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Upper Stage Plane Bed in the Netherlands

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Preface

This report is the result of my master thesis for the study Water Engineering and Management at the University of Twente. It will mark the end of a personal era, my life as a student. It will also mark the start of a new one, the working life of a civilian.

The last six and a half years I spent at the University of Twente and I can look back to a wonderful period over there. I made lots of friends and met wonderful people. I would like to thank them all for making this period in my life as awesome as it was. Luckily these friendships don’t end and we will continue to have lots of fun with all of us.

The report in front of you could not have been there without the help of lots of people. First of all I would like to thank Kees Vermeer for offering me the opportunity to do the research for my master thesis at HKV consultants. Every time I was a little stuck I could walk by your office and you had some ideas to continue with and along with those ideas you always told a story of how you encountered a similar problem yourself. I just want to say once more that I really enjoyed those stories and appreciated your help. I also would like to thank Jord Warmink and Suzanne Hulscher for their supervision and critical feedback that greatly helped to improve this report.

To make sure I don’t forget anyone to thank I want to thank you, the reader right now!

I hope you enjoy reading my thesis!

Roy Daggenvoorde

Lelystad, December 2016

Summary

The Netherlands is vulnerable to flooding, both from the rivers and the sea. To counter these threats the Dutch protect themselves with dikes and other flood protection measures. These protective measures are designed to withstand a design water level. To be able to predict the design water levels the processes determining the water levels need to be understood. Amongst others bed roughness is an important factor determining the water depth. So it is important to know the form of the river bed.

Upper Stage Plane Bed (USPB) is a river bed form. When USPB is present at the bottom of a river, the river bed is less rough compared to dunes and ripples. The presence of USPB in a river in the Netherlands during design discharge is expected to reduce the design water levels up to 0.5 meter. Whether USPB in the Netherlands develops under design conditions is still unknown and is the focus of this study.

The study comprehends two mayor parts. The first part focusses on finding the location with the most USPB favourable conditions and the second part uses a dune evolution model in order to predict dune evolution under design discharge.

The USPB-index has been formulated to find the most probable location for USPB in the Netherlands. This index is based upon the Froude and Suspension numbers along with a threshold which is based upon observations of dunes and plane beds. The index allows comparing different locations to each other on their probability to develop USPB. The lower the USPB-index the more likely the location is to develop USPB and when the index drops below zero, USPB is expected to develop. This index indicated the IJssel near Kampen as the most probable location for USPB to develop in the Netherlands, with the river Lek near Tienhoven-Lopik as the second location.

The second part of this study applied the model of Van Duin (2015) on the IJssel near Kampen and the Lek near Tienhoven-Lopik. By performing three calibrations the model could be applied on river scale. The morphological module of the model has been calibrated upon equilibrium dune heights in flume experiments (Coleman et al., 2005; Naqshband et al., 2014c), the calibration led to a Nash-Sutcliffe-coefficient (NS-value) of 0.69. Secondly the hydrodynamic module was calibrated on a river scale, aiming to reproduce the observed dune heights in the Waal in 2002-2003 (Sieben, 2004), resulting in an NS-value of 0.3. The morphological module did not need to be calibrated again since it is standardized for different water depths (applicable on flume and river scale). The third calibration aimed to correctly reproduce the moment when the bed form in a simulation changes from dunes to a plane bed. This has been done by changing the step-length-model such that the conditions when USPB is present have an UPSB-index below zero. This step-length-model is within the morphological module of the model and could be changed without influencing the resulting dune heights.

The fully calibrated model showed that the IJssel near Kampen did develop USPB. In the river Lek near Tienhoven-Lopik dunes remained present during the design discharge wave. So, within the Netherlands, USPB is only expected to occur in the river IJssel near Kampen. Due to the lack of data on the transition to USPB in both flumes and rivers this transition to USPB is calibrated upon observations of dunes and plane beds, instead of the transition itself. To cover this and other uncertainties further research is needed. The transition to USPB needs to be validated by field observations or flume experiments and the calibrated model needs to be validated for other rivers than the Waal. These follow-up-studies can lead to enough knowledge to be able to use the beneficial water level reducing effect of this plane bed when designing flood protection measures.

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Nomenclature

Symbol	Physical quantity	Unit
A_v	Eddy viscosity	m^2/s
B	River width	m
C	Chézy-coefficient	$m^{1/2}/s$
D_{50}	Median grain size	mm
F_0	Model constant determining pick-up-rate	-
Fr	Froude number	-
f_i	Predicted values	-
f_s	Probability of a particle settling at distance x-s	-
g	Gravitational acceleration	m/s^2
h	water depth	m
h_{ref}	Reference water depth	m
i	Bed slope	-
NS	Nash-Sutcliffe-Coefficient	-
p_d	Sediment deposition rate	s^{-1}
p_s	Sediment pick up rate	s^{-1}
q	Unit discharge	m^2/s
q_b	Sediment transport	m^2/s
s	Distance from the pick-up point ‘x’	-
S	Resistance parameter	m/s
u	Flow velocity in the horizontal direction	m/s
u_*	Shear velocity	m/s
u_*/w_s	Suspension number	-
v	Kinematic viscosity	m^2/s
w	Flow velocity in the vertical direction	m/s
w_s	Fall velocity	m/s
x & z	Horizontal & Vertical model directions	m
$\bar{y}$	Average value of the observations	-
y_i	Observed values	-
z_b	Bed level	m
α	Dimensionless step length	-
α_{min} & α_{max}	Dimensionless step lengths corresponding to θ'_{min} & θ'_{mas}	-
β_1 & β_2	Turbulence model calibration constants	-
Δ	Relative density	-
ϵ_p	Porosity	-
ζ	Free surface elevation	m
θ	Shields parameter	-
θ'	Dimensionless grain shear strength	-
θ'_{min} & θ'_{mas}	Dimensionless grain shear strength determining α_{min} & α_{max}	-
θ_{cr}	Critical Shields parameter	-
κ	von Karman-constant	-
Λ	Mean step length of a particle	m
ρ	Density of water	kg/m^3
τ_b	bed shear stress	N/m^2

Table 1 List of Symbols

1 Introduction

1.1 Context

The Netherlands is famous for its battle against water throughout history. It is vulnerable to flooding by sea and rivers, since a large part of the country is located below sea level or along mayor rivers (Figure 1). This battle against water has been going on for centuries (van der Brugge et al., 2006). The last decades a technocratic-scientific approach has been dominant (van der Brugge et al., 2006; van der Ham, 1999). Predicting river discharges and corresponding water levels is an important topic within this field of work. Dikes, levees and other protective structures are built to protect the Netherlands against flooding (van der Brugge et al., 2006). The dimensions and levels of these structures rely upon the predictions based upon design water levels, which result from a normative discharge, set by the government.

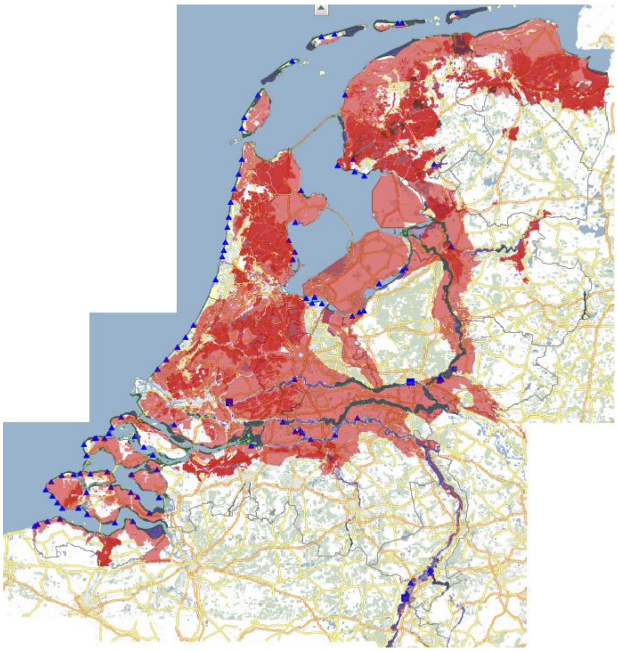

Figure 1 Flood risk chart of the Netherlands, in red the area vulnerable to flooding (Interprovinciaal-Overleg, 2014)

Along with the protection against flooding the Netherlands also uses its waterways for navigation. The port of Rotterdam and the Dutch waterways are an important connection for the German Ruhr Region. This means that maintaining minimum water levels for navigation is important as well, along with the protection against flooding.

A lot of research has been done in order to predict and manage the water levels within the rivers. Relations between discharges and water levels are known for rivers in the Netherlands. These relations are updated when new measurements are available for calibration. However, not all processes are included within the predictive methods, because they are not entirely understood. One of those principles, and the main focus of this research, is Upper Stage Plane Bed (USPB). USPB is a river bed form wherein the entire bottom of the river has become flat (Figure 2, (Knighton, 1998)). This flattening of the bottom causes the form roughness to reduce and hence the resistance is lower, which allows water to flow faster. Faster flowing water results in lower water levels when discharge and river width remain constant. If USPB would occur within the Netherlands under design discharge conditions, it could mean that the corresponding design water level will be lower at that location while causing problems at other locations. This means that dikes and levees can be constructed at a lower level at some locations, while reinforcement could be necessary somewhere else.

A report of Rijkswaterstaat (Adriaanse, 1986) describes discharge and water level measurements which suggest the presence of a plane river bed in the Bergsche Maas near Heusden. While this indication of USPB in Dutch rivers was already observed 30 years ago, there is still no evidence whether USPB occurred or not. In other countries USPB has been observed in mayor rivers. In the Missouri River (USA) USPB was observed between March and November 1967 (Delft-Hydraulics, 1986).

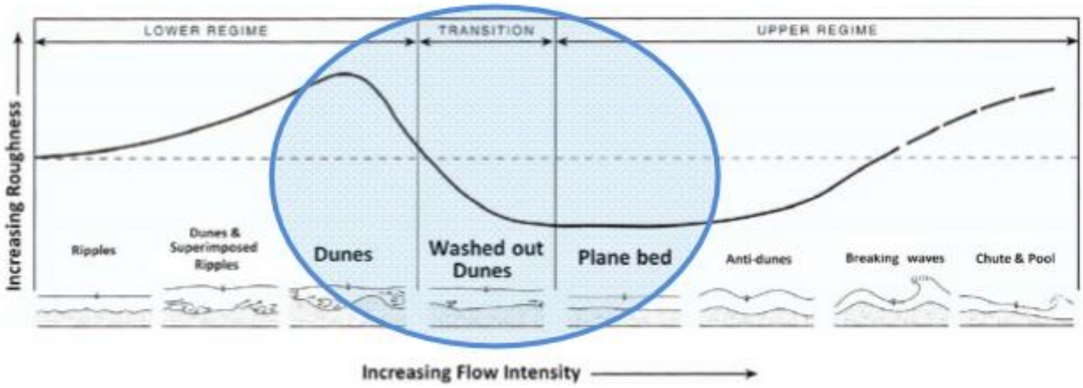

Figure 2 River bed forms and corresponding roughness under increasing flow velocity (Knighton, 1998)

1.2 Previous research on USPB

Various studies have investigated river bed forms and USPB. This prior research on river bed forms led to several stability diagrams, which mostly use the Shields parameter and the sediment transport capability of the flow as bed-form-predictors. These stability diagrams also showed the possibility of USPB, which was always found in the region with higher sediment transport capability and a low critical Shields parameter (Simons & Richardson, 1966; Southard & Boguchwal, 1990; Van den Berg & Van Gelder, 1993; Van Rijn, 1984c). This higher transport capability is related to higher flow intensity. The leading expectation is that the occurrence of USPB is caused by higher flow intensities and the corresponding increase in suspended sediment concentration (Best, 2005; Fredsøe, 1981). This increase in suspended sediment concentration can be caused by either higher flow velocities or finer sediment. The influence of finer sediment corresponds with the previously mentioned stability diagrams, since finer sediment means lower required value for the Shields parameter.

Naqshband et al. (2014c) studied the influence of suspended sediment on bed forms, especially on the development of dunes towards USPB. They claim that the occurrence of USPB can be predicted by two parameters; the Froude-number and the Suspension number. The prior is a parameter describing the relation between flow velocity and water depth (equation 1), the latter is a parameter presenting the ratio between bed shear velocity (u_*) and the particle fall velocity (w_s), also see equation 2.

$$Fr = u/\sqrt{gh} \tag{1}$$

$$suspension\ number = u_*/w_s \tag{2}$$

When the combination of these two values is situated above the threshold (dashed line in Figure 3) USPB is observed. The values in Figure 3 are based upon flume experiments and field observations collected by Naqshband et al. (2014b). Using these two predictors and the empirically determined Figure 3, Naqshband (2014a) analysed the river Rhine in the Netherlands. Naqshband (2014a) used two extreme cases in the Rhine to check whether transition to USPB would occur: (1) the maximum discharge during the 1995 flood wave (12,000 m^3/s) and (2) the design discharge (16,000 m^3/s). The values he found for the Froude and Suspension numbers, calculated for two different median grain sizes ($3.34*10^{-3}$ m and $0.73*10^{-3}$ m), suggest that USPB is not expected to occur in the Rhine river. This short analysis does not exclude the possibility of USPB in the Netherlands, since only average values are used.

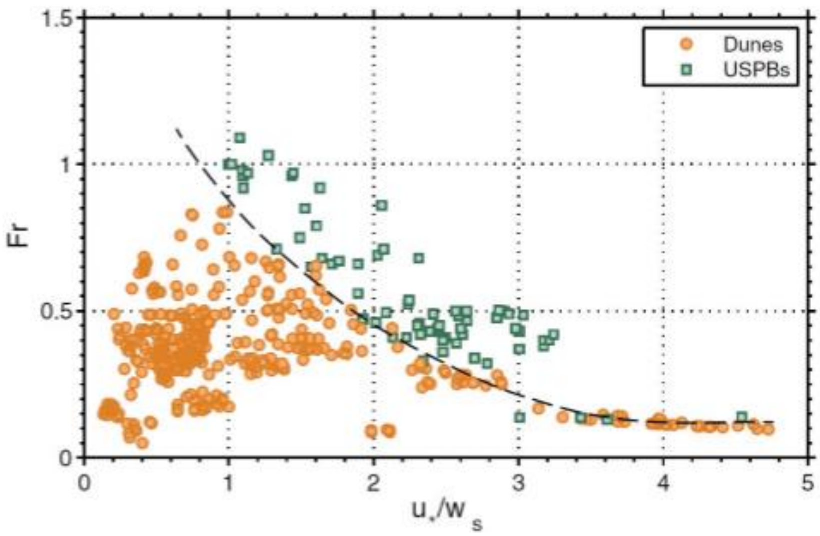

Figure 3 USPB-prediction graph based upon Suspension and Froude numbers (Naqshband et al., 2014b)

Stability diagrams are not the only method used to predict bed forms in rivers. Modelling the processes influencing bed form evolution is another approach to predict the bed form. Shimizu et al. (2009) used a numerical model to analyse different discharge scenarios for flume conditions. They used increasing and falling discharge in their scenarios and found that the stage-discharge relation is significantly dependent on the pattern of the discharge in the time. By using these different scenarios with differently shaped hydrographs they found that the transition to USPB occurs with almost the same Froude-number in all scenarios. Scenarios with different duration but the same shaped hydrograph show different results, this implicates that flood wave duration is a significant factor in determining the bed form evolution. These dependencies on the shape and duration of a discharge wave mean that bed form evolution, and the transition to USPB, is dependent on the flood wave flowing through the river. This leads again to the suggestion that the analysis done by Naqshband (2014a) using only a constant value for the discharge might not cover all possibilities for the development of USPB, since the effects of rising or falling discharge are not included.

Giri et al. (2014) applied a version of the model used in the research of Shimizu et al. (2009) to real world rivers. Giri et al. (2014) applied the model to replicate the bed form evolution in the Chiyoda experimental channel in the Tokachi river (Japan) and field observations in the Waal river (The Netherlands). The results of this application were rather satisfactory given the complexity of the problem, according to Giri et al. (2014). However, the flow velocities and water levels simulated did not correspond with the observed values, so in its current version this model is not applicable on a river scale.

Van Duin (2015) also developed a model for dune evolution which is capable of modelling USPB. This model is an extension of the dune evolution model described in Paarlberg et al. (2009). Van Duin (2015) adapted this model by introducing the stochastic sediment transport model of Nakagawa and Tsujimoto (1980). Van Duin (2015) applied his model on a river scale to simulate the high water in the river Waal in 1998. This model simulated water depths which correspond well to the observations. However it did not show the development of USPB under normal circumstances. When the discharge in this scenario was increased by 5% USPB did develop in the simulation. So this model is capable of predicting USPB in a river scale simulation. The model of Van Duin (2015) is less demanding in terms of computational time than the model of Shimizu et al. (2009), due to the turbulence closures used in both models. This, along with the access to the actual model code and the better simulation of water depths, gives the model of Van Duin (2015) an advantage over the model of Shimizu et al. (2009).

1.3 Research gap

The suggestion of USPB in the Netherlands has already been given in 1986. However, it is still unknown whether USPB might occur in the Netherlands. There has been an exploratory test by Naqshband (2014a), which showed no occurrence of USPB. This exploratory study did only cover one single river within the Netherlands and did not include differences within the river. The influence of a different discharge wave was also not included in the analysis, even while it was shown by Shimizu et al. (2009) to have significant influence on the stage-discharge relation. Van Duin (2015) did an analysis with his model using the discharge wave of the high water period in 1998 in the river Waal. This analysis also indicated that USPB did not occur, however a slightly increased discharge did develop USPB, suggesting that USPB can develop under conditions which do not exceed the design conditions. However the model of Van Duin (2015) still has its downsides; the morphological part of the model has only been calibrated upon the dune heights from simulations made by Shimizu et al. (2009) and the river scale application has only been validated with one single comparison of water depths. Along with these two concerns the transition to USPB also lacks validation, no specific validation has been done for this transition.

The differences between the various rivers in the Netherlands cause differences in flow velocities, water depth and grain sizes along the rivers. The spatial variance means that the exploratory analysis (Naqshband, 2014a) does not cover all possibilities for the occurrence of USPB in the Dutch river system. Along with this spatial variance, the temporal variance in the discharge means that the analysis by Naqshband (2014a) does not cover all possibilities for USPB. To include the temporal variance in the discharge on a river scale a dynamic model like the models of Van Duin (2015) or Shimizu et al. (2009) should be used. However, these models need further validation for dune height and USPB-prediction on a river scale.

To fill these gaps in knowledge on USPB concerning small scale variety and unsteady discharge, this study will focus on the question whether USPB can develop within the Netherlands.

1.4 Research objective & questions

To improve the knowledge around USPB and to give a direction to this study the following research goal has been formulated.

Determine which conditions are necessary for upper stage plane bed to occur within the Netherlands and determine at which locations USPB is most likely to occur.

Achieving this goal will lead to a location or multiple locations within the Dutch river network where it is likely for USPB to occur. Or it leads to the conclusion that USPB is not likely to occur within the Dutch river network.

To be able to achieve the objective, it is broken down into four separate research questions; for each of these questions a short description on methodology and goals is given:

1. *Which locations in which river branches in the Netherlands are most likely to develop USPB?*

In order to analyse in which river branch USPB is most likely to develop within the Netherlands, it is important to know what the conditions of those branches are under design discharge, because it is expected that USPB is most likely to occur when higher flow intensities are present (Figure 2). Using the design conditions along with sediment data Froude and Suspension numbers can be determined. These parameters can be used to apply the criterion of Naqshband et al. (2014b)

(Figure 3). The criterion uses a threshold above which USPB will take place; this threshold is defined by the Froude and Suspension numbers. The distance to this line is a quantification of the USPB-likeliness. The analysis will be performed with a constant design discharge of 16,000 m^3/s at Lobith for the Rhine and 3,800 m^3/s at Eijsden for the Meuse. To assess the impact of another discharge the river Waal will be analysed with a constant discharge of 18,000 m^3/s as well.

2. *Under which conditions is USPB most likely to occur and can this be modelled using a dune evolution model?*

A dune evolution model will be used in order to check the influence of the various parameters on dune height evolution. This information shall be used to calibrate the model on dune heights. This is going to be done on flume scale, since it is easier to calibrate and validate on this scale, because more observed data are available and simulation times will be shorter. With the calibrated and validated model an analysis of the influence of the natural variables on USPB is made. During this research question the morphological module of the model will be calibrated with the use of observed equilibrium dune heights, so the transition to USPB has not yet been calibrated.

3. *Can the dune evolution model be used to simulate USPB in a river section?*

Since the dune evolution model is calibrated on dune heights in flume-conditions during the second research question, it has to be upgraded to the river scale in order to be applicable for river analysis. Van Duin (2015) showed promising river scale simulations. But in order to get usable, valid results the model should be calibrated and validated on the river scale first. This will be done using the dune-height data of Sieben (2004). This river scale calibration will be performed by adjusting the hydrodynamic module of the model, especially the turbulence description. This is done because the morphological module is already calibrated and validated during the previous research question and due the standardization of the water depth in this module it is applicable on different scales.

4. *Which locations within the Netherlands are capable of developing USPB?*

The validated river scale model (RQ3), with the USPB-likely-conditions (RQ2) is applied on the USPB-most-probable-location (RQ1). This might lead to development of USPB in a river section during a simulation. If so, the model will be applied on the next most-probable location, possibly leading to more locations and situations where USPB can occur. If not, USPB will most likely not occur within the Netherlands during design conditions, since the most probable location under the most probable conditions does not develop USPB. In the case where USPB does not develop extra simulations are made with more extreme conditions in order to check what conditions are required for USPB to develop.

1.5 Thesis outline

Chapter 2 describes the first research question. A WAQUA-simulation and sediment-characteristics are used to determine the Froude and Suspension numbers within the Dutch river system. With these numbers the USPB-index is formulated, which allows to compare different locations and conditions on USPB-likeliness.

Chapter 3 concerns the dynamic modelling of river dune evolution. The chapter starts with the model choice and a description of the chosen model. Also the data used for the calibration are described. The calibration will be done by altering the morphological module of the model resulting in a model which predicts dune heights and is capable of developing USPB. The calibrated model will be used to perform a sensitivity analysis in order to answer the second research question.

