grain diameter and Nikuradse parameter

According to Van Rijn the Nikuradse parameter can be calculated with a constant multiplied by D_{90}. This constant can vary between 1 and 5 (Yen, 1992).

$$k_s = d * D_{90} \qquad 1 \leq d \leq 5 \tag{A4.1}$$

This means that there is a positive correlation between the Nikuradse bed roughness and the 90% grain diameter. The correlation is not a causation, because the constant d can also change which will change the Nikuradse coefficient without changing the D_{90}.

A4.2. Relation between 90% grain diameter and number of sediment classes

The 90% grain diameter and number of sediment classes have no correlation, because the change in the number of sediment classes will not change the value of the grain diameters. Furthermore, the amount of 90% grain diameters stays the same with every number of sediment classes.

A5. Relation between the sediment density and other input parameters

In the previous section the relations between the sediment density and other input parameters have been defined except for the relation with the number of sediment classes and Nikuradse parameter. The relation between the sediment density and the Nikuradse parameter is found by combining their relations with the median diameter from equation A1.12 and A1.15. The number of sediment classes do not have a relation with the sediment density, because it only changes the number classes for sediment. It does not change the value of these classes which then can change the sediment density.

A6. Relation between the Nikuradse parameter and other input parameters

In the previous sections the relations between the Nikuradse parameter and other input parameters have been defined, except for the relation with the number of sediment classes. The number of sediment classes do not have a relation with the Nikuradse parameter, because it only changes the number classes for sediment. It does not change the value of these classes which then can change the Nikuradse parameter.