Chapter 4 is about the application of the calibrated model on a river scale. The first step is to calibrate the model on dune heights observed in the river Waal (Sieben, 2004). This second calibration will be performed by altering the hydrodynamic module of the model. This way, the calibrated morphological module of chapter 3 does not have to be altered. This choice has been made to ensure the validity of the morphological module. After this calibration on dune height a last step will be made to validate the prediction of USPB.

Chapter 5 is the combination of the previous three chapters, by applying the calibrated and validated model with the most probable conditions on the most probable location. This will lead to an answer to the fourth research question.

Chapter 6 discusses the methods used and results obtained in the previous chapters.

Chapter 7 contains the conclusions of this study and the recommendations and directions for future research.

2 Most probable locations for USPB

2.1 Indicators for Upper Stage Plane Bed

As mentioned in section 1.2 Naqshband et al. (2014b) found that the presence of USPB can be predicted based upon two indicators: the Froude and Suspension number. The Froude number has already been presented in equation 1, the Suspension number is shown in equation 2, but requires additional explanation.

The Suspension number is determined by the shear velocity (equation 3) and the fall velocity (equation 4 (Van Rijn, 1993)). The shear velocity requires the density, gravitational acceleration, flow velocity and Chézy-coefficient in order to be calculated.

$$u_* = \sqrt{\frac{\tau_b}{\rho}}\ with\ \tau_b = \rho * g * \frac{u^2}{C^2} \tag{3}$$

While the fall velocity requires the specific gravity, gravitational acceleration, median grain size and kinematic viscosity.

$$\begin{aligned}
w_s &= \frac{\Delta g D_{50}^2}{18v} && 1 < D_{50} \leq 100\ \mu m \\
w_s &= \frac{10v}{D_{50}}\left(\left(1 + \frac{0.01\Delta g D_{50}^3}{v^2}\right)^{0.5} - 1\right) && 100\mu m < D_{50} < 1000\mu m \\
w_s &= 1.1(\Delta g D_{50})^{0.5} && D_{50} \geq 1000\mu m
\end{aligned} \tag{4}$$

The constant parameters in these two formulas can be found in Table 2. The flow velocity, water depth, Chézy-coefficient and grain size are the required variables to calculate the Froude and Suspension numbers, which vary spatially. The acquisition of these data will be discussed in the next paragraph.

Constant	Value
$\boldsymbol{\rho}$	1000
$\boldsymbol{g}$	9.81
Δ	1.65
$\boldsymbol{v}$	10^{-6}

Table 2 Constants required for Froude & Suspension numbers

2.1.1 Data acquisition

The flow characteristics (flow velocity, water depth & Chézy-coefficient) will be obtained from the WAQUA-model. The WAQUA-model is a 2D-model of the Dutch river system (Helpdeskwater, 2016). It uses the bathymetry of the river system along with a set discharge wave to calculate flow velocities, water depths and other flow characteristics along the Dutch river system (Becker, 2012). The flow characteristics calculated by WAQUA are depth-averaged and calibrated upon historical data by changing the Chézy-coefficient (van Velzen, 2003a, 2003b). The calibration upon Chézy means that the Chézy-coefficient contains uncertainty. This uncertainty is caused by processes which are not included in the model. However, the deviation of the Chézy-coefficient from reality is not expected to be very large, since the simulated values are within the expected range.

Two WAQUA-simulation are used to analyse the Dutch river network; one for the Rhine and one for the Meuse. Both use a constant discharge at the entry points of the Dutch river system: 16,000 m^3/s at Lobith for the Rhine and 3,800 m^3/s at Eijsden for the Meuse. To analyse the impact of a different discharge through a river system the river Waal will be assessed with a norm of 18,000 m^3 as well. The discharge of 18,000 is chosen, because it is expected to be the maximum discharge for the Rhine by 2100 (Deltacommissaris, 2016). More extreme conditions might lead to more locations that indicate USPB. Only the river Waal is assessed with this discharge, because no WAQUA-simulations with this constant discharge are available for the other Rhine-branches.

The grain size data used are collected by Rijkswaterstaat (RWS, the Dutch authority responsible for (wet) infrastructure) in the past decades. The most recent complete analysis of the top layer of the main Dutch rivers is done in 1995. This dataset consists out of measurements with an interval of one kilometre. Measurements for the river Rhine have been taken at the three mayor branches: The Bovenrijn-Waal-branch, The Nederrijn-Lek-Branch and the IJssel. Measurements have been made at each kilometre, in the middle of river and both sides.

The measurements for the Meuse are also performed for every kilometre. However, only the resulting maps of these measurements are available. These maps show the grain size with an interval of one kilometre. Another remark is the measurements of the grain sizes on the bed of the Meuse are only performed till river kilometre 228; which is located just in front of the village “Heusden”. The last part of the Meuse has to be estimated. The grain size for this part is set to 0.45 mm which is an extrapolation of the grain size in the last few measurements in front of Heusden. This assumption is deemed allowable since the Meuse is known to show downstream fining (Murillo-Muñoz & Klaassen, 2006), which means that the grain size becomes smaller the further downstream it is measured. So continuing with a constant value is quite conservative when looking into the development of USPB, because it is expected that the downstream grain size will be smaller. Smaller grain sizes will correspond to a higher Suspension number increasing the probability for USPB.

2.1.2 Data processing

The data are formatted in a way that the flow velocity, water depth, Chézy-coefficient and grain size data have the same spatial grid. This way, it is possible to analyse the Froude numbers and Suspension numbers along the different river branches. These formatted data are obtained by interpolating along river-lines which represent the middle of the river. The interpolation allows to obtain Froude and Suspension numbers with an interval of 20 meters. This brings a small error within the data, since not every small twist or bend within the river course is included and it assumes a distance of exactly one kilometre between all river kilometre points, which is quite often not the case. Using the interpolated river points, the flow characteristics are obtained from the WAQUA-results (40x20 meter grid).

The grain size data is also interpolated; this is done linearly using the known grain sizes at the various kilometre points. These interpolation methods result in spatially corresponding datasets of the four previously mentioned spatially varying variables. So for all locations the Froude and Suspension numbers can be determined.

The most probable location for USPB is the location where the highest Froude and Suspension numbers occur. However, these two variables will likely not reach their maximum value at the same location. Figure 3 is used to compare different locations. The dashed line represents a threshold which has to be exceeded for USPB to occur. The distance to this line of each plotted location will be used to compare the various locations. Locations far above the threshold will have the most-USPB-favourable combination of Froude and Suspension numbers. The locations underneath the line will less likely to develop USPB. Locations above the line are indicated as negative values, this way the locations can be sorted from most likely to least likely. This quantified likeliness will be referred to as the USPB-index from now on. This USPB-index does allow to see whether USPB occurs (<0) and which of two locations is more likely (lowest value).

2.2 USPB-index along the Dutch river system

2.2.1 Current design conditions

The current design conditions are a discharge of 16,000 m^3/s at Lobith and 3,800 m^3/s at Eijsden for the Rhine and Meuse respectively. The two WAQUA-simulations in combination with the grain size data result in Figure 4. The blue dots in Figure 4 show all locations analysed along the Dutch river system. Figure 4 shows that the river IJssel contains the most likely location (USPB-index = 0.04). The number in the graph represents the river kilometre (RKM, indicating the location along the river) at which the most likely location is found. RKM 993.92 and the other likely locations correspond with a stretch of river just upstream of the town of Kampen (RKM 993-994). In the other rivers USPB is less likely to occur compared to the IJssel. The second most likely location is located in the river Lek near the towns of Tienhoven and Lopik (USPB-index =0.31). For the river Meuse and Bovenrijn-Waal the most likely locations are near Heusden (0.55) and near Lobith (0.41). The location near Heusden is interesting, because lower water levels than the expected levels given the observed discharge were observed here (Adriaanse, 1986), but the USPB-index does not show that this location is likely to develop USPB.

All of these locations have several things in common. The grain size at those locations is small when compared to the rest of the river branch. These smaller grain sizes result in higher Suspension numbers. The Froude numbers at these locations do not show peaks and are all in the range of 0.2–0.25. More detailed information about these and other variables along the rivers can be found inAppendix A: Variables along the river.

An important note to make is that the WAQUA does not simulate a plane bed. If a plane bed would occur in these extreme conditions, it will influence the results in Figure 4. This is because a plane bed allows the water to flow faster and reduce the water depth. The increased velocity and decreased water depth will increase the Froude number and the higher flow velocity will increase the Suspension number as well. The threshold obtained from Naqshband et al. (2014b) is based upon observed conditions; which means that these effects of a flat bed are included in the threshold. So the threshold could be set too high when using input data obtained without a plane bed.

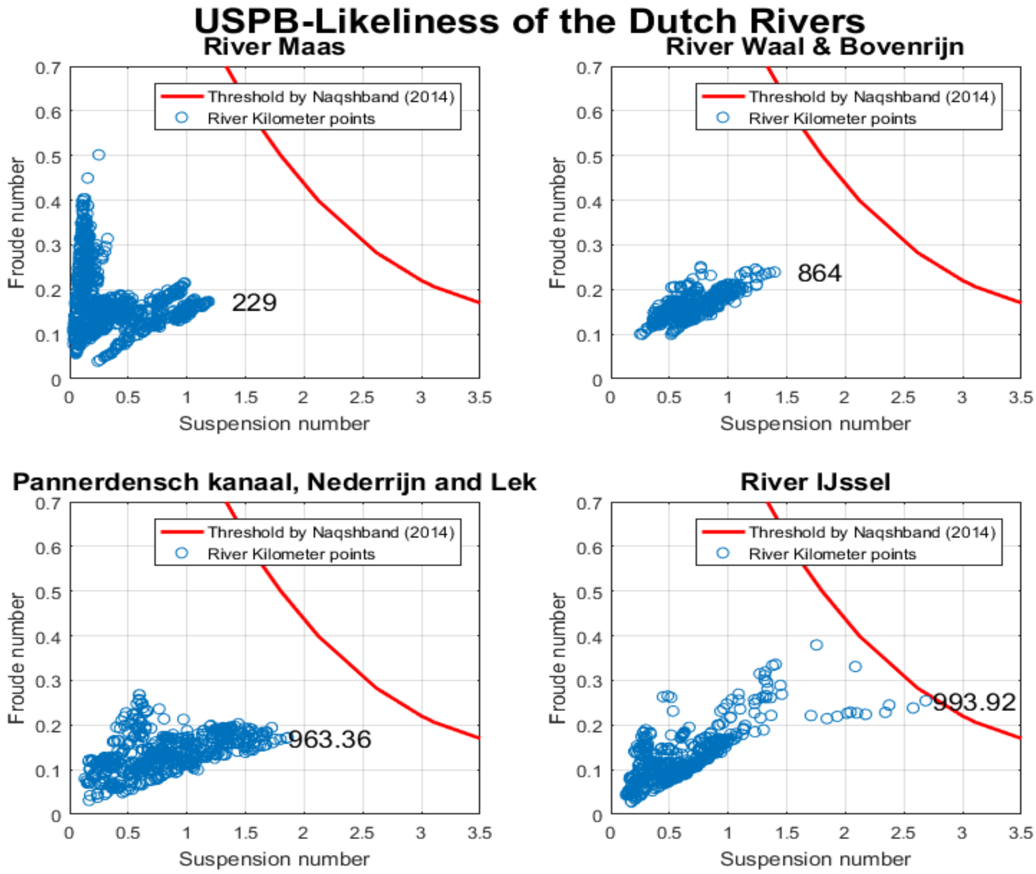

Figure 4 USPB-likeliness of the Dutch rivers

The four mentioned locations from Figure 4 are plotted in Figure 6 to be able to analyse their spatial distribution and to introduce the USPB-index. The figure shows that three of the four locations are located quite far downstream. This observation raises the question whether tidal or base water level effects do influence the conditions at these locations. Figure 5 shows that RKM 994 is just inside the discharge-dominant region, the region where the flow is dominated by the river discharge. The transition region for the Rhine-Meuse delta in the west of the Netherlands is much larger, but the most-probable locations are all in the discharge dominated region.

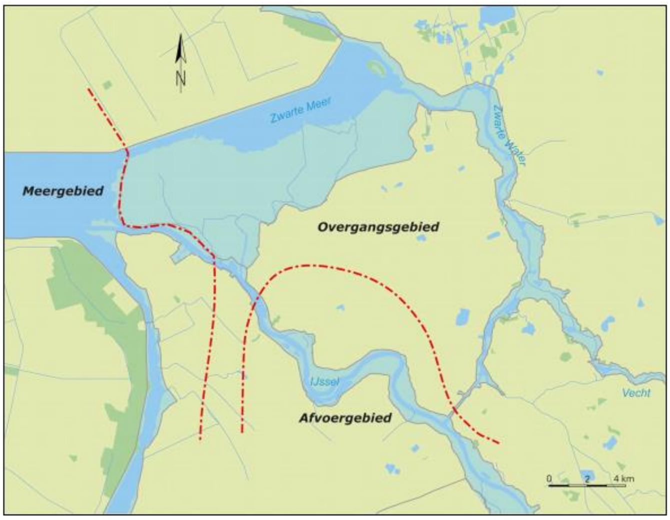

Figure 5 The Lake-dominated, Discharge-dominated and the transition region (Meergebied, Overgangsgebied and Afvoergeboied respectively) in the IJsseldelta (Kroekenstoel, 2014)

A last important note is the exclusion of the Keteldiep, this last stretch before the river IJssel ends in the Lake IJssel. A few kilometres after Kampen the river IJssel bifurcates in the Keteldiep and Kattendiep. At this bifurcation a sill is present in front of the Keteldiep in order to prevent bed load transport into the channel. This sill is implemented to reduce sedimentation to maintain navigability. This sill causes only suspended sediment to enter the channel resulting in a small grain size in this bifurcation. Since this situation does not represent the configuration in the rest of Dutch river system it is chosen to exclude the Keteldiep from any further analysis.

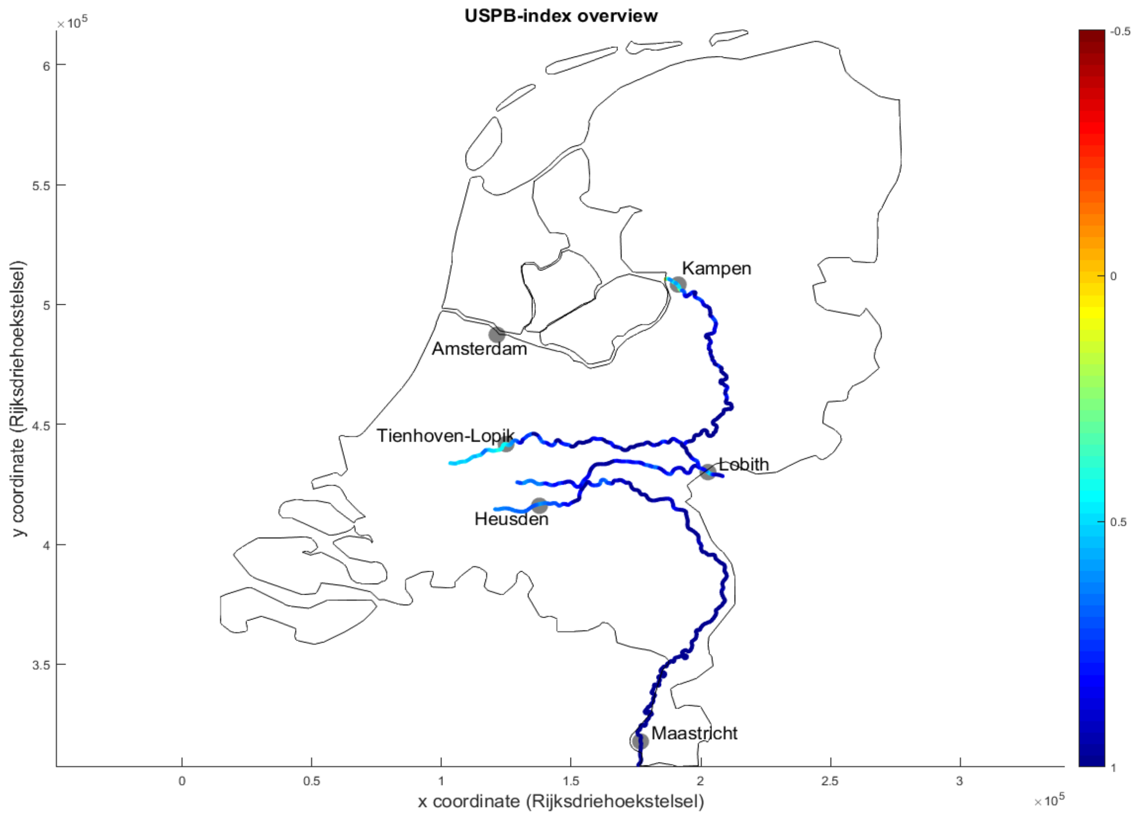

Figure 6 USPB-index map

2.2.2 Increased design conditions

The analysis with the WAQUA-simulation of with discharge of 18,000 m^3/s led to Figure 7. When compared to the top right of Figure 4 not a large difference can be seen, the RKM-points show a similar pattern. The same location (Lobith, RKM 864) is the most probable location in this river branch. The USPB-index has slightly decreased, 0.37 instead of 0.41 before. This is caused by an increase in both Froude and Suspension numbers (Froude +0.01 and Suspension +0.06). This is caused by an increase in flow velocities. This decrease in the USPB-index leads to the expectation that an analysis with a discharge of 18,000 m^3/s the Ijssel near Kampen will get a negative USPB index indicating that USPB will develop.

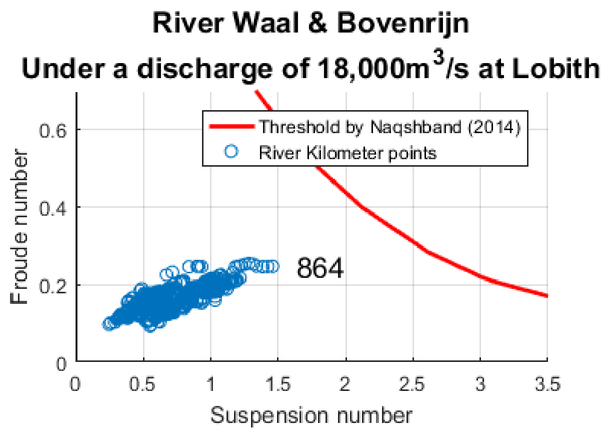

Figure 7 USPB-likeliness in the Waal with a discharge of 18000 m^3/s at Lobith

2.3 Synthesis on the most probable locations for USPB

Under design discharge it is not expected that USPB will develop. Still a most probable location can be distinguished. The IJssel upstream of Kampen (RKM 993-994) did show the lowest USPB-index (0.03), followed by the river Lek near Tienhoven and Lopik (0.31). It was shown that an increase in discharge results in a decrease in the USPB-index. It is expected that a discharge of 18,000 m^3/s by Lobith results in a negative USPB-index near Kampen. However, this analysis with the USPB-index does not give a concluding answer to the occurrence of USPB in the Netherlands due to various reasons for uncertainty.

The grain size data are quite old and it could not be a representation of the current situation anymore. The water depth, flow velocity and Chézy-coefficient are all obtained from the WAQUA-model. This model is calibrated upon historical data which do not contain the discharge scenario used in this analysis, meaning that the flow conditions are outside the range used for the calibration.

The last source of uncertainty is the fact that the WAQUA-model uses the Chézy-coefficient for calibration. The Chézy-coefficient normally represents the smoothness of the bed, while calibrating upon this parameter means that the expected depth-discharge-relation, instead of the present bed form, determines the smoothness. This means that the presence of a plane bed within this discharge-scenario would not be influencing the simulated roughness. In reality the presence of this plane bed would influence the flow velocity and water depth in such a way that the USPB-index would decrease. So it might be possible that this scenario does develop USPB, but the WAQUA-model does not represent this, resulting in an USPB-index above zero.

This last uncertainty asks for another approach to get an answer to the question whether USPB occurs. In the next chapter the bed form will be predicted and it will influence the depth-discharge-relation with its corresponding roughness, instead of determining the bed roughness assuming a certain depth-discharge-relation.

3 Modelling dune development of flume experiments – Driving factors for USPB

3.1 Dune evolution model choice

Modelling river dune evolution and the transition to USPB requires a model that includes several phenomena. First of all, sediment transport should be included in the model, because dune evolution is dependent on sediment transport. Both suspended and bed load transport are important in this process (Jerolmack & Mohrig, 2005; Kostaschuk et al., 2009; Kostaschuk & Villard, 1996; Nittrouer et al., 2008; Smith & McLean, 1977). Bed load transport tends to increase the dune height, while suspended transport tends to decrease dune height (Fredsoe, 1982; Kostaschuk, 2005; Kostaschuk & Best, 2005; Naqshband et al., 2014c). Along with the sediment transport, amalgamation and superposition might play a role (Ditchfield & Best, 1992). Amalgamation is the merger of dune migrating at different velocities (Martin & Jerolmack, 2013; Venditti et al., 2005) and superposition is the presence of small river dunes superimposed on larger dunes (Best, 2005). Along with the inclusion of these three required phenomena, three logistical criteria have been formulated for the model choice: Validation & accuracy, availability and computational time. This total of six criteria has been used to compare various dune evolution models.

Several dune evolution models are developed in the past (Lefebvre et al., 2014; Martin & Jerolmack, 2013; Nabi et al., 2013a; Nelson et al., 2005; Shimizu et al., 2009; Van Duin, 2015). These six models are analysed upon the six criteria (Appendix B: Dune evolution models & model choice). With these six criteria it was found that the model of Van Duin (2015) is the most suitable for this study.

3.1.1 Model description

The Van Duin (2015) model is based upon the model of Paarlberg et al. (2009). Which on its turn is a modified version of the process-based morphodynamic model of Németh et al. (2006), which is based upon the numerical model of Hulscher (1996). The model is a 2DV-model, which uses shallow water equations to simulate unidirectional flow. The used turbulence closure is constant eddy viscosity in combination with partial slip boundary conditions. The partial slip and constant eddy viscosity are determined by flume experiments (Paarlberg et al., 2005). The model of Paarlberg et al. (2009) uses a flow separation line (Paarlberg et al., 2007) to speed up the simulation. The version used in this study does not use this separation line (Van Duin, 2015; Van Duin et al., 2016), since the presence of this line does not represent a plane bed.

The model simulates the development of one single river dune, so the domain length is always equal to the dune length. However, the model uses periodic boundary conditions; this implies that the flow at the downstream boundary of the model is used as the input at the upstream boundary. The simulated dune can be depicted multiple times in order to represent multiple dunes.

The model is schematized by Figure 8. The model consists of three modules: the flow module, the sediment transport module and bed evolution module. Each of these three is described in the upcoming sub-paragraphs. The schematization on the right of Figure 8 shows the simulated dune on a sloped bed. In this figure the free surface elevation (ζ), water depth (h), bed elevation (z_b) and the dune height (H) are shown.

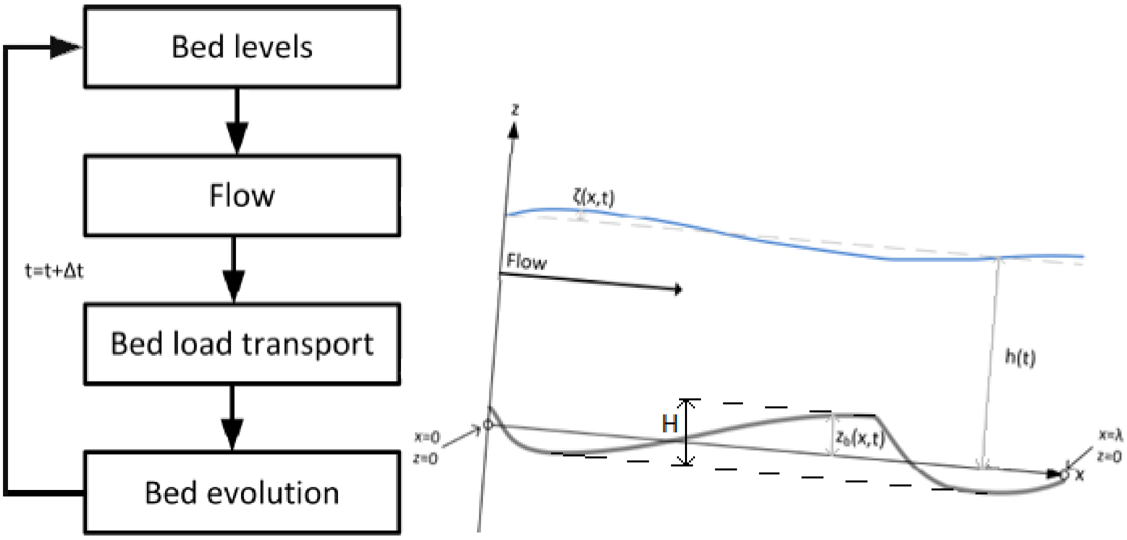

Figure 8 Schematized model (Van Duin, 2015)

Flow-module

A more extensive description of the flow module can be found in Van Duin et al. (2016). The momentum and continuity equations in the model are shown in equations 5 and 6:

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -g\frac{\partial \zeta}{\partial \mathrm{x}} + \mathrm{A_v}\frac{\partial^2 u}{\partial z^2} + gi \tag{5}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{6}$$

Where u and w are velocities in x and z the directions respectively, A_v is the eddy viscosity and i is the bed slope. To solve the flow equations 5 and 6 boundary conditions are needed. Three boundary conditions are given to be able to solve the equations. The boundary conditions can be found in equation 7.

$$u\frac{\partial \zeta}{\partial x}\bigg|_{z=h+\zeta} = w, \qquad \frac{\partial u}{\partial z}\bigg|_{z=h+\zeta} = 0\,, \qquad u\frac{\partial z_b}{\partial x}\bigg|_{z=z_b} = w \tag{7}$$

These three boundary conditions represent the following: The first boundary condition implies that there can be no flow through the surface, the second represents the absence of shear stress at the surface and the third boundary condition represents the absence of flow through the bed. Along with these boundary conditions a turbulence closure is needed. A time- and depth-independent eddy viscosity is assumed, which leads to a parabolic velocity profile (Engelund, 1970; Hulscher, 1996). In order to reproduce a realistic bed shear stress along with a constant eddy viscosity a partial slip condition at the bed is necessary. This condition can be found in equation 8.

$$\tau_b = A_v\frac{\partial u}{\partial z}\bigg|_{z=z_b} = Su_b \tag{8}$$

Where τ_b is the volumetric bed shear stress (m^2/s^2); u_b is the flow velocity at the bed and S is the resistance parameter. The resistance parameter and the constant eddy viscosity are expressed by the following equations (equation 9 and 10) (Paarlberg et al., 2009):

$$A_v = \beta_1\frac{1}{6}\kappa u_* h \tag{9}$$

$$S = \beta_2 u_* \tag{10}$$

In these equations β_1 & β_2 are calibration coefficients for the turbulence model. Paarlberg et al. (2009) calibrated their model to flume experiments and found that the calibration coefficients had to be set to 0.5 in order get valid simulations. Paarlberg and Schielen (2012) showed in their study that both β-coefficients need to be set to 0.2 in order to make realistic river scale simulations. So to scale up the model from flume, to river scale application, it is expected to have to reduce the β_x-values. This will reduce the value for A_v and S, which reduces the bed shear stress.

The average water depth is needed to solve the flow equations. However, the unit discharge is the input for the model. To find the average water depth an estimated initial water depth is used to start an iterative procedure. This iteration will be continued until a water depth is found which corresponds with the set unit discharge. More details for the numerical solution procedure can be found in Paarlberg et al. (2009) and Van den Berg et al. (2012).

Sediment transport module

The initial model of Paarlberg et al. (2009) only considers bed load transport which is determined by the formulae of Meyer-Peter and Müller (1948). In order to simulate USPB it is necessary to include suspended load as well. Van Duin (2015) did this by introducing the sediment transport model of Nakagawa and Tsujimoto (1980).

The model of Nakagawa and Tsujimoto (1980) uses a stochastic sediment-transport approach. This method uses an expression for the sediment pick up rate (equation 11) and sediment deposition rate (equation 12).

$$p_s(x) = F_0\sqrt{\frac{\Delta g}{D_{50}}}\,\theta(x)\left[1-\frac{\theta_{cr}}{\theta(x)}\right]^3 \qquad (11)$$

Where p_s is sediment pick up rate; F_0 is a model parameter (0.03); Δ is the specific gravity; θ is the Shields parameter; and θ_{cr} is the critical Shields parameter. The deposition is determined by the following formula (equation 12):

$$p_d(x) = \int_0^\infty p_x\,(x-s)f_s(s)ds \qquad (12)$$

Where $f_s(s)$ determines the probability of a picked-up particle to be deposited at a distance 's' from the pick-up point (x-s). f_s is given in equation 13.

$$f_s(s) = \frac{1}{\Lambda}\exp\left(-\frac{s}{\Lambda}\right) \qquad (13)$$

Where Λ is mean step length and s is the distance of sediment motion from the pick-up point. Since this model only gives a description for bed load transport it is not yet valid for modelling USPB. Van Duin and Hulscher (2014) incorporated the suspended load implicitly, like Shimizu et al. (2009) did. The step length is made dependent on the water depth; increasing water depth means an increasing step length. A grain which takes a long step can be seen as suspended sediment since the particle is picked up, remains in suspension for a while and settles down later. This assumption is based upon the principle that a larger water depth means there will be more turbulent vortices which, in turn, lead to sediment higher in the water column. This increased step length is the only way in which a form of suspended transport is included. This principle becomes visible in the expression of the step length of a single particle (equation 15). This non-dimensional step length is used to determine the mean step length 'Λ' (equation 14).

$$\Lambda = \frac{u_*}{w_s}\exp\left(-\alpha\frac{w_s}{u_*}\right)\frac{C}{\sqrt{g}}h \qquad (14)$$

The dimensionless step length of a single particle is given by the following formula (equation 15).

$$\alpha(\theta',h) = \begin{cases} \alpha_{min}\dfrac{h}{h_{ref}}\; for\; \theta' \leq \theta'_{min} \\ \left[\alpha_{min} + (\theta'-\theta'_{min})\dfrac{\alpha_{max}-\alpha_{min}}{\theta'_{max}-\theta'_{min}}\right]\dfrac{h}{h_{ref}}\; for\; \theta' > \theta'_{min} \end{cases} \qquad (15)$$

Van Duin (2015) calibrated this step-length-model upon a synthetic dataset obtained with the more advanced model of Shimizu et al. (2009). So the model has not been calibrated upon observed dune heights. The advantage of the calibrating on the synthetic dataset was the inclusion of USPB, since there are no data available of experiments with the transition to USPB. This calibration led to the values presented in Table 3.

Entity	Value
$\boldsymbol{\alpha_{min}}$	50
$\boldsymbol{\alpha_{max}}$	350
$\boldsymbol{\theta'_{min}}$	0.5
$\boldsymbol{\theta'_{max}}$	0.8
$\boldsymbol{h_{ref}}$	0.116

Table 3 Sediment transport model parameters

The factor h_{ref} is important for the scaling of the model to a river scale later in Chapter 4. In the current chapter the morphological module of the model will be calibrated to reproduce observed dune heights in flume experiments. When the model is applied on a river scale, the step length will increase with increasing the water depth. Dividing the water depth by a reference depth, in both flume and river scenarios, the step length is standardized. Allowing the step-length-model to be applied on various water depths without the requirement to calibrate again.

The dimensional step length of a particle can be found by multiplying the value for α by the median grain diameter (D_{50}). The introduction of the water depth in the equation for the step length by Van Duin (2015) might lead to non-dimensional step length values larger than the maximum step length value (250) found in the bed load experiments of Nakagawa and Tsujimoto (1980). This means particles take larger steps than the maximum step length of a particle in bed load transport. Particles that take a non-dimensional step larger than 250 are considered as suspended transport, this way suspended transport is implicitly included in the model.

Bed evolution module

The functions for pick-up and deposition rates along the domain can be used to create an expression for the transport gradient along the domain, equation 16 (Van Duin et al., 2016). For each cell in the domain the amount of erosion and deposition can be calculated resulting in the gradient.

$$\frac{\partial q_b}{\partial x} = D_{50}[p_s(x) - p_d(x)] \tag{16}$$

This transport gradient is used with the porosity and the Exner-equation (equation 17) to determine the bed evolution in each cell.

$$\left(1 - \epsilon_p\right)\frac{\partial z_b}{\partial t} = -\frac{\partial q_b}{\partial x} \tag{17}$$

ϵ_p represents the porosity of the bed material and is usually set to 0.4.

3.2 Model sensitivity & calibration

The model of Van Duin (2015) has only been calibrated upon a synthetic dataset made with the model of Shimizu et al. (2009). Van Duin (2015) did this in order to have a dataset that included the transition to USPB. However, the model has not been validated on observed dune heights. To validate the morphological module of the model it will be calibrated upon observed equilibrium dune heights in flume experiments (Coleman et al., 2005; Naqshband et al., 2014c).

The choice to calibrate upon simulated dune height is made, because this will validate the way the morphological module simulates bed and suspended load transport. Bed and suspended load are known to increase and decrease dune height respectively. If the morphological module is capable of reproducing the observed dune heights the relative magnitudes of the bed and suspended load are valid, since they reproduce the correct dune height. Before the calibration a short sensitivity analysis of the dune height on various model parameters and natural variables is given in order to understand the effect of changing various parameters.

3.2.1 Sensitivity of dune height

To understand the effects of the different model inputs and model parameters a sensitivity analysis has been performed. The entire sensitivity analysis can be found in Appendix C: Sensitivity of the equilibrium dune height. The most important findings in this analysis will be discussed shortly in this paragraph. The analysis has been done on model inputs, the step-length-model and the Dunelengthfactor. The model inputs are assessed to get insights in dune height evolution under different conditions. The step-length-model is looked into in order to be able to calibrate upon the morphological part of the model. The Dunelengthfactor is a factor which can be used within the model. This factor describes the dune length as a multiplication of the water depth. The main advantage of this approach is that using this factor avoids using a stability analysis to find the dune length. This approach saves on computational time. The base conditions for the sensitivity analysis are shown in Table 4. It is a simulation of two hours of constant discharge, starting with a plane bed.

Input	Magnitude
q	0.15
i	$2*10^{-3}$
Duration	2
D50 (mm)	0.28
θ_{cr} (-)	0.040
F_0 (-)	0.03
α (-)	50-350
H_{ref} (m)	0.1166
θ' (-)	0.5-0.8
Dunelengthfactor	7

Table 4 Base case sensitivity analysis

Model inputs

Figure 9 shows the developed equilibrium dune height for different discharge magnitudes, different grain sizes and varying slopes. Lower discharge results in less transport and hence lower dunes, if the discharge increases dunes do not develop, because they are washed away.

The grain sizes show a more interesting pattern. Grain sizes ranging from 0.20 mm till 0.75 mm show dune growth as expected. Normal dunes develop varying a few millimetres in height with along this domain. Grain sizes smaller than 0.2 mm show a different behaviour, grain of 0.15 mm are flushed away, while even smaller grains do develop dunes. No explanation is found for this

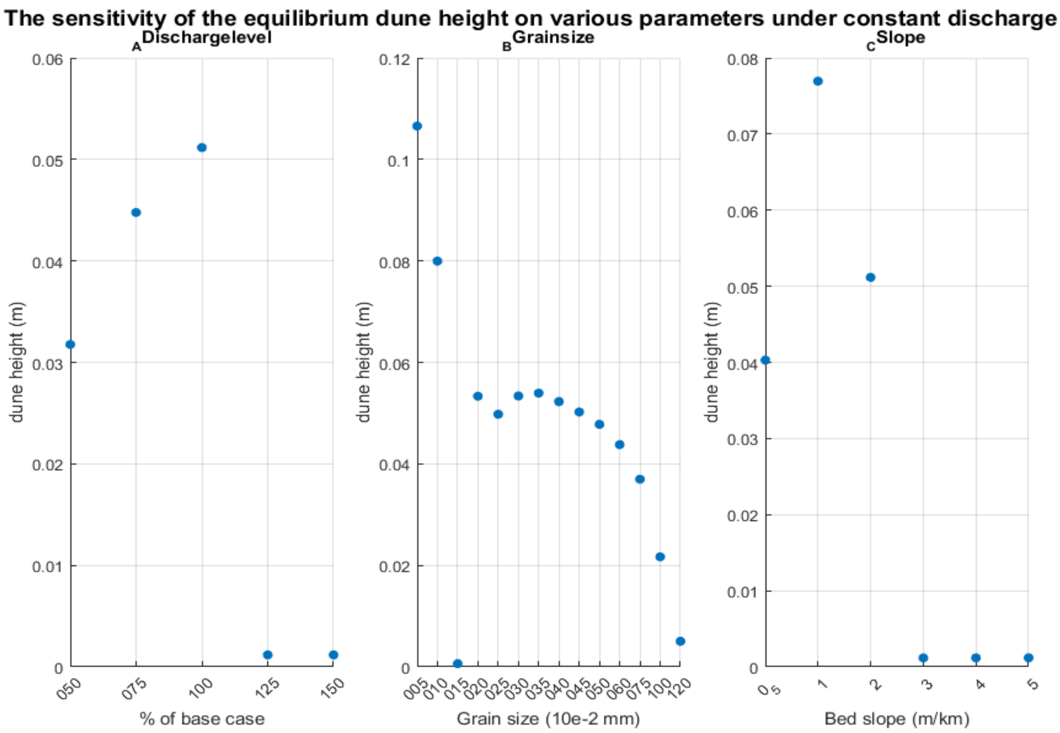

Figure 9 Sensitivity of the dune height on model inputs

behaviour, so it has to be concluded that the model is not applicable for grains smaller than 0.2 mm. Grain larger than 0.75 mm develop smaller dunes, this is caused to the reduction in transport as these grains are less likely to be transported.

The effect of increasing the bed slope is the washing away of dunes due to higher flow velocities. A small reduction in slope results in higher dune height, this is caused by the larger fraction of sediment transported as bed load instead of suspended load. Decreasing the slope even further results in a reduction in height, because the total sediment transport reduces.

The step-length-model

The step-length-model is determined by the reference height, the F_0-constant, the dimensionless step length and the dimensionless grain shear stress. The effect of reducing the reference height is that the dune height reduces, because the increasing step length causes more suspended transport. Increasing the reference height does not have large effects since the material in the base is already simulated with a short step-length, representing bed load. The effects of the F_0-constant are straight forward. Increasing the value will result in more transport and higher dunes while reducing does give the opposite result.

Figure 10 explains the step-length-model-principle. The minimum and maximum points are defined by θ' and α. The main principle of the step-length-model is that when the step length is large, particle transport can be seen as suspended transport. The θ'-value is determined by the flow and sediment characteristics and is translated to the step length using the graph below. So changing the coordinates of the maximum and minimum will result in another model. If the red line shifts up by these changes (increase in α-values or a decrease in θ'-values) the overall step length increases, resulting in more suspended transport. This results in lower dunes. Changing these four values vice versa will result in a decrease in step length, more bed load transport, hence higher dunes.

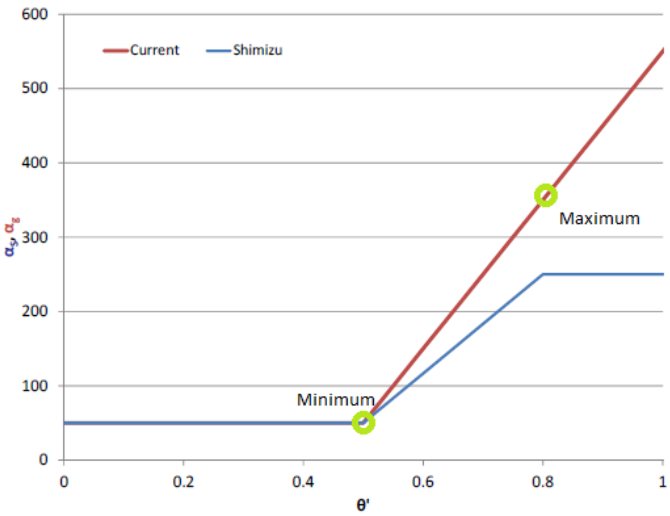

Figure 10 Step-length-model-principle (Van Duin, 2015) – red line represents model used in this study

It is important to note that changing the model such that the graph becomes extremely steep all dune development is suppressed. This is caused by the fact that nearly all sediment in this case will be transported in suspension.

Dunelengthfactor

The Dunelengthfactor did not show large variations in the resulting dune height. When the factor was set to 5 no dunes did develop. This does not pose a problem since the dune length is about 7 times the water depth (Paarlberg et al., 2009). Therefore, a Dunelengthfactor of 5 is not realistic to use and the factor will be set to 7.

In order to check the validity of using the Dunelengthfactor simulations with the stability analysis are made as well. This did not lead to large differences in the resulting equilibrium dune height. However, it proved to be usable in the scenarios where the model experienced stability issues.

3.2.2 Calibration

The insights of the sensitivity analysis have been used in the process of calibrating the model. The model is calibrated upon 17 flume experiments that use a constant discharge to develop an equilibrium dune height. 15 experiments of Coleman et al. (2005) and 2 from Naqshband et al. (2014c) are used (more details on these experiment in Appendix D: Flume experiments used for calibration).

The target of the calibration is to validate the morphological module of the model. The target of the calibration is to achieve an Nash-Sutcliffe-value (NS) for the observed and simulated dune heights of at least 0.7, see equation 18 (Nash & Sutcliffe, 1970). Along with this calibration on the morphology the hydrodynamic conditions have to be realistic as well. So the simulated and observed water depths and flow velocities will be analysed as well, again with the NS-value.

$$\text{Nash-Sutcliffe} = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \tag{18}$$

Where y_i are the observed values, f_i are the predicted values by the model and $\bar{y}$ is the average value of all observations y_i. A NS-value of 1 represents a perfect simulation, where a value of 0 or a negative value means a better prediction can be given by using the mean of the observed values.

Observed and simulated dune heights

Figure 11 shows the results of the calibration. The NS-value for the simulated dune height is 0.69. This has been achieved by adjusting the step-length-model as shown in Table 5. This NS-value of 0.69 does not exceed the targeted value of 0.7. Still the calibrated model is considered accepted, because it reproduces dune with height in a realistic order of magnitude. An important note is that Figure 11 only shows 13 simulations while 17 simulations were made for the calibration. Four simulations did not develop any dunes. These simulations have been removed from the calibration process.

Parameter	Old	New
H_{ref}	0.1166	0.1166
α_{min} & α_{max}	50 & 350	50 & 400
θ_{min} & θ_{max}	0.5 & 0.8	0.35 & 0.8
F_0	0.03	0.03

Table 5 Updated step-length-model

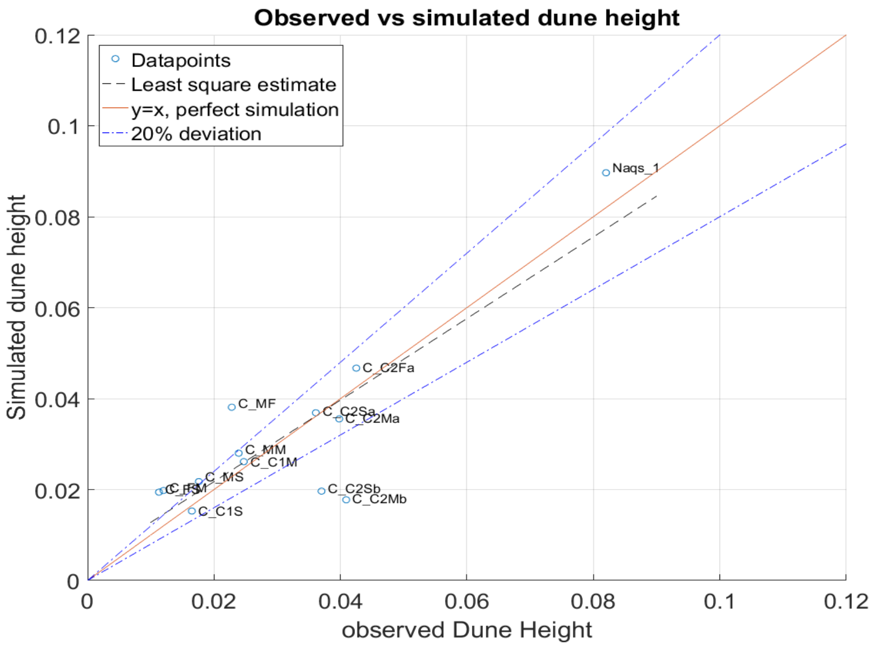

Figure 11 Results calibration morphological model (the codes represent the various experiments, see Appendix D)

The hydrodynamics are also assessed. The NS-value for the water depth was found to be 0.76 and for the flow velocity 0.73. These values indicate that the simulation of the hydrodynamics is realistic as well. Considering both the morphodynamic and hydrodynamic results these settings for the morphological module are considered acceptable for the further analyses.

3.3 Driving factors for USPB

To find the most important parameters for USPB, the calibrated model is applied under various conditions and the development of USPB will be assessed. This analysis will be another sensitivity analysis. This sensitivity analysis focuses on the occurrence and duration of USPB under a dynamic discharge.

The base scenario is a two hour long discharge peak shown in Figure 12-Base. This discharge scenario is based upon scenario A4 in Shimizu et al. (2009). This is the scenario Van Duin (2015) used to reproduce the plane bed results with his model. The standard bed slope used in this sensitivity analysis is $2*10^{-3}$ (-) and the grain size is 0.28 mm.

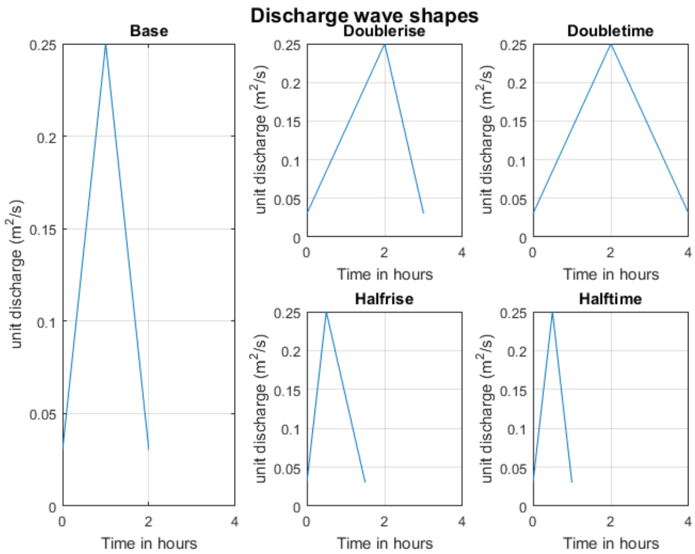

Figure 12 Discharge waves used to analyse USPB

To find the driving factors behind USPB, the four variables used as input have been varied. These four variables are the magnitude of the peak, the bed slope, the grain size and the shape of the discharge wave. The first three variables can be described by magnitudes, which have been increased and decreased to analyse the influence of these variables. The discharge wave shapes analysed are shown in Figure 12. These five shape are chosen because Shimizu et al. (2009) showed that the steepness of the rising and falling limbs of the discharge wave might affect the development of USPB.

3.3.1 USPB development under various conditions

Figure 14 shows the occurrence of USPB in the different scenarios. The blue axis on the left shows how long USPB was present within the simulation. In red it is shown what the discharge was when USPB started to occur.

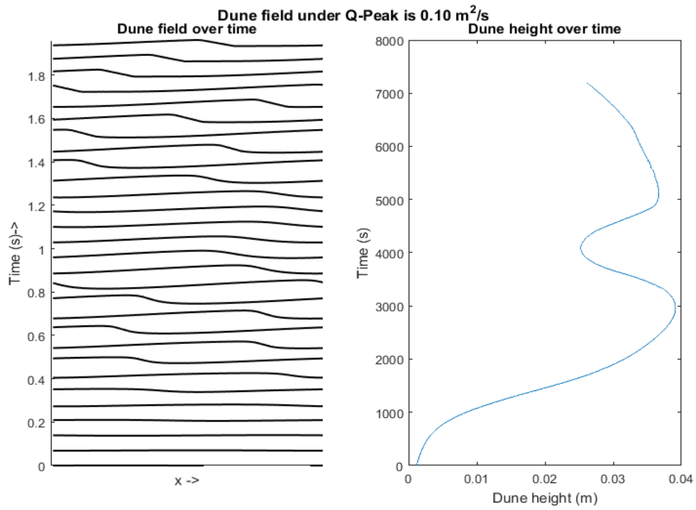

Figure 13 Dune field and dune height over time

Figure 14 'AQpeak' shows that USPB starts to occur when the unit discharge is above roughly 0.08 m^2/s. The duration increases when the peak height increases, since the unit discharge is above 0.08 m^2/s for a longer period. These observations indicate that USPB occurs when the unit discharge is 0.08 m^2/s or higher. However, the scenario where the unit discharge peak is 0.10 m^2/s does not develop USPB. The detailed results (Figure 13) show that this discharge wave indeed resulted in a reduction in dune height (t ≈ 3000s-5000s), but this period of dune reduction was not long enough to achieve plane bed, the entire reduction to a plane bed takes approximately 20 minutes. Hence, along with the threshold value, the period during which this value is exceeded is important for the development of USPB as well. So in order to develop USPB the peak discharge should be high and long enough.

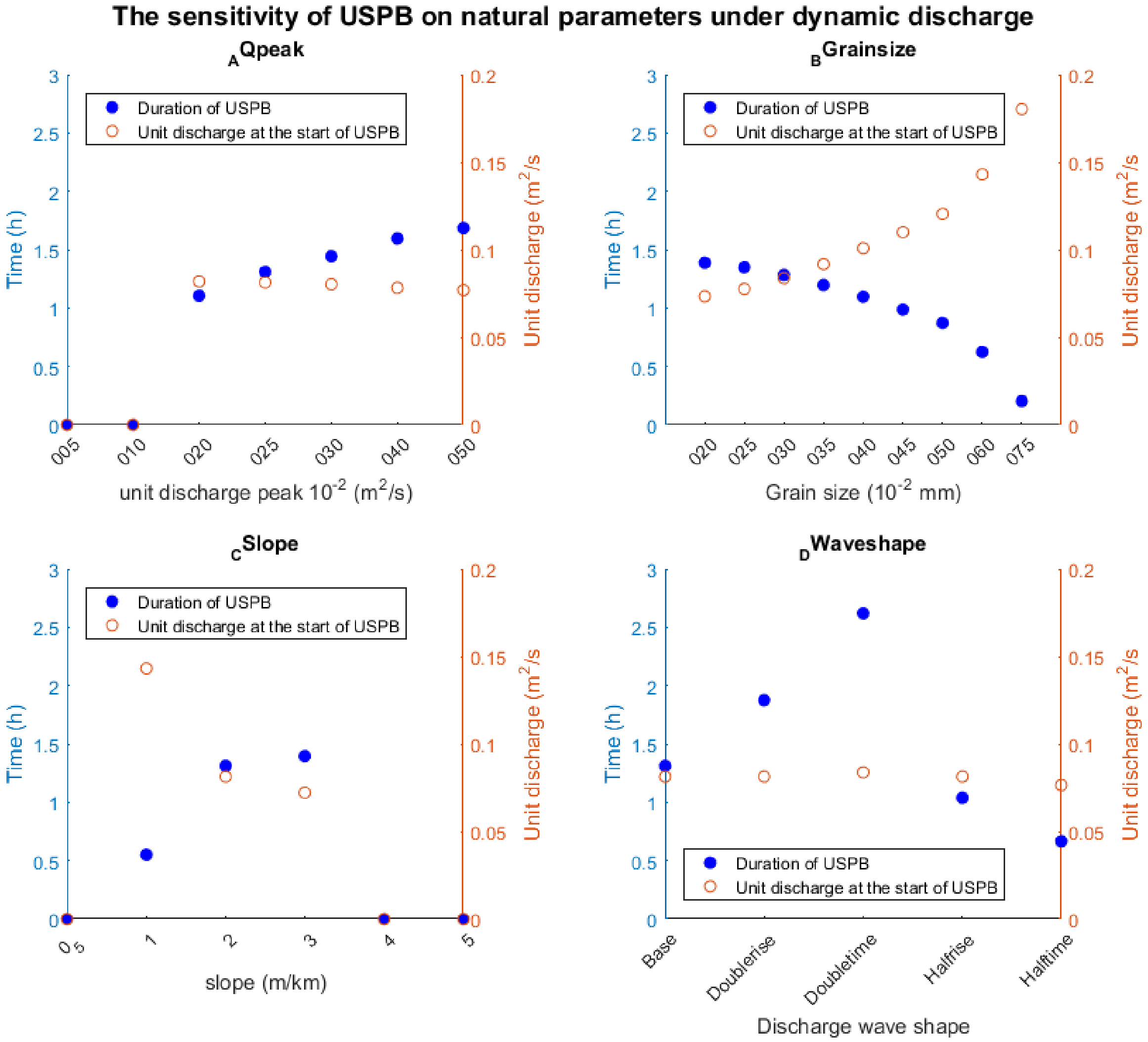

Figure 14 USPB-development under various conditions

The different grain sizes in Figure 14 also show the development of USPB. The smaller the grain, the longer the duration of USPB. The required discharge level is also lower when the grain size is smaller, because the smaller the grain the earlier it is transported in suspension.

The USPB-development under different bed slopes shows a less straight forward pattern. A slope too gentle does not develop USPB under this discharge wave. When the bed is steeper USPB does develop. The discharge required is lower when the bed is steeper, this can be explained by the higher flow velocities which transport more sediment in suspension. The two steepest slopes do not develop USPB, in these two cases the flow velocities are too high for dunes to develop in the first place.

The different shaped discharge waves also show the development of USPB when the unit discharge is 0.08 m^2/s. The duration varies, because the period in which the unit discharge is above the threshold value is longer. This observation implies that the shape of the discharge wave hardly influences the development of USPB. This is opposing the observations done in Figure 14 'ΔQpeak' and Figure 13, where it was shown that the duration of a discharge wave is important. These different observations lead to the expectancy that the shape of the discharge wave is only important if the discharge is just above the threshold value.

3.4 Synthesis on the model and USPB in flume conditions

The model of Van Duin (2015) has been calibrated for predicting equilibrium dune heights. The predictions are compared to the observations within the flume experiments of Coleman et al. (2005) and Naqshband et al. (2014c). This led to a NS-value of 0.69 which is considered acceptable. Especially when the predicted water depths and flow velocities are taken into account, which reproduce NS-values of 0.76 and 0.73 respectively. In the process of the calibration it was found that the model shows behaviour which cannot be explained physically when the grain size is smaller than 0.2 mm. So the model is not applicable with grain sizes smaller than 0.2 mm. When the model is subjected to high discharges or steep slopes with a relatively small grain size the model does not simulate any dunes. This is caused by the fact that the dunes are constantly washed away.

The calibrated model is used to analyse the development and occurrence of USPB under different conditions. It is found that USPB starts to develop in a simulation when the unit discharge exceeds a certain threshold. The magnitude of this threshold is dependent on the grain size and bed slope; the shape of the discharge wave does not seem to have any influence. The threshold value decreases when the grain size decreases, since a smaller median grain size results in more sediment being transported in suspension. A steeper bed also results in a lower threshold value, since a steeper bed causes higher flow velocities and lower water depths under a certain discharge. Higher flow velocities increase the sediment transport and the step length of single particle being transported, hence more suspended transport and a transition to USPB under a lower discharge.

4 Modelling dune development on river scale – Transition to USPB

4.1 Scaling up to river scale

A model which is valid to reproduce observed dune heights in a flume is not directly valid for doing the same on a river scale. To be able to simulate dune heights on a river scale the model will be calibrated again. This second calibration will be performed by changing the hydrodynamic model. In paragraph 3.1.1 the flow module is described; the turbulence model uses a constant eddy viscosity in combination with partial slip condition (equation 8). This description of the turbulence uses the resistance parameter and the eddy viscosity to describe turbulence. The magnitude of these two parameters can be altered by changing two calibration coefficients β_1 and β_2 (equations 9 & 10). Paarlberg et al. (2009) showed that these two coefficients are independent of the flow conditions. By calibrating these two coefficient the turbulence model and hence also the flow module can be calibrated.

The calibration will be performed upon the dune height data of Sieben (2004) (see paragraph 4.1.1). To get a calibrated model the hydrodynamic module of the model will be calibrated. The morphological model from paragraph 3.2.2 will be used in this river scale application of the model. The morphological model is already calibrated on reproducing the dune height. Another reason not to change the morphological model is the use of the reference height in the equation for the step length (equation 15). This reference height is used to standardize the step-length-model for different water depths. Paarlberg and Schielen (2012) also changed the coefficients β_1 and β_2 in order to simulate realistic river scale conditions and achieved realistic results.

4.1.1 Dune height data Sieben (2004)

The dataset of Sieben (2004) consists of dune height, dune length and discharge values at several moments in 2002 and 2003. The dataset ranges from Dutch-German-border and continues till Woudrichem, covering the Bovenrijn and a large part of the Waal. Sieben (2004) describes a method to extract dune-dimensions from bed measurements. These dune-dimensions are obtained from multi-beam echo-sounding. The river Waal is split up in section of 500 meter (roughly 10 times the bed form length) in order to include a sufficient amount of bed form fluctuations per domain. The width of the domain is 50 m (roughly 1/5 of the bankfull width). In total Sieben (2004) defined 63 so-called morphological units. Using a concept of statistical equivalency Sieben (2004) developed and tested a procedure that characterizes bed forms.

Along with the dune height and length data in this dataset the daily discharge is known at Lobith (Dutch-German border) and Tiel. This gives the possibility to compose subsets of data consisting of dune heights at several moments and discharge over time in the corresponding period at various locations. Along with the grain size data presented paragraph 2.1.1 and the known bed slope of the river Waal ($i = 1.1 * 10^{-4}$) a complete dataset for a river scale analysis is composed.

4.2 Calibration & validation of dune height simulation on river scale

Using the dataset of Sieben (2004), along with the grain size data and the bed slope the model is calibrated. The calibration is performed at Beneden-Leeuwen (morphological unit 37) over the entire year 2002. This location is chosen because it is close to Tiel, where the discharge is known. Another advantage of this location is the relatively straight configuration of the river which means that effects of curves which are not present in the model are less influential on the measurements.

To validate whether the calibrated model is applicable under different conditions, two validations will be performed. The first validation will be performed on the same location but in the year 2003. The second validation will be performed in 2002 at another location. This location is Varik (morphological unit 47), which is chosen again for its relative straight channel. A second reason to choose Varik is the absence of bifurcations between Tiel and Varik, which means that using the discharge wave at Tiel is possible. Using this discharge wave will slightly overestimate the peak discharge since some diffusion of the discharge peak will take place. The different variables used during the calibration and validation can be found in Table 6.

Variable	Beneden-Leeuwen	Varik
D_{50}	1.6 mm	1.0 mm
i	$1.1 * 10^{-4}$	$1.1 * 10^{-4}$
B	250 m	260 m

Table 6 Variables at the calibration and validation locations

Both the calibration and validation will use the Nash-Sutcliffe-coefficient to analyse the performance of the model. A satisfactory NS-value is anything above 0.3. This is not a high value for the NS-coefficient, but given the simplicity of the model, the complexity of river dunes on a river scale and uncertainties within the 2D-model it is unrealistic to aim for a higher value. A model of this accuracy level can still be used to create qualitative conclusions.

The model will be calibrated over the entire year 2002, to save upon computational time it is chosen to split up this period. Four parallel simulations are made, each of a period of one quarter (Table 7). A downside of this method is that the simulation of each quarter starts with a flat bed, meaning that the simulated dune heights in the first few days of each quarter do not show realistic results. This does not affect the calibration, since the dune heights are not observed in the first days of each quarter.

Period	Start date	End date
A	01-01-2002	01-04-2002
B	01-04-2002	01-07-2002
C	01-07-2002	01-09-2002
D	01-10-2002	01-01-2003

Table 7 Simulations periods

4.2.1 Calibration of dune height on river scale

The results of the calibration are shown in Figure 15. The achieved NS-value is 0.31, a higher value would be desirable but could not be achieved when calibrating the β_1 and β_2-coefficients. However, this configuration of the model is deemed acceptable, since the target of 0.3 has been achieved. Both β_1 and β_2 are set to 0.245.

Figure 15 also shows two blue dashed lines, these lines indicate a 20% deviation from the observed dune height. It is visible that only three simulated dune heights deviate more than 20%. A more detailed representation of the simulations behind this

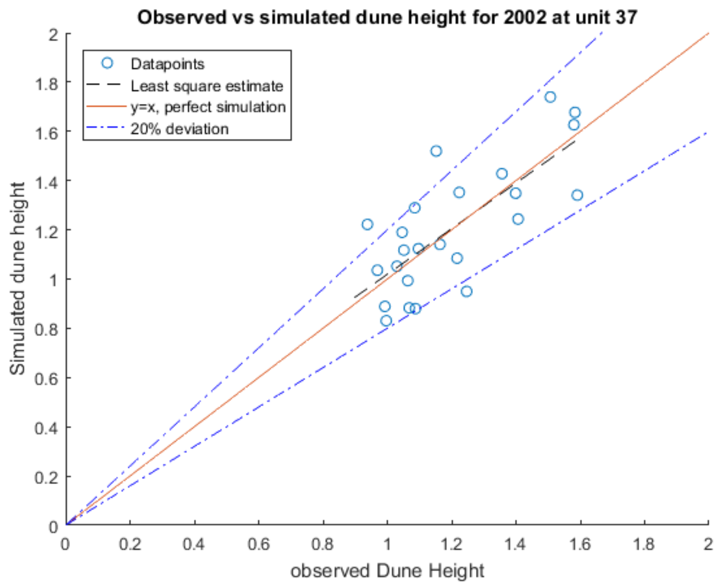

Figure 15 Calibration results for the observed dune heights, Beneden-Leeuwen 2002

calibration can be found in Appendix E: Dune height evolution. The water depth within these simulations ranges from a minimum of 3.48 m till a maximum of 9.67 m. The observed water depths in the period 2002-2003 range from 1.90 m till 9.61 m (dataset (Sieben, 2004)). The minimum water level is overestimated by the model; this does not pose a problem since this study focusses on the conditions during high water. The maximum water level is predicted correctly, so the simulated water depths correspond well to the observed water depths during high water. Meaning the both the hydrodynamic and morphodynamic modules of the model show realistic results.

4.2.2 Validation on river scale

Validation at Beneden-Leeuwen, 2003

The validation at Beneden-Leeuwen gave an NS-value of 0.58. This is higher than was achieved during the calibration. The discharge and observed dune heights in 2003 cover a larger range and the predictions deviate less from the observations, resulting in a higher NS-value. The water depth within this validation ranged from a minimum of 2.21 m till a maximum of 10.50 m. The maximum simulated water depth did exceed the maximum observed water depth by 89 cm. This is considered accepted since the calibration did focus upon the dune height evolution and despite this overestimated water depth the dune height evolution showed good results.

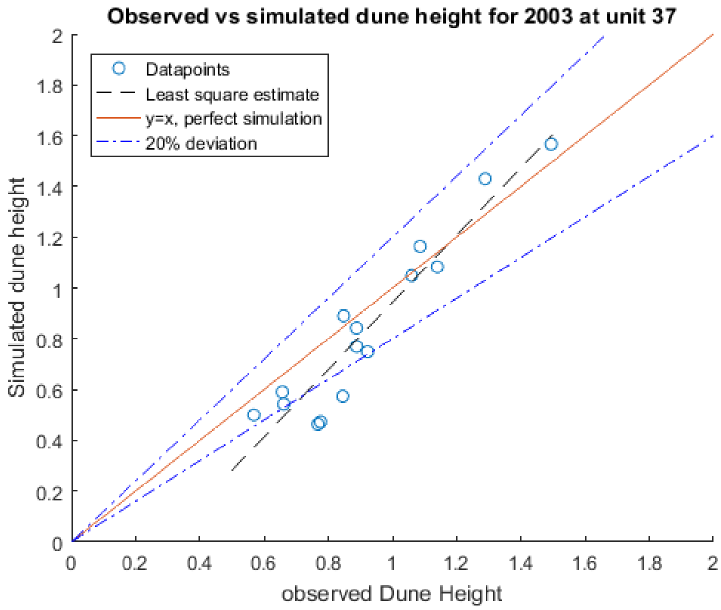

Figure 16 Validation results for the observed dune height, Beneden-Leeuwen 2003

Validation at Varik, 2002

The NS-value at Varik resulted in -4.26, which means that the model does not reproduce the dune heights in a sufficient manner. Figure 17 shows that two observed dune heights are simulated with a height of roughly 0.2 m. Figure 18 shows that this is caused by the simulated of plane bed in in the first quarter and in November. However, a plane bed is not observed in these cases. So the calibrated model does reproduce correct dune heights, but the transition to USPB takes place under conditions which do not develop USPB in reality (the

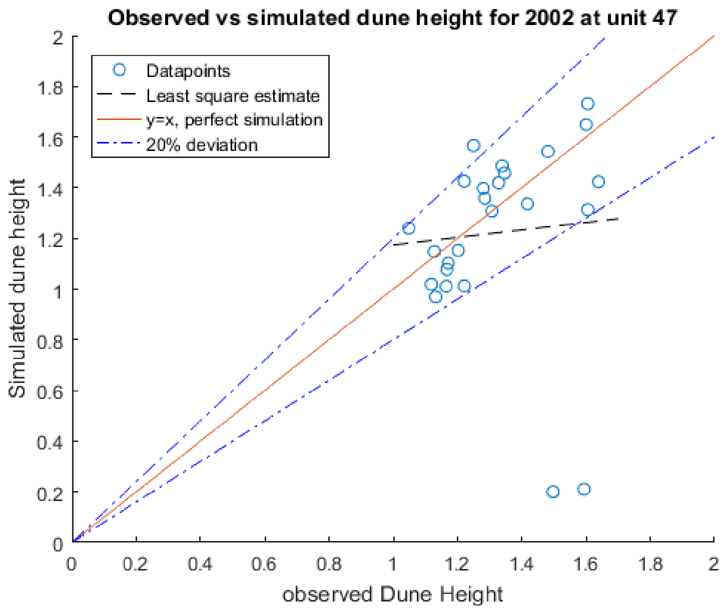

Figure 17 Validation results for the observed dune height, Varik 2002

transition takes approximately 35 minutes). To solve this issue the model needs to be calibrated upon the transition to USPB. This process will be explained in the next section.

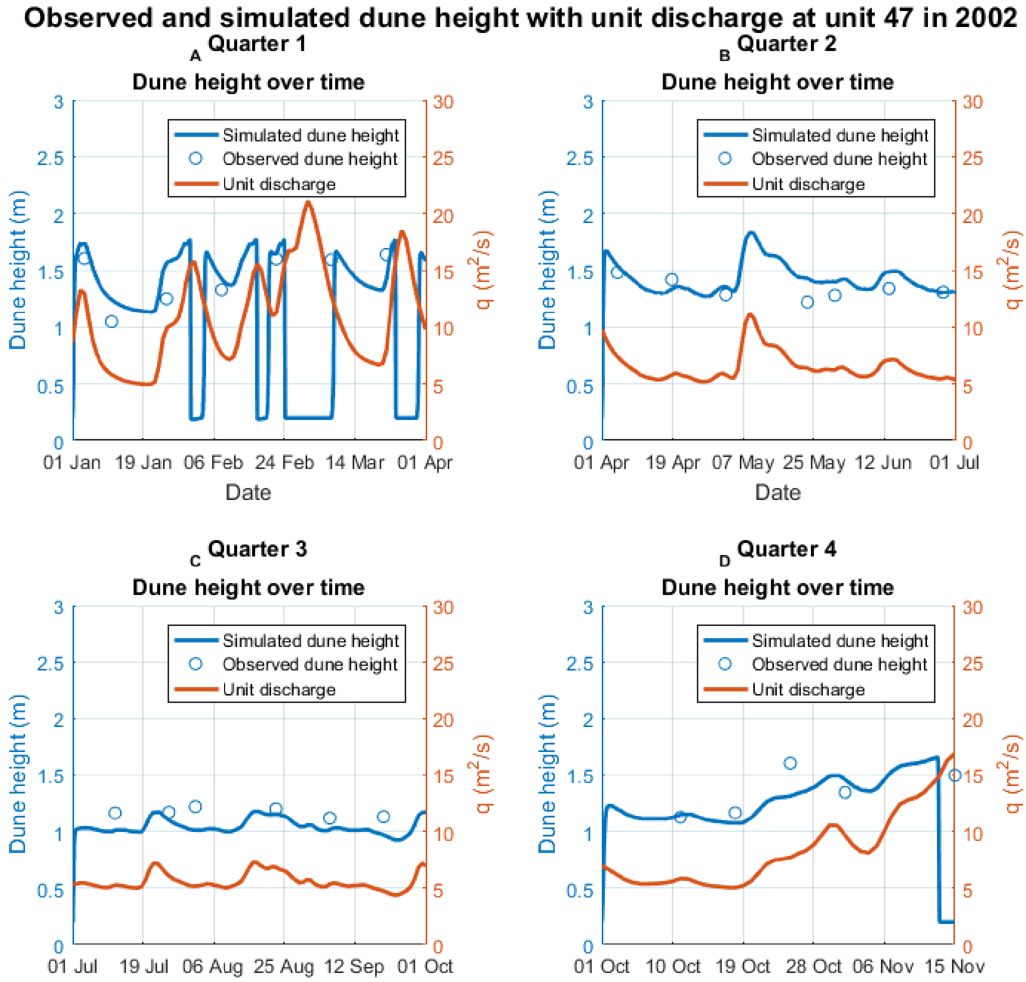

Figure 18 Dune development at Varik, 2002

4.3 Calibration of the transition to USPB

Figure 18 shows that the model does predict USPB when dunes are observed. In order to solve this issue the model has to be calibrated for a third time. This time on the transition to USPB, however no data are available over the exact transition are available. The available data upon USPB is the threshold for USPB determined by Naqshband et al. (2014b). Since the Froude and Suspension numbers can be calculated at the moment the simulated bed is evolved to USPB and this point can be plotted in the figure of Naqshband et al. (2014b).

Shifting the step-length-model to the right was found to delay the development of USPB while simulating the same dune heights as before. Figure 19 illustrates the principle of shifting the step-length-model, a larger dimensionless grain shear strength is required to get a certain step-length. The effect of this principle is shown in Figure 20. Figure 20 shows simulations where the step-length-model is shifted to different extend, these simulations use a constantly increasing unit discharge, because this way the unit discharge will eventually exceed the threshold required to develop USPB. The larger the shift the higher the unit discharge, which is present when USPB develops. This higher unit discharge corresponds with different flow conditions. These flow conditions result in new Froude and Suspension numbers. In Figure 21 the results of the different step-length-models are shown together with the threshold of Naqshband et al. (2014b). Figure 20 and Figure 21 use the grain size observed at the Ijssel near Kampen (D_{50} = 0.25 mm) It is visible that the shift with a magnitude of 0.45 is just above the threshold. This means that the simulated conditions when USPB is present correspond with the observed conditions in the field and flume experiments collected by Naqshband et al. (2014b). The same process has been applied for other grain sizes, in Appendix F: USPB-transition for different grain sizes it is visible that other grain size give different results and require another shift. This is caused by the lower Suspension numbers, which means that the magnitude of the shift is dependent on the grain size. It will also be dependent on the bed slope since the bed slope will influence the flow velocities, which influence the Froude and Suspension numbers. Hence, the magnitude of the shift can be described with equation 19:

$$magnitude\ of\ shift = f(D_{50}, i) \tag{19}$$

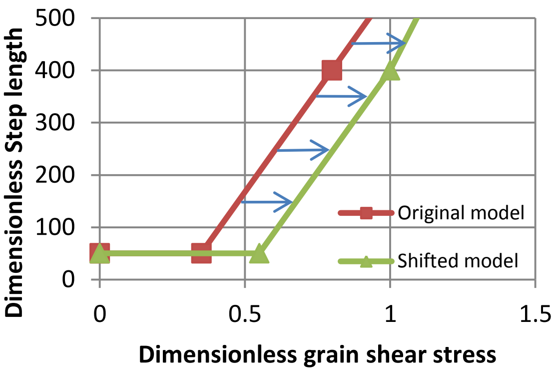

Figure 19 The principle of 'shifting' the step-length-model

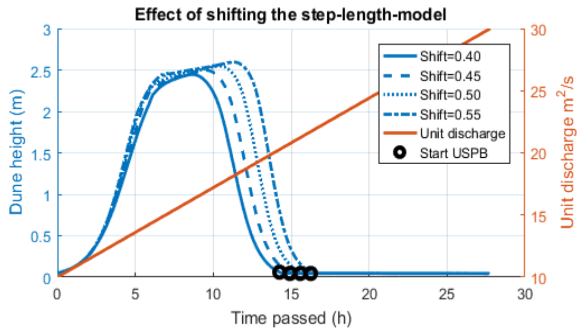

Figure 20 The effect of 'shifting' the step-length-model

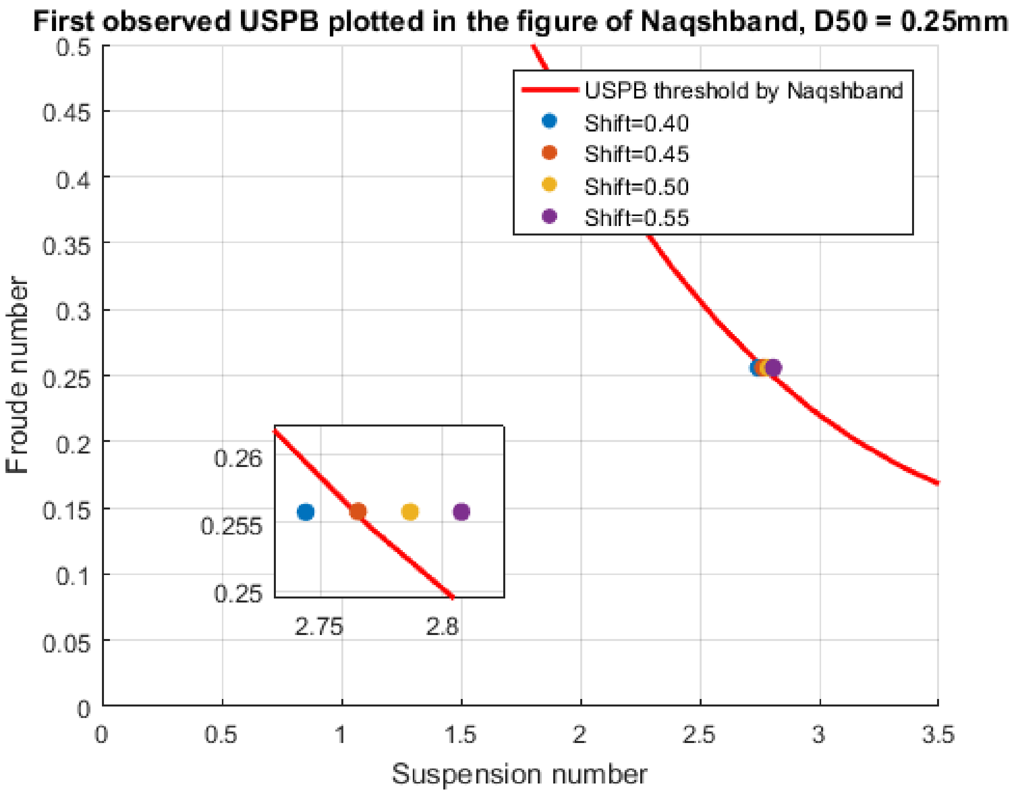

Figure 21 The calibration of the transition to USPB for the IJssel near Kampen

The updated step-length-model at the river IJssel near Kampen is shown in Table 8. This model is applied again on the calibration and validation simulations at Beneden-Leeuwen and Varik. This resulted in the NS-values and water depths shown in Table 9. Using the updated step-length-model did result in slightly different minimum water depth during the calibration, however it still remains within a realistic range (1.90m - 9.61m). Figure 22 shows that the updated model did not result in a plane bed at Varik in 2002.

What	Value
α	50 - 400
θ'	0.8 - 1.25
Shift	0.55

Table 8 Updated step-length-model for D50 = 0.25 mm

Simulation	NS-value	Water depth range (m)
Calibration at Beneden-Leeuwen, 2002	0.31	3.86 – 9.67
Validation at Beneden-Leeuwen, 2003	0.58	2.21 – 10.50
Validation at Varik, 2002	0.30	3.55 – 9.52

Table 9 Results of the calibration and validation with the updated step-length-model

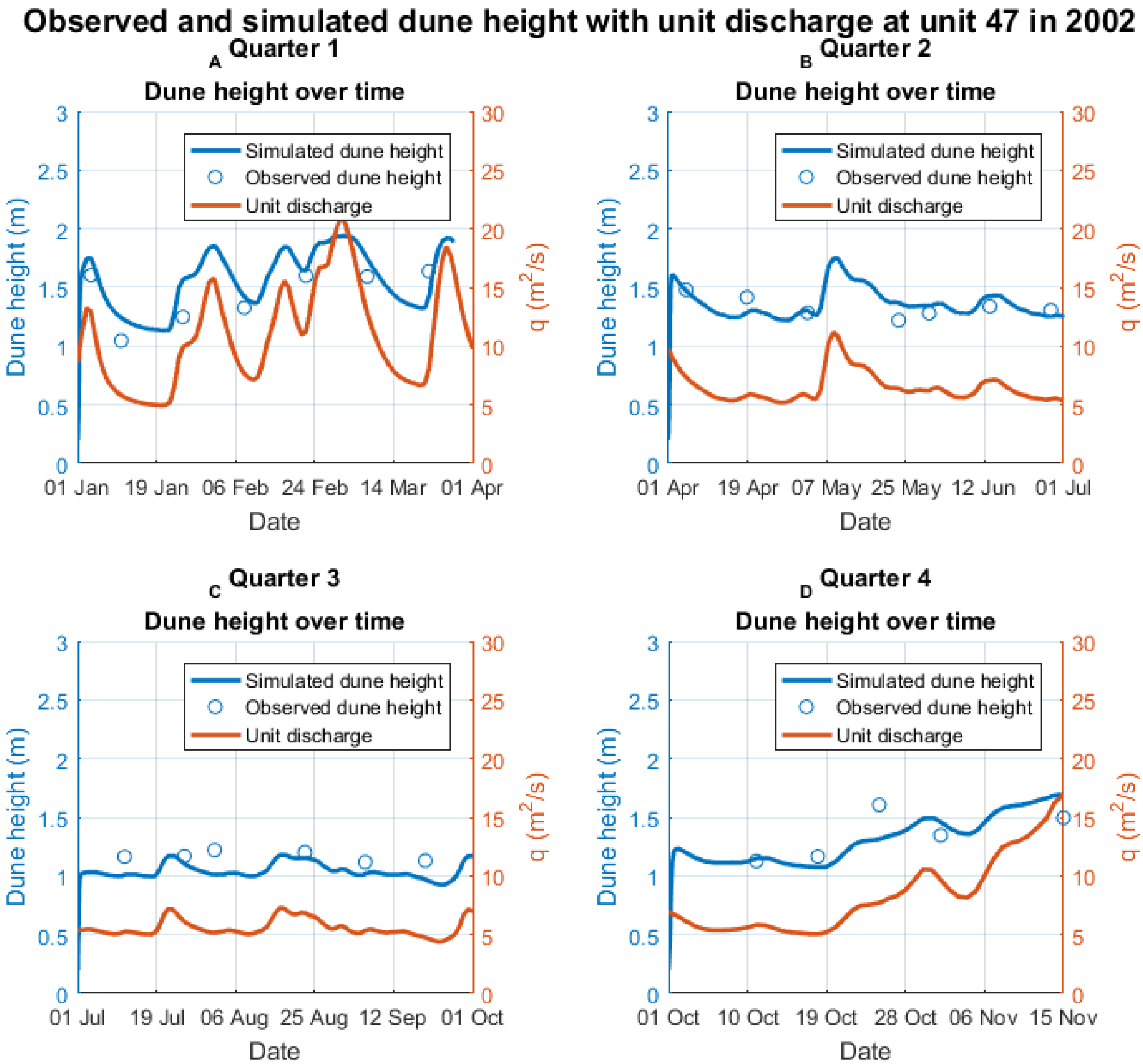

Figure 22 Dune evolution with the updated step-length-model near Varik in 2002

4.4 Synthesis on the model application on river scale

The calibrated model of Van Duin (2015) is shown to be applicable on a river scale to predict the dune height on a river bed. The model was made applicable for a river scale by adjusting the hydrodynamic module of the model. This was done by adjusting the turbulence model to reproduce the observed dune heights in the Waal (Sieben, 2004). The calibration-coefficients of the turbulence model, β_1 and β_2, are set to 0.245. Calibrating the model only on the observed dune heights resulted in a simulation that predicted USPB at moments where dunes were observed. The model did not reproduce USPB under the right conditions.

In order predict USPB under realistic conditions the transition to USPB had to be calibrated as well. No dataset is available which contains observations of this transition. To be able to validate the prediction of USPB the observed bed forms of Naqshband et al. (2014b) are used. The threshold based upon the observation is applied to the model outcomes, when the model predicts USPB the conditions should be such that they end up above the threshold. To increase the required conditions before USPB occurs in a model simulation the step-length-model can be shifted. This adjustment in the relation between dimensionless grain shear stress and dimensionless step length keeps the predicted dune heights constant.

5 USPB development in Dutch rivers

5.1 USPB development in the Dutch river system

Whether and where USPB can occur in the Netherlands will be determined in this chapter. The model calibrated for the river scale and the transition to USPB (Chapter 4) will be applied at the most probable locations for USPB (Chapter 2). First on Kampen, secondly on Tienhoven-Lopik, this is the second-most likely location for USPB to develop. If both locations do develop USPB, the model will be applied to the next most-probable location to create a list of locations which can develop USPB. If the model does not develop USPB for both locations, the discharge will be increased to find which conditions are required to develop USPB. Finally, if only the most probable location near Kampen develops USPB and the Location near Tienhoven Lopik does not, it can be concluded that only the location near Kampen is likely to develop USPB.

In Chapter 3 it was found that USPB is most-likely to develop in a steep river, with a small grain size under the highest possible discharge. These first two factors are already set at the simulated locations. The third factor, the highest possible discharge, is obtained by using the design discharge wave through the Dutch river system. To obtain the design discharge wave at the suspected locations the WAQUA-model will be used again. Simulating the design discharge through the Dutch river system results in the unit discharge in each cell in the WAQUA-model. This grid of unit discharge values can be used with the river-lines in the same way as in paragraph 2.1.2 to obtain the discharge wave at a certain location.

For each location where the model is applied, the USPB-transition has to be calibrated a second time. This will be done by the method presented in section 4.3, for each calibrated location the new step-length-model will be given. The model for the Ijssel near Kampen has already been calibrated in paragraph 4.3.

5.1.1 Dune development near Kampen

The dune height evolution over time in the IJssel near Kampen can be found in Figure 24. Visible in Figure 24 is that USPB does develop at the start of day six of the design discharge wave. The dune height starts to decay when the unit discharge is roughly 13.5 m^2/s. To check whether the conditions when USPB developed were realistic, the conditions are plotted with the threshold of Naqshband et al. (2014b) in Figure 23. The corresponding USPB-index is above zero (0.09), but is close to zero. So it could be possible that USPB will develop in reality. This USPB-index corresponds with the USPB-index found in Chapter 2 (0.03). The index of Figure 23 is slightly higher. This is caused by the lower unit discharge present when determining Froude and Suspension numbers for Figure 23 than the unit

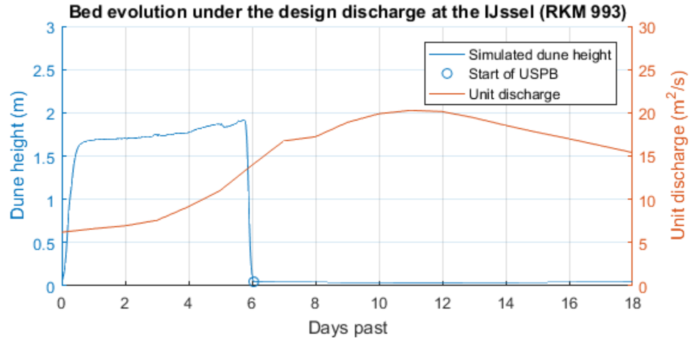

Figure 24 Bed evolution near Kampen under design discharge

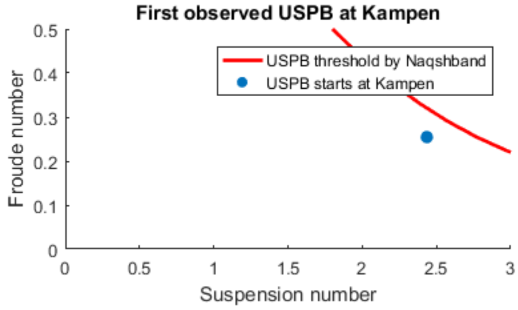

Figure 23 The conditions during the start of the plane bed period near Kampen

discharge which is used to determine the Froude and Suspension number for Figure 4. The discharge increases further till day 11 this leads to an USPB-index of 0.02, still indicating that the location is below the threshold. Some reasons can be given for the development of USPB, while the threshold of Naqshband et al. (2014b) is not met.

The threshold is based upon observed bed forms, some observations of dunes are above the threshold and some observations of USPB are below. This indicates that the presence of USPB is possible when the conditions do not meet the threshold.

Another remark about the threshold based upon observation is that the observations are done over a larger width, the width-averaged conditions required to develop USPB are probably higher than the conditions required for the most-USPB-favourable middle of the river. When USPB is observed over a larger width the average conditions need to be above the threshold, when looking only to the middle of the river, like the model simulates, the required conditions are expected to be lower. In the middle of the river the flow velocities are higher and the Froude and Suspension numbers will be higher than when the observations are performed closer to the river bank. These observations closer to the river bank are influencing the conditions found for the threshold of Naqshband et al. (2014b)

The reason for developing USPB while the threshold is not met could be within the model. The model is a 2D-model and does only include the processes in the flow direction and vertical processes. Cross-river effects can affect the resulting bed form and are not included in the model, this could explain the simulation of USPB under these flow conditions, flow in another direction near the bed can influence the bed form evolution, possibly hindering the transition to USPB.

Another explanation could be the calibration method for the transition to USPB. The transition to USPB has been calibrated with model scenarios with an increasing unit discharge. This means that in the period between the moment when the dune heights start to decay and a fully developed plane bed the unit discharge has increased. Meaning that the transition to USPB started with lower Froude and Suspension numbers than were used in the calibration. A slower increasing discharge can result in a fully developed plane bed under a lower discharge.

Yet another source for this deviation in USPB-conditions can be found in the representation of the bed material in the model. The model uses a uniform grain size, while this is not a representation of reality. In reality the variance in grain size causes differences in the erosion and deposition. For example, larger grains can cover smaller grain withholding them from entrainment, causing the amount of suspended sediment to be lower. This results in a lower amount of sediment in suspension, which will require more extreme condition for the development of USPB.

Overall it can be stated that USPB can be expected in the river IJssel when the river discharges a unit discharge above 13.5 m^2/s in the middle of the river. When the design discharge wave passes through the IJssel the unit discharge in the middle of the river will exceed 20 m^2/s near Kampen so USPB is expected. To validate this expectation, experiments should be performed to develop a dataset for calibration and validation of the transition to USPB. These experiments could be replicating the discharge scenario shown in Figure 20. If the dune height evolution in the experiments is similar to the dune height evolution in the model the transition to USPB is validated.

5.1.2 Dune development near Tienhoven-Lopik

To find the dune height evolution during design discharge the USPB-transition needs to be calibrated for the present grain size. The grain size in the river Lek near Tienhoven-Lopik is 0.32 mm. Calibrating the USPB-transition for this grain size led to a shift of 1.65. This shift did not lead to an USPB-index below zero (Figure 25), but the plane bed developed with these conditions with a unit discharge of 45 m^2/s. This is roughly 2.5 times the maximum observed discharge in the river Lek. This leads to the expectation that USPB will not develop at this location. Due to this expectation it is chosen to use these setting. These settings develop USPB under less extreme conditions than the threshold of Naqshband et al. (2014b). If USPB does not develop, it can be concluded that USPB will not develop near Tienhoven-Lopik.

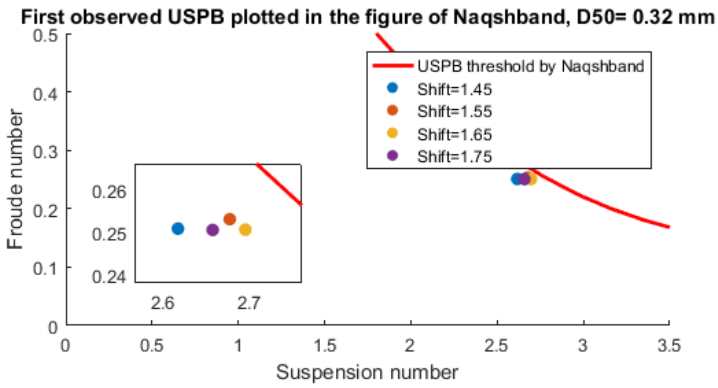

Figure 25 The calibration of the transition to USPB for the Lek near Tienhoven-Lopik

Figure 26 shows the dune evolution under the design discharge at the second most-probable location for USPB to develop in the Netherlands. The dune height grows to a maximum of 1.67 m, but dunes remain present throughout the period. This means that USPB is not expected to develop in the Lek near Tienhoven and Lopik.

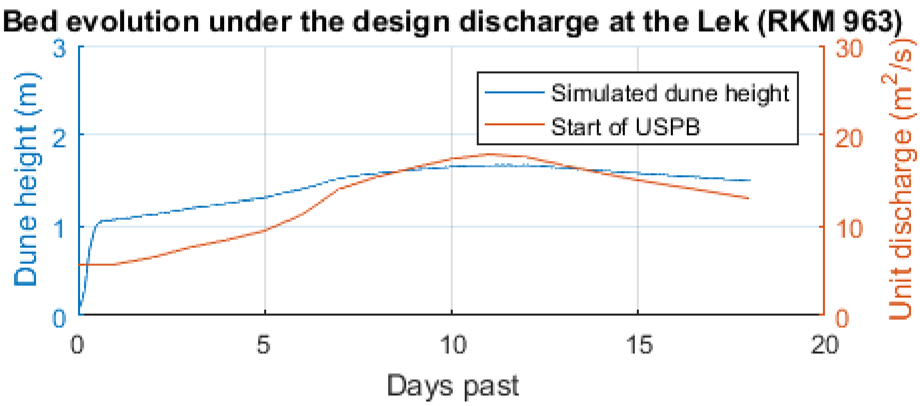

Figure 26 Dune evolution under design discharge at the Lek

5.2 Synthesis on USPB-development in Dutch rivers

USPB is expected to develop in the river IJssel near Kampen. This was already the most probable location for USPB to develop (Chapter 2). The second location for the development of USPB, Lek near Tienhoven-Lopik, was found not to develop USPB. The bed form evolution was assessed under the design discharge wave, this way the conditions most likely to develop USPB (Chapter 3) were reproduced.

To validate prediction of USPB near Kampen more research is needed. This is caused by the fact that the observed conditions during the plane bed period do not exceed the threshold of Naqshband et al. (2014b). The calibration of the transition to USPB needs to be validated. The transition to USPB is calibrated upon width-averaged observations of bed forms, while the model only simulates the most-probable middle of the river. This inconsistency is caused by the lack of a dataset containing the transition to USPB. Experiments could be conducted to create such a dataset, which will lead to the possibility to validate the model settings used for the analysis of the different river sections.

6 Discussion

In order to be able to formulate solid conclusions and recommendations in Chapter 7 it is needed to put the methods used and the results obtained within the study in perspective.

The first analysis within this study used a WAQUA-simulation together with grain size data of the Dutch river system to determine Froude and Suspension numbers. Together with the threshold of Naqshband et al. (2014b) these numbers were used to determine the USPB-index, which is used to find the most probable location for USPB. By using this USPB-index, it is possible to compare different locations on their probability to develop USPB; however the USPB-index does not represent the magnitude of this probability.

The WAQUA-model uses the Chézy-coefficient for calibration which normally represents the smoothness of the bed. Calibrating upon this parameter means that the present bed form is not determining the smoothness, but that the expected depth-discharge-relation determines the smoothness. This means that the presence of a plane bed will not be represented in the simulated roughness. While the presence of a plane bed would influence the flow velocity, water depth and Chézy-coefficient in such a way that the USPB-index would decrease. So it might be possible that USPB would develop in reality, but the WAQUA-model does not represent this. This gives a positive USPB-index, representing the presence of dunes. This overestimation of the bed roughness is opposed by Warmink (2014). Warmink (2014) describes that the bed roughness under design conditions might be underestimated due to the presence of hysteresis effects under a fast flood wave multiple shorter dunes develop, providing more form roughness. So, in general it can be stated that the bed roughness under these extreme condition is not yet well understood.

This uncertainty of the WAQUA-model also has implications for the final model application on the IJssel near Kampen. The discharge wave used in this simulation is based upon the WAQUA-model and does not incorporate the effects of the developed plane bed. However, this implication does not alter the outcome of this analysis since the unit discharge will still exceed the required threshold.

The choice of using a constant discharge of 16,000 m^3/s for the Rhine and 3,800 m^3/s for the Meuse result in higher simulated discharges in downstream areas due to the absence of dispersion. This results in a lower USPB-index than in the case the design discharge wave was used (20.5 m^2/s instead of 20.2 m^2/s). If the normative discharge is increased to 18,000 m^3/s in the future the USPB-indices will decrease and it is expected that the USPB-index near Kampen will become negative. So increasing the normative discharge might lead to the occurrence of USPB which will cause lower design water levels.

The grain size data are quite dated (1995), so it is possible that the grain size used in this study does not represent the current situation anymore. Another choice influencing the determination of the Froude and Suspension numbers is the choice to analyse only the middle of the river. Transverse variability is not included due to the analysis on the middle of the river, while faster flows in outer bends or regions with finer sediments could provide locations with lower USPB-indices.

The second analysis is the analysis with the model of Van Duin (2015). Several remarks have to be made on this analysis as well. The model is calibrated a total of three times: first the equilibrium dune height is used on a flume scale to calibrate the morphological module; the second calibration is on dune heights on a river scale to calibrate the hydrodynamic module and the third calibration has been performed to calibrate the transition to USPB. Each calibration will be discussed shortly.

The first calibration was on equilibrium dune heights in flume conditions. The calibration was performed by altering the morphological module of the model. Flume experiments with a constant discharge were used, while the final application of the model is about the dune evolution under a dynamic discharge. The model has not been calibrated on the appearance of USPB, but was only shown to be able to simulate USPB. So it is unknown whether the moment when USPB develops is simulated correctly. A more general remark about the model is that the model uses a uniform grain size, which means all natural variability is excluded and phenomena where larger particles hinder small particles to erode are excluded together with this variability.

Overall it can be stated that the results from Chapter 3 give good insights in the development of dune height and the processes behind USPB development, but that the exact values around USPB development are uncertain.

In the fourth chapter the model is applied on a river scale and calibrated using the hydrodynamic module of the model. The scaling up of the model was proven to be possible and the model gives good results in terms of dune height and simulated water depths. However, the resulting NS-values are not really high, only just above 0.3. This is still deemed satisfactory because of the amount of processes which are absent in the model. All 3D-variability, movement or processes, is either simplified or absent in the model, for example transverse variability in flow velocity is not included. This means that the results of the model can only be used as indication of what will happen in reality. The results of the model show the correct trends (higher dunes when the discharge is higher, see Figure 22) and a realistic order of magnitude (the maximum simulated dune height in all performed river scale simulations below 2 meter, where the maximum observed dune height by Sieben (2004) was 2.5 m).

Along with these simplifications in the model another remark has to be made as well. As input for the model the discharge at Tiel is used, while the calibration and validation locations are located just up- and downstream of Tiel which means the discharge is not exactly the same.

In the fourth chapter the model is also calibrated on the transition to USPB. This calibration performed with the use of the observed bed forms of Naqshband et al. (2014b). The transition to USPB has been calibrated with model scenarios with an increasing unit discharge. This means that in the period between the moment when the dune heights start to decay and a fully developed plane bed the unit discharge has increased. Meaning that the transition to USPB started with lower Froude and Suspension numbers than were used for the calibration. A slower increasing unit discharge can result in a fully developed plane bed under a lower discharge. An improvement to this calibration method would be to perform the calibration with a slower increasing unit discharge, limiting the increase in unit discharge during the transition to USPB. The calibration of this transition is not valid for different locations, it needs to be performed for each analysed location. This is not supposed to be necessary, since the step-length-model aims to simulate the correct step length for different grain sizes. This inconsistency is probably caused by the extension made to step-length-model in order to implicitly include suspended transport by letting the step length increase with the water depth. The initial step-length-model by Nakagawa and Tsujimoto (1980) was formulated for bed load only, this formulation described the step length based upon the grain size. The extended step length formula, to include the suspended transport, does possibly not hold for different grain sizes under extreme conditions.

The last remark about the calibrations performed in Chapter 4 is the uncertainty in the dune height data (Sieben, 2004). These data give a single characteristic dune height for an entire stretch of river. In reality dune fields do show a large spatial variance, which is not included in the model. The dune height derived by Sieben (2004) only gives the most dominant dune height. So there is some uncertainty within these data. However, given an observed dune height in the field it is shown that the model is capable of reproducing these realistic dune heights, resulting in dune heights that have a realistic range in heights. If better dune height data would become available it is possible to calibrate the model again, to increase the validity.

The last step in this study was applying the fully calibrated model on the most probable locations under design discharge. The model only had a NS-value of 0.3, meaning that care has to be taken with the conclusions based upon the model, however qualitative conclusions can be made. Again the difference between the conditions in the middle of the river in the model opposed to the width-averaged in the observation of Naqshband et al. (2014b) is a point of discussion. This because of the USPB-transition calibration being performed on the width-averaged observations and has been applied on the middle of the river.

Overall it can be stated that the model predicts dune heights in the correct order of magnitude (maximum deviations just above 20%) and is useful for predicting dune dimensions. The model also gives insights in the moment the transition to USPB takes place. However, there is too much uncertainty to directly apply the outcomes in the design of flood protection measures.

Despite these numerous points of discussion, this study did lead to some new developments. The first one is the introduction of the USPB-index; this index can be applied throughout the world to find rivers which are expected to develop USPB. This quick exploratory analysis will probably lead to several locations where USPB is expected. Knowing these locations can be useful when a measurement campaign tries to obtain field measurements of USPB.

Another new development is the application of a dune evolution model on a river scale which gave good results for both dune height evolution as water depth, this is an improvement of the river scale application of dune evolution models tried before by Shimizu et al. (2009) and Van Duin (2015), which were not calibrated on observed dunes or did not reproduce realistic hydrodynamic conditions.

The last notable development is the procedure which can be used to calibrate the transition to USPB. This will help when further developing river dune evolution models in order to incorporate the transition to USPB. When further research and experiments have been performed on this transition to USPB, this method can be used to recalibrate the model quickly.

7 Conclusions & Recommendations

7.1 Conclusions

This section will first give an answer to the four research questions which were formulated in section 1.4. After these answers the research objective will be discussed.

The first research question was:
Which locations in which river branches in the Netherlands are most likely to develop USPB?

It was found that the river IJssel near Kampen is the most-probable location within the Dutch river system to develop USPB under a constant design discharge. This was found by using the newly introduced USPB-index (0.03 near Kampen), this index allows the comparison of different locations and conditions for the likeliness to develop USPB. The other locations within the Netherlands are less probable to develop USPB, where the river Lek near Tienhoven-Lopik is the second-most likely location (USPB-index = 0.31).

The second research question sounded:
Under which conditions is USPB most likely to occur and can this be modelled using a dune evolution model?

The dune evolution model of Van Duin (2015) was already capable of developing a plane bed. The sediment transport description of the model has been further validated by calibrating on the equilibrium dune heights that developed in flume experiments (NS-Value 0.69). The model also correctly reproduces the water depth (NS-Value 0.76) and flow velocity (NS-Value 0.73). With this model it was found that the unit discharge, bed slope and grain size influence the development of USPB. For a specific location the grain size and the bed slope will be constants, these two variables determine a threshold-value that the unit discharge needs to exceed to develop USPB. The steeper the bed or the smaller the grain size, the lower this threshold value is. This is because a steeper bed or a smaller grain size results in larger step-lengths for the individual particles, meaning there will be more suspended transport.

The shape of the discharge wave was found to have some influence, the peak of the discharge needs to be above the threshold long enough in order to develop USPB. In the flume experiments simulated with the model this period had to be around 20 minutes in order to fully develop a plane bed. In the field simulation this took about 35 minutes (Figure 18A). In opposition to Shimizu et al. (2009) the steepness of rising and falling limbs was not found to have any influence on the USPB-development. The duration of the transition to a plane bed has not been calibrated and validated, since no transition data are available.

The third research was formulated as follows:
Can the dune evolution model be used to simulate USPB in a river section?

The dune evolution model can be used to simulate USPB in a river section (Figure 24). It has also been shown that the calibrated model predicts dune heights in the right order of magnitude (NS-value of 0.3) and water depths in a realistic range.

In order to get the predicted transition to USPB under realistic conditions the model has been calibrated upon the threshold of Naqshband et al. (2014b). This calibration alters the step-length-model by shifting this model such that the transition to USPB is delayed as long as needed for the

USPB-index to become below zero. The step-length-model needs to be calibrated for each different location where it is applied, since one step-length-formulation does not reproduce the transition to USPB correctly for different grain sizes. For the IJssel near Kampen where the grain size is 0.25 mm this shift had to be 0.45.

The version of the model of Van Duin (2015) was not calibrated upon observed river dune heights and the model of Shimizu et al. (2009) did not reproduce realistic water depths. So the adapted model created in this study is able to predict the hydrodynamic conditions and dune heights on river scale better than those models.

The last research question was:
Which locations within the Netherlands are capable of developing USPB?

USPB can develop in the middle of the river IJssel near Kampen. This is the only location in the Netherlands that was found to be able to develop USPB, since the next most-probable location (Tienhoven-Lopik) did not develop USPB. USPB started to occur within the model when the unit discharge was above 13.5 m^2/s. It is expected that USPB will be present over a larger width, since the unit discharge will exceed 13.5 m^2/s over a larger area of width when the maximum unit discharge in the middle of the river is 20.2 m^2/s. However, these values are subject to the model uncertainties, so the exact unit discharge at which USPB starts to occur in reality is unknown.

With these answers on the research questions some reflection upon the research objective can be performed. The research objective was set to:

Determine which conditions are necessary for upper stage plane bed to occur within the Netherlands and determine at which locations USPB is most likely to occur.

The IJssel near Kampen is the only location in the Netherlands that can develop USPB, according to the model-analysis performed in this study, in the Netherlands. The dune evolution model of Van Duin (2015) is applied upon a river scale and is shown to be able to predict dune heights (NS-value 0.3) and realistic hydrodynamic conditions. Also the exploratory analysis with the newly developed USPB-index indicated that this location is the most likely to develop USPB. Other locations scored higher on the USPB-index, indicating that USPB is less likely to develop, the model did also show that these locations do not develop USPB.

Since the model-analysis in this study is discussed extensively and several sources of uncertainty have been elaborated in Chapter 6 the occurrence of USPB in the IJssel needs to be investigated further before it will be usable in the design of flood protection measures. These recommendations will be presented in the next paragraph.

7.2 Recommendations

USPB is expected to develop in the river IJssel near Kampen under design conditions. In order to be able to use this expectation and its corresponding decrease in design water level more research is needed.

A large source of uncertainty within this study is the transition to USPB. This transition is calibrated upon observed bed forms, not on the transition itself. To improve the validity of the simulated transition to USPB several follow-up studies are recommended. These suggestions for follow-up studies can also help to validate the duration of the transition to USPB.

The first advised follow-up study would be to apply the USPB-index to low-land rivers worldwide to find locations where USPB is more likely to develop than in the IJssel near Kampen. This can lead to several locations where USPB is expected under conditions which are more likely to occur than the design discharge near Kampen. Field observations at these locations can be performed during periods of high water in order to create a dataset which contains the occurrence of and the transition to USPB in rivers. This dataset can be used to verify the modelled transition to USPB.

A second follow-up to improve on the validity of the transition to USPB will be a more theoretical approach. In equation 19, section 4.3, it is stated that the magnitude of the shift in the step-length-model is dependent on the grain size and the bed slope. Simulations with different slopes and different grain sizes can be used to find the magnitude of the shift in the step-length-model under different conditions. It is expected that this dataset can be used to find an expression for the magnitude of the shift as a function of grain size and bed slope. This relation saves time when analysing other locations with the calibrated model of Van Duin (2015) and can give insights in the behaviour of the step-length-model in conditions where the step length implies suspended transport.

An experimental approach can also be taken in order to improve the validity of the transition to USPB. Flume experiments can be set up with an constantly increasing discharge (like the simulations behind Figure 20). The sandy bed in these flume experiments will eventually change from a dune covered bed to a plane bed. Measuring the flow conditions during this transition (water depth, flow velocity) and knowing the grain size and bed slope will allow to calculate Froude and Suspension numbers during the transition. Having the transition to USPB in a dataset will allow to validate the simulated transition to USPB. Naqshband (2014a) did perform such an experiment, but in this experiment the bed slope was not kept constant and the discharge was not increased linearly. These two inconsistencies in this experiment made this experiment not applicable for the validation of the transition to USPB within the model.

Along with these recommendations on the validation of the transition to USPB. Some recommendations on other parts of the research can be given as well.

The model has been calibrated upon the dune heights provided by Sieben (2004). This dataset only contained dune heights averaged over stretches of the river Waal in 2002/2003. Using data from other rivers and other periods will help to improve the calibration or can be used to validate the dune evolution model on river scale. These data can possibly be extracted from the measurements by the COVADEM-program (Bos-de Koning, 2014). This program equips vessels in the Dutch rivers with depth-measurement equipment and collects all depth measurements. This dataset containing water depths at various location over a longer period can possibly be used to determine dune heights. This new dataset can be used to further improve the calibration and validation of the model.

To increase the value of the results from the model-analysis and the USPB-index-analysis new grain size measurements should be performed. More recent data will reduce the risk of other material being present in reality. The data of 1995 can be outdated at various locations due to dredging or other human activities.

Finally, a follow-up research on the effects of USPB is advisable. It is expected that USPB under design discharge can lead to a design water level reduction of 0.5m (Van Duin, 2015). However, it is unknown along which part of a river cross section USPB has to be present to achieve this effect. In order to analyse this, several simulations can be made at the IJssel near Kampen, each simulation will be performed several meters away from the middle of the river. This will result in the development of USPB for a certain part of the cross-section. Knowing the bed forms along the cross-section can be used to find the water depth associated with the design discharge.

Again, the present grain size is necessary to know for this location. When the dune development at this location is known the bed roughness can be determined. Knowing this bed roughness along the entire width of the river will allow to calculate the water depth corresponding to the design discharge.

All these recommendation can lead to more certainty when predicting USPB. If this certainty is large enough to be deemed acceptable the occurrence of USPB can be incorporated within the water level predictions at several locations. This could lead to a lower design water level near Kampen, which would mean the required dimension of flood protection measures will be lower, resulting in potential savings on flood protection.

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Appendices

Appendix A: Variables along the river branches

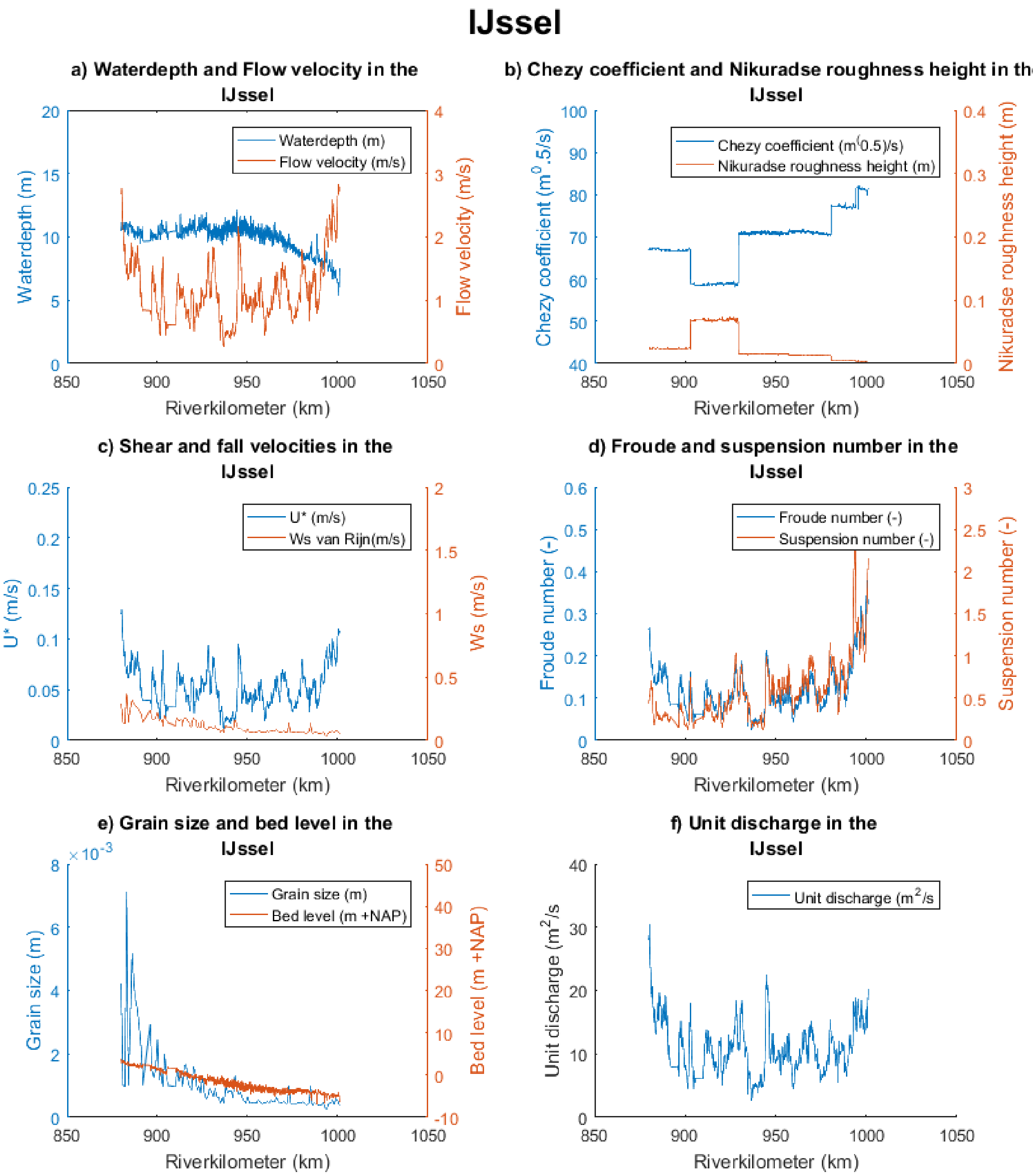

Figure 27 Fluctuation of variables along the IJssel

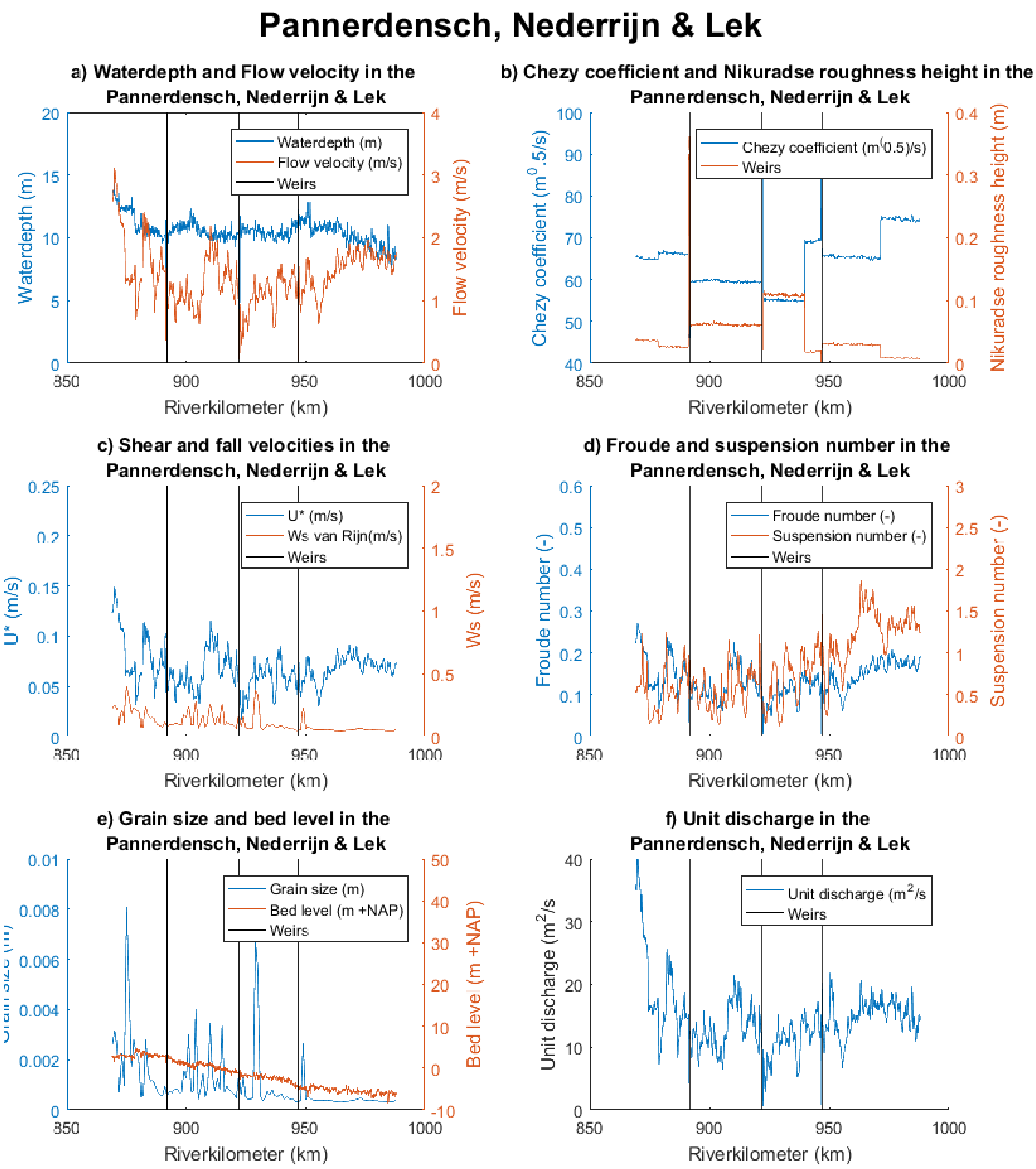

Figure 28 Fluctuation of variables along the Pannerdensch Kanaal, Nederrijn & Lek

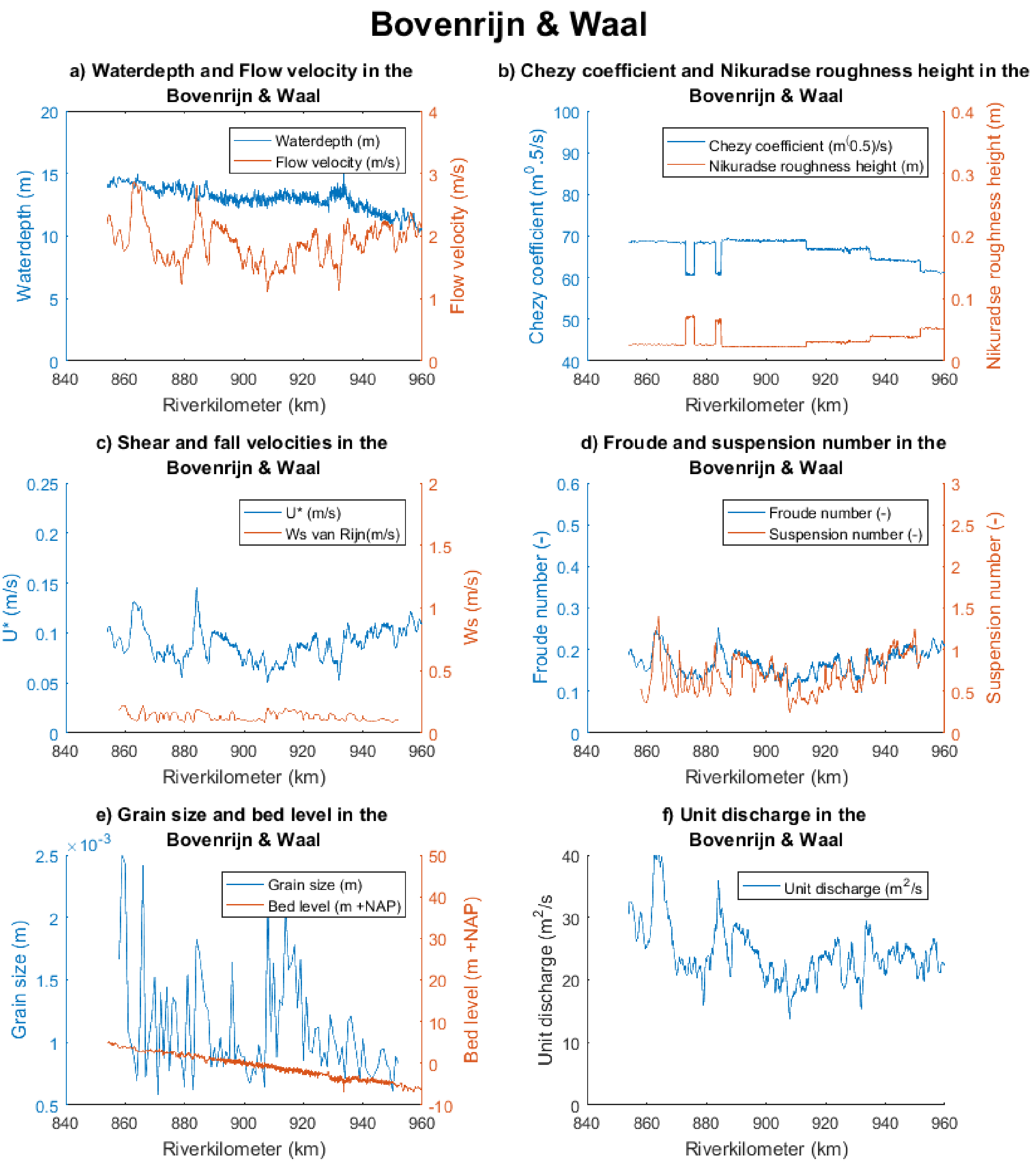

Figure 29 Fluctuation of variables along the Bovenrijn & Waal

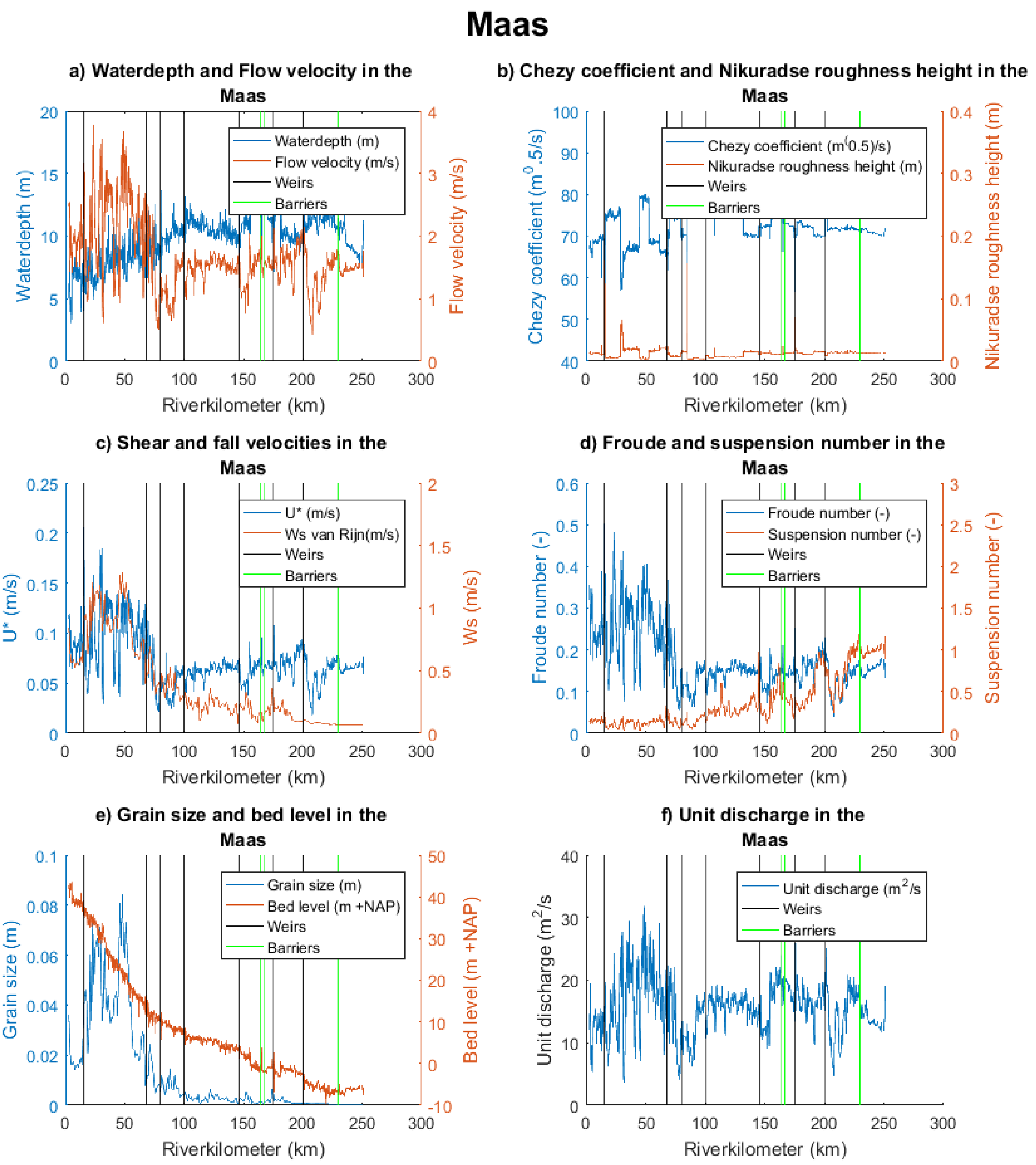

Figure 30 Fluctuation of variables along the Maas

Appendix B: Dune evolution models & model choice

Paarlberg (2009)

Paarlberg et al. (2009) uses hydrostatic two dimensional vertical (2DV) shallow water equations to simulate flow. As a turbulence closure a constant eddy viscosity is used in combination with a partial slip boundary condition. This results in a good representation of the vertical flow structure and the shear stress at the bed (Soulsby, 1990). The partial slip and constant eddy viscosity are determined by flume experiments (Paarlberg et al., 2005). Within this model the flow separation line (Paarlberg et al., 2007) is used. This is a method to describe the zero velocity line on top of the flow separation zone by a third order polynomial, this line can be determined independently of the flow conditions. The determination is done by the dune shape and a fixed angle of the separation streamline at the reattachment point.
The model of Paarlberg et al. (2009) only considers bed load transport, which is determined using the formulae of Meyer-Peter and Müller (1948). Since suspended load and amalgamation are not considered within the model it is not very suitable for analysing USPB.

Expansion by Van Duin (2015)

Van Duin and Hulscher (2014) continued working on the model of Paarlberg (2009). He introduced a step-length-model into the model of Paarlberg (2009). The step-length-model is the pick-up and deposition model by Nakagawa and Tsujimoto (1980). This model uses a probability of a particle being picked-up per unit time. This probability is used to calculate the fraction of sediment that is pick-up at each cell within the domain. Than for each cell it calculates how far downstream the picked up particles will settle down using a distribution function. This distribution model is based upon a mean step length; Van Duin and Hulscher (2014) derived a new model for the mean step length. This model lets the step length increase with increasing flow strength, in line with the experimental results. To account for suspension the step-length-model is also made dependent upon the water depth. This model set up has proven to be capable of predicting USPB. However, when simulating using river conditions the model showed an overestimation of dune height. When extreme river conditions are used the model predicts USPB while measurements indicate USPB is not present. This means the model needs further validation and calibration in order to correctly predict USPB.
Van Duin (2015) stated that despite the expansion of the model the model is still computationally efficient. This is partly driven by the presence of the flow separation line of Paarlberg et al. (2007).

Expansion by Naqshband (2016)

As stated above the model by Paarlberg (2009) is not suitable for assessing USPB, since the essential suspended transport is not included. To counter this Naqshband et al. (2016) improved the model with a sediment relaxation model. Details on this relaxation model can be found in Naqshband et al. (2016). This extended model showed good results when modelling USPB under increasing discharge.

Lefebvre (2014)

The numerical, Delft3D based model of Lefebvre et al. (2014) describes flow by solving the Reynolds-averaged Navier-Stokes equations (RANS). A k-ε turbulence closure, which parameterizes the contribution of eddies, is used. This flow calculation method is inexpensive on computational time in comparison to other descriptions of flow and turbulence. The grid size within the model is dependent on the simulated bed form height; this ensures that in different simulations the same number of grid cells is present in the flow separation zone. Amalgamation and superposition are not included within this model still the model is calibrated and validated with flume and field data. Mean flow, turbulent kinetic energy and water levels are modelled correctly. However, the model of Lefebvre et al. (2014) uses fixed bed forms to focus on the effects in the flow separation zone. Hence, sediment transport is not modelled and this model does not seem suitable for studying bed form evolution.

Nabi et al. (2013)

The model developed by Nabi et al. (2013a) uses the full 3D, unsteady, incompressible Navier-Stokes equations to simulate hydrodynamics. Large eddy simulation is used as a turbulence closure. This means the model is expensive in terms of computational time (Kimura & Hosoda, 2003; Lefebvre et al., 2014). This model is capable of performing well for problems with a relatively large temporal scale, such as alluvial processes (Nabi et al., 2013a). The sediment transport is modelled by the model described in Nabi et al. (2013b). This morphological model uses four sub models: Sediment pickup, transport over the bed (bed load without saltation), transport in the water column (saltation and suspended load) and deposition.
For every single particle an algorithm is used to determine the movement. The first step is determining whether the particle moves (shields criterion), the second step determines whether the particle suspends or not. When is does not suspend the sliding sub-model is used to determine the extent of the motion and the particle is added to the bed at its final location. When the particle does suspend the transport sub-model is used to determine the distance it travels in suspension. Than it particle either deposits or remains in suspension for the next time step in the transport sub-model. If it deposits it can come back in suspension by elastic rebound or it is added to the bed level at its final location.
Since this model considers both bed and suspended transport in great detail it seems suitable for analysing USPB, a downside would be the large computational effort which comes with this model. Another downside is that the merging of smaller and larger bed forms was found to yield irregularities in the evolution of dune length and height. This means that amalgamation is not correctly represented within the model. This was found during the validation of the model by simulating four laboratory experiments which were found to agree with the experimental findings.

Shimizu & Giri (2006-2009)

The three-dimensional model Shimizu et al. (2001) is simplified to a vertical two-dimensional model and enhanced by imposing non-hydrostatic, free surface flow conditions. The hydrodynamic model is completed by a non-linear k-ε turbulence closure. It is found that this non-linear turbulence model gives a better reproduction of reality than the standard k-ε-turbulence model (Kimura & Hosoda, 2003).
This hydrodynamic model is coupled with a sediment model. Bed load transport is included by a stochastic bed load model, which is based upon the work of Nakagawa and Tsujimoto (1980). Since a model which only considers bed load transport is not valid for upper flow regimes Giri and Shimizu (2006) expanded the stochastic bed load model to introduce suspended load as well. This was done by expanding the sediment continuity equation by an upward suspended sediment flux per unit area corrected with the fall velocity times an equilibrium sediment concentration. This means that when there is no equilibrium concentration of sediment in suspension part of the saltating particles will be brought into suspension and vice versa. This model set up was validated with movable bed experiments (Venditti et al., 2005) and own experiments and showed satisfactory results. However the model was not verified for the upper flow regime.
Shimizu et al. (2009) continued with their model and came with an updated version of their model to analyse upper flow regime as well. A kinematic boundary condition is used at the free surface. A no-slip boundary condition is used at the bed. The equations are transformed into a boundary-fitted coordinate system. The suspended transport within this model is not simulated as in the 2006 version, but is simulated by the method proposed by Itakura and Kishi (1980). Simulations of morphodynamics within a flume using this model showed bed form development to USPB and

back to dunes again. This is explained by the process of amalgamation by Shimizu et al. (2009). The computational results of the various simulations made with this model corroborate with previous observations. A downside to the validity of this model would be the assumed relation between the mean step length and the boundary shear stress. This assumption is different to the conventional relation between step length and grain diameter with an empirical constant, but this assumption is made in order make the step length dependent on the flow intensity. Good observations under varying flow are needed to validate this.
So this newer version of the model showed development of USPB and linked it to amalgamation. The development of USPB took place when discharge was rising. However development of USPB is expected to be dependent on the step length of saltating particles (Giri & Shimizu, 2007; Toyama et al., 2007) and this step length needs further validation.
Giri et al. (2014) applied the model to the Dutch river Waal. In this study the step length was described by the formulation proposed by Sklar and Dietrich (2004). This simulation of the Waal river under flood conditions gave satisfactory results given the complexity of the problem.

Nelson (2005)

The numerical model developed by Nelson et al. (2005) uses a nonlinear k-ε closure to compute unsteady flow in a 2DV-model. This is a simplification of the original model which used a numerical integration of the Navier-Stokes in combination with large eddy simulation. Because 3D-simulation is very CPU-time consuming and unnecessary when looking into 2D bed forms the simplification to 2DV with the nonlinear k-ε closure was made.
To model sediment transport Nelson et al. (2005) tested the pick-up and deposition model by Nakagawa and Tsujimoto (1980). After testing Nelson et al. (2005) concluded that the approach of Nakagawa and Tsujimoto (1980) seems appropriate for computing morphodynamic evolution of bed-forms when combined with a suitable flow solution. The sediment transport model of Nakagawa and Tsujimoto (1980) is not expanded with a suspended load expression within this model so it is not modelling suspended transport.
No attention was given to verification with flume or field data and this model does not include amalgamation. So the accuracy of this model is unknown. However, the simplification to 2DV made is a lot faster and the computational time required to run the model was largely reduced.

Martin & Jerolmack (2013)

The model presented in the paper of Martin and Jerolmack (2013) takes a different approach than the five previously described models. Martin and Jerolmack (2013) assume that bed form development is on collision and merger of different bed forms. They build there model with phenomenological models that account for the different processes of bed form growth (merger and pass-through) and decay (based upon dissipation). The model for merger and pass-through is a 1D-numerical-model based upon Fuhrboter (1983) and Raudkivi and Witte (1992). The evolution of trailing and leading dunes is dependent on maximum dune length. When the sum of the trailing and leading length is smaller than the maximum length the dunes will merge, is the sum larger than pass trough will occur. The decay of the bed forms is based upon dissipation and is modelled by a relaxation equation.
The model is validated using data from the Rhine river in the Netherlands and the Calamus River in Nebraska (USA). The results of the validation are promising; however under highly varying unsteady flow the results are not very good.
This model does not look into sediment transport, but into the growth and decay of river dunes through migration and dissipation. This method is computationally efficient, includes amalgamation (merger) but does not seem usable for predicting USPB since suspended and bed load are not modelled.

Comparison between dune evolution models

The six criteria and the descriptions of the various models are used to compare the models (Table 10). The different models are graded as; positive (+), negative (-) or in between (+/-). The scores for bed load, suspended load and amalgamation are based upon the model descriptions. Validation and accuracy is based upon the validation done within the papers accompanying the models. Availability is positive (+) if the model and model code are available, negative (-) when it is not or unknown and in between is given when only the model without the code is available (+/-). Computational time was largely based upon the statements made within the papers accompanying the models, combined with the used turbulence closure. Since using a RSM or a LES turbulence model results in high computational efforts.

Model	1. **Bed load**	**2. Suspended load**	**3. Validation & Accuracy**	**4. Availability**	**5. Computational time**	**6. Amalgamation**
Van Duin (2016)	+	+	+/-	+	+*	-
Lefebvre (2014)	-	-	+	-	+	-
Nabi (2013)	+	+	+	-	-	+/-
Shimizu & Giri (2009)	+	+	-	+/-	-*	+
Nelson (2005)	+	-	-	-	+	-
Martin & Jerolmack (2013)	-	-	+/-	-	+	+

Table 10 Comparison of dune evolution models *these computational time scores are based upon preliminary tests with the models.

Table 10 shows that the models by van Duin (2015) and Shimizu et al. (2009) are the best options for this study. Exploratory tests with both models resulted in the choice for the model of van Van Duin (2015). This choice is based upon multiple pros and cons Table 11. These pros and cons led to the choice to use the model of Van Duin (2015), this is mainly based upon the access to the model code and the computational time.

	Pros	**Cons**
Shimizu et al. (2009)	- Accurate for flume studies - Applied on Chiyoda channel and Waal - Amalgamation included	- Large scale application with suspended sediment did not show satisfactory results - Computational time on large scale experiments - No access to model code
Van Duin (2015)	- Corresponds with Shimizu et al. (2009) - Showed realistic results on river scale - Lower computational time - Access to model code	- Suspended load only implicitly included - No amalgamation

Table 11 Pros and cons for the models of Shimizu et al. (2009) and Van Duin (2015)

Appendix C: Sensitivity of the equilibrium dune height

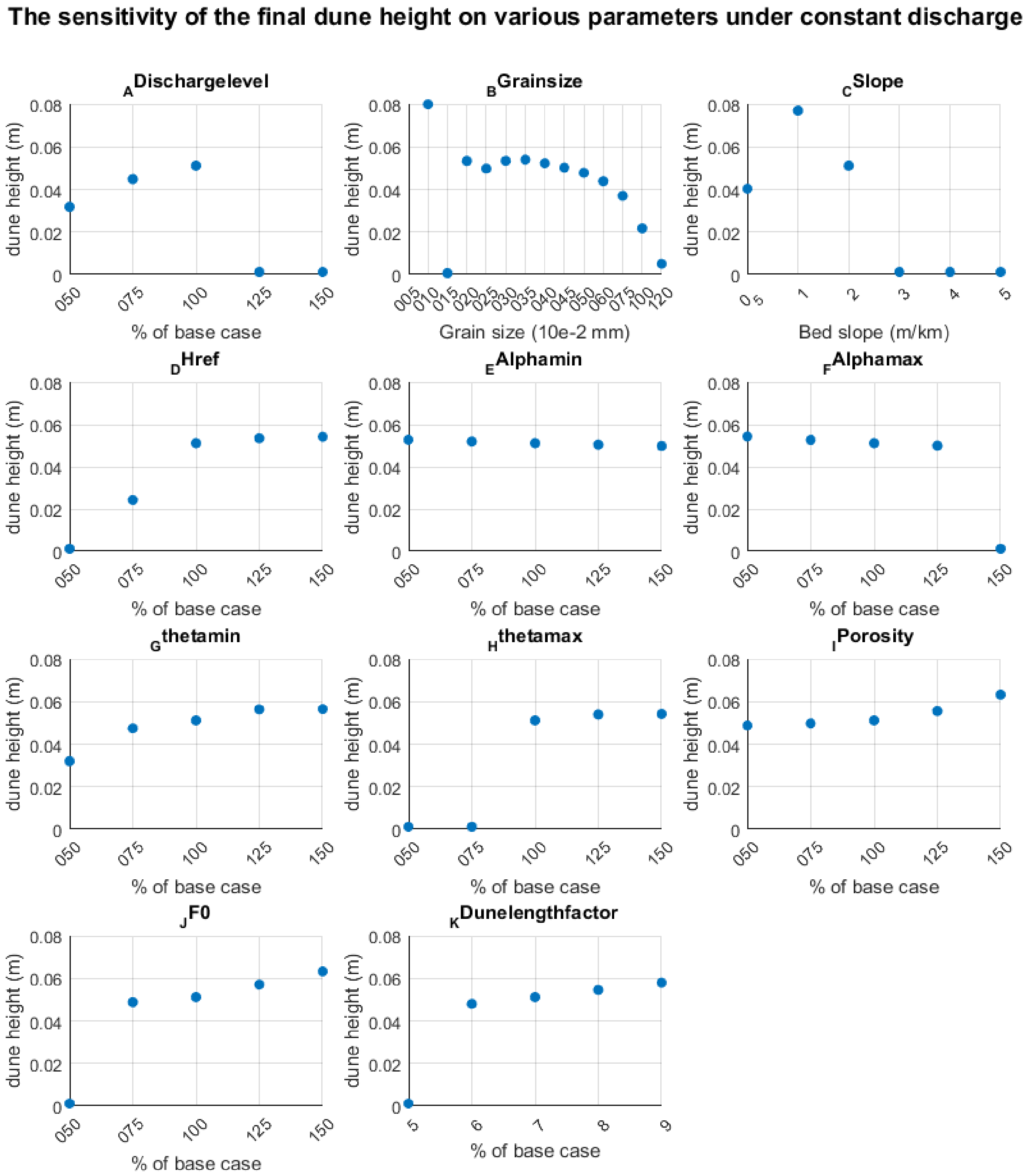

Figure 31 Sensitivity of the equilibrium dune height on various parameters under constant discharge

Appendix D: Flume experiments used for calibration

Scenario	b(m)	h(m)	U(m/s)	u* (m/s)	i (-)	q (m^2/s)	D50 (mm)	θ_{cr}	H_{obs}
C1F	0.44	0.145	0.728	0.0733	1.23E-01	0.0638	0.74	0.03	0.0286
C1M	0.44	0.135	0.492	0.0488	5.61E-02	0.0594	0.74	0.03	0.0247
C1S	0.44	0.1	0.432	0.0252	4.32E-02	0.044	0.74	0.03	0.0165
C2Fa	1.5	0.17	0.806	0.0725	4.41E-02	0.255	0.74	0.03	0.0425
C2Fb	1.5	0.1	0.752	0.0641	3.84E-02	0.15	0.74	0.03	0.0302
C2Ma	1.5	0.17	0.686	0.059	3.20E-02	0.255	0.74	0.03	0.0398
C2Mb	1.5	0.1	0.594	0.0522	2.40E-02	0.15	0.74	0.03	0.0409
C2Sa	1.5	0.17	0.465	0.0373	1.47E-02	0.255	0.74	0.03	0.0361
C2Sb	1.5	0.1	0.475	0.0373	1.53E-02	0.15	0.74	0.03	0.037
FF	0.44	0.125	0.504	0.0657	5.88E-02	0.055	0.23	0.045	0.0097
FM	0.44	0.1	0.346	0.0497	2.77E-02	0.044	0.23	0.045	0.012
FS	0.44	0.095	0.264	0.038	1.61E-02	0.0418	0.23	0.045	0.0113
MF	0.44	0.12	0.596	0.0607	8.23E-02	0.0528	0.44	0.031	0.0228
MM	0.44	0.11	0.457	0.0457	4.84E-02	0.0484	0.44	0.031	0.0239
MS	0.44	0.085	0.38	0.0296	3.35E-02	0.0374	0.44	0.031	0.0176
EXP1	0.5	0.25	0.8	-	1	0.16	0.29	0.0391	0.082
EXP2	0.5	0.25	1.28	-	2.2	0.2	0.29	0.0391	0.072

Table 12 Characteristics of the flume experiments used for the first calibration, the first fifteen experiments are from Coleman et al. (2005) and the last two from Naqshband et al. (2014c)

Appendix E: Dune height evolution

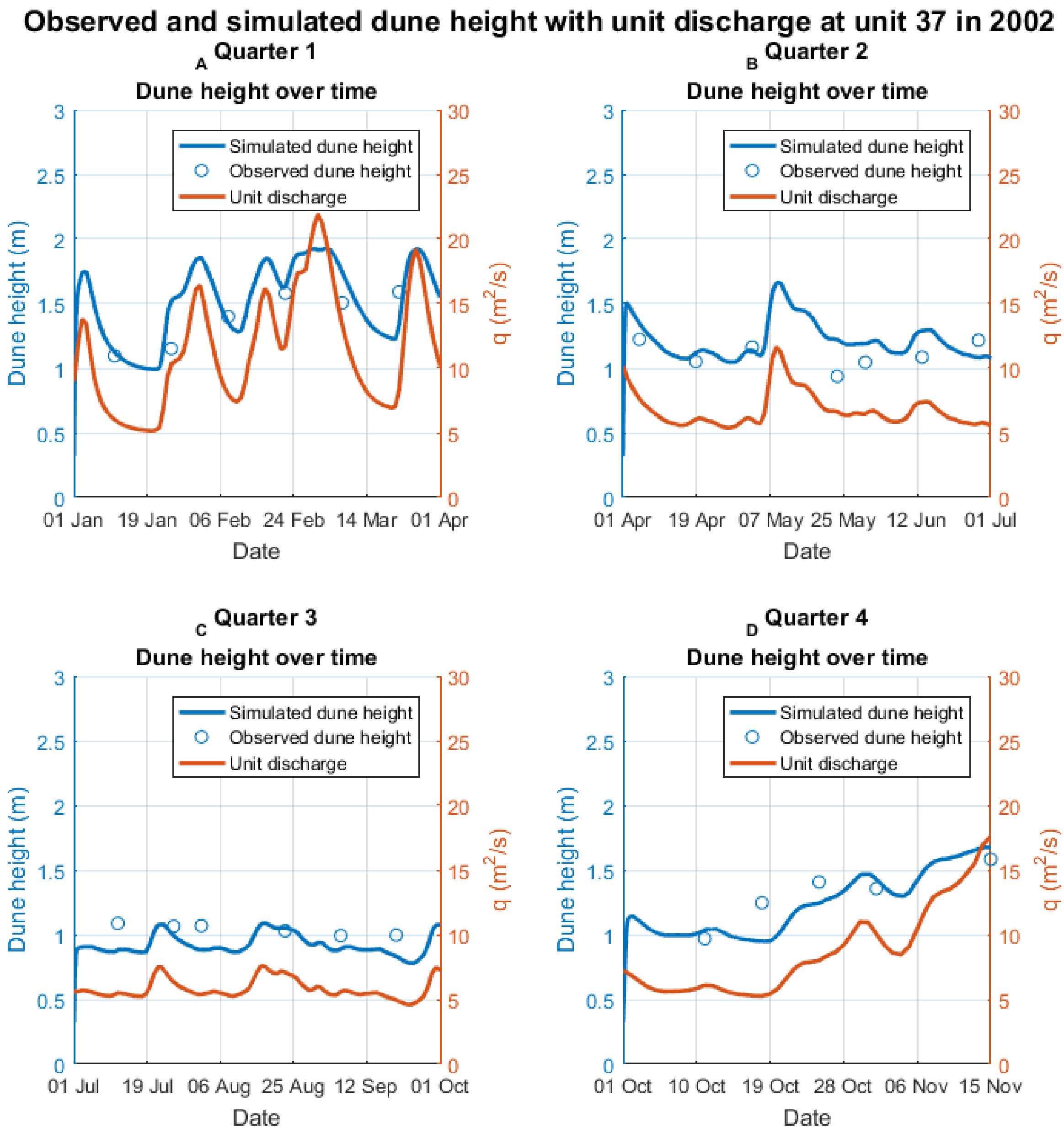

Figure 32 Dune height evolution near Beneden-Leeuwen with the initial step-length-model in 2002

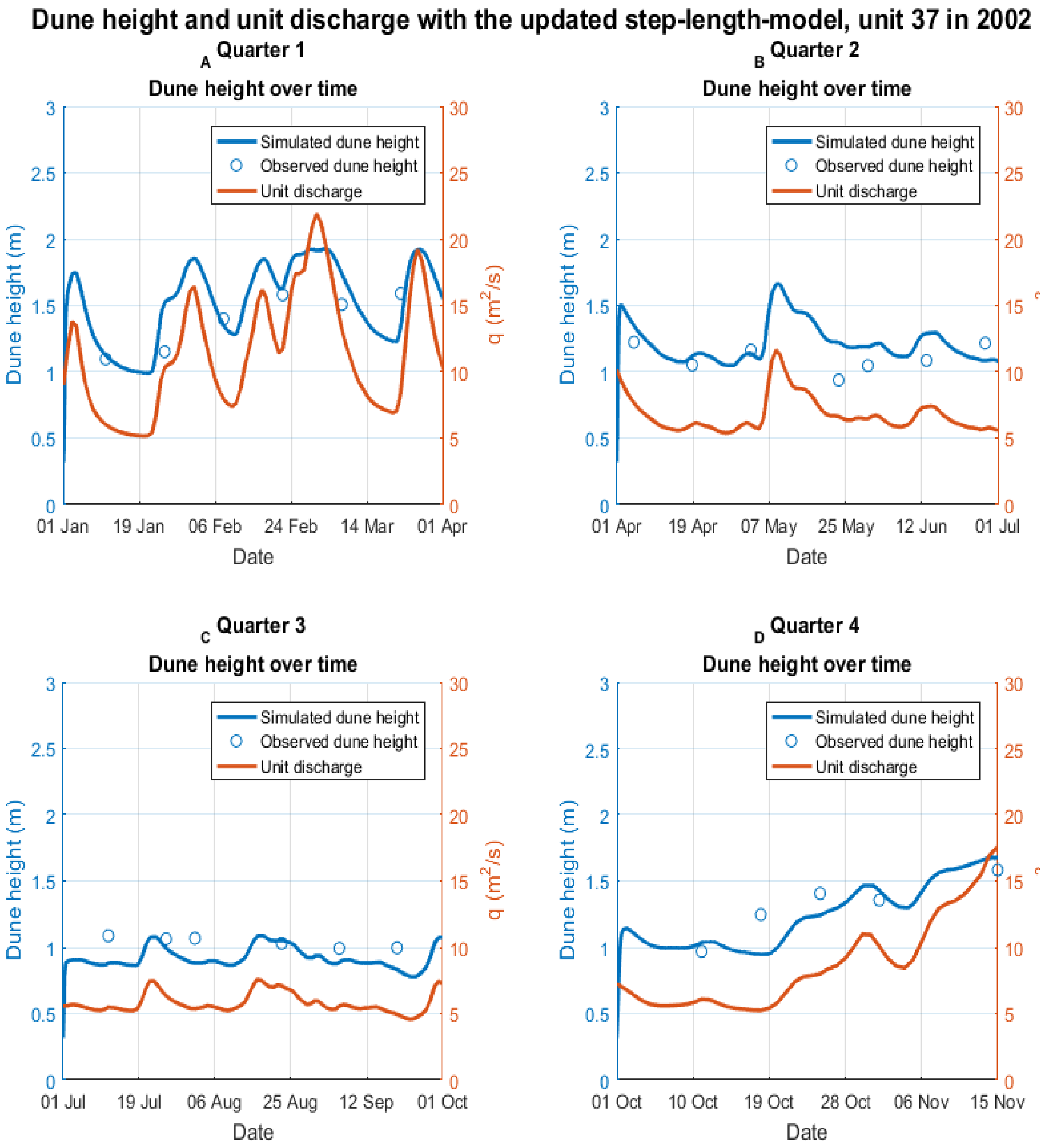

Figure 33 Dune height evolution near Beneden-Leeuwen with the updated step-length-model in 2002

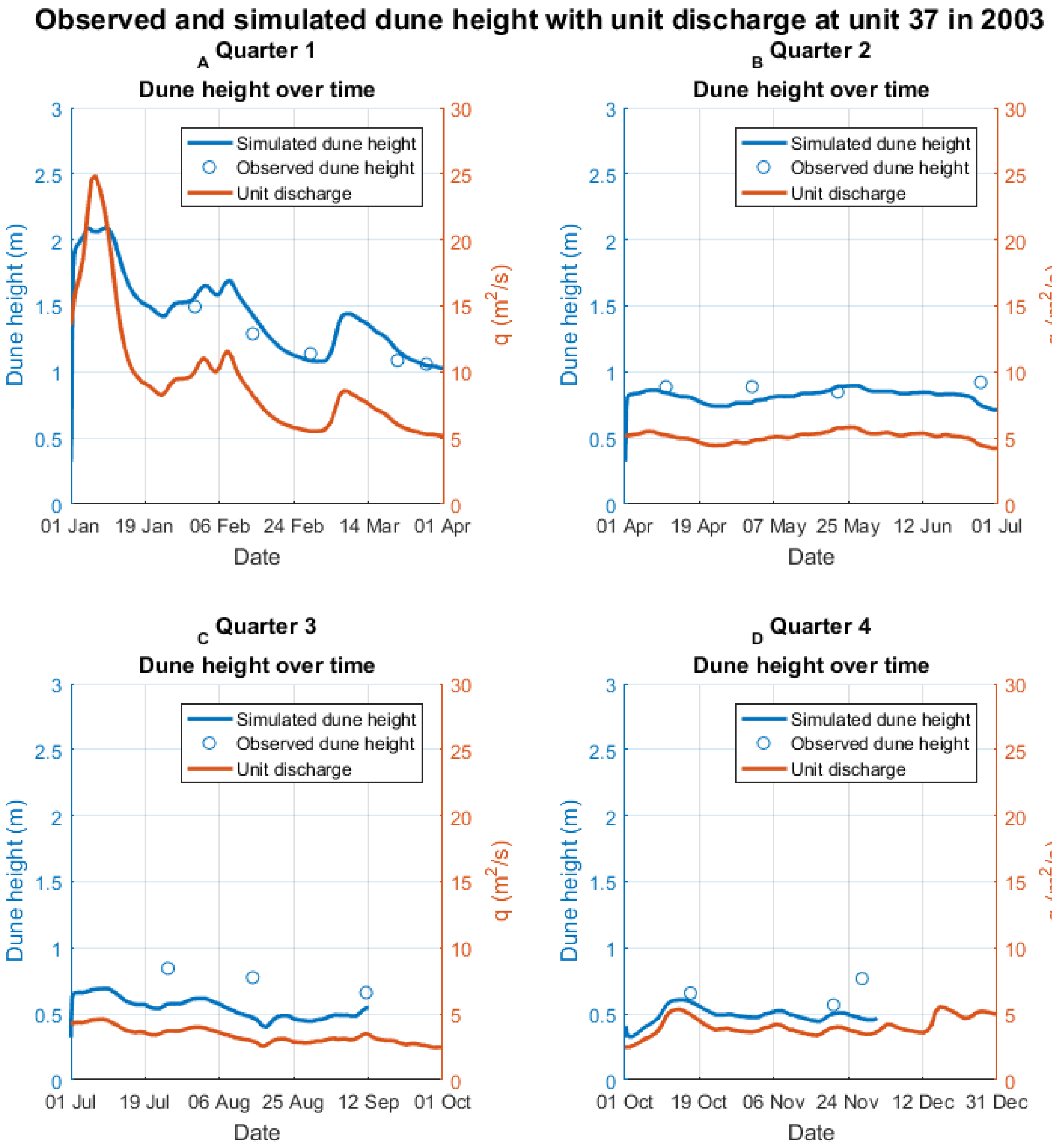

Figure 34 Dune height evolution near Beneden-Leeuwen with the initial step-length-model in 2003

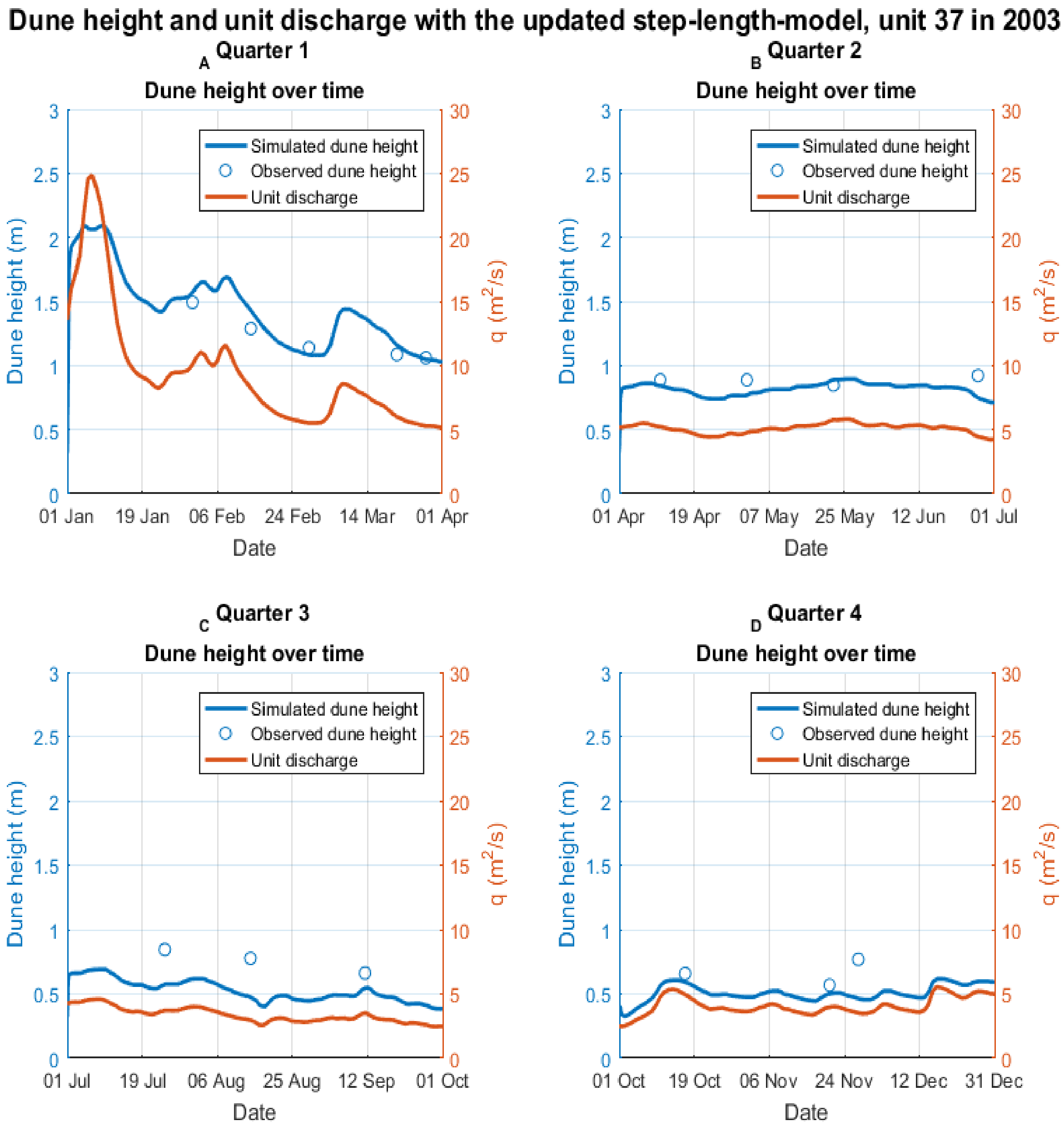

Figure 35 Dune height evolution near Beneden-Leeuwen with the updated step-length-model in 2003

Appendix F: USPB-transition for different grain sizes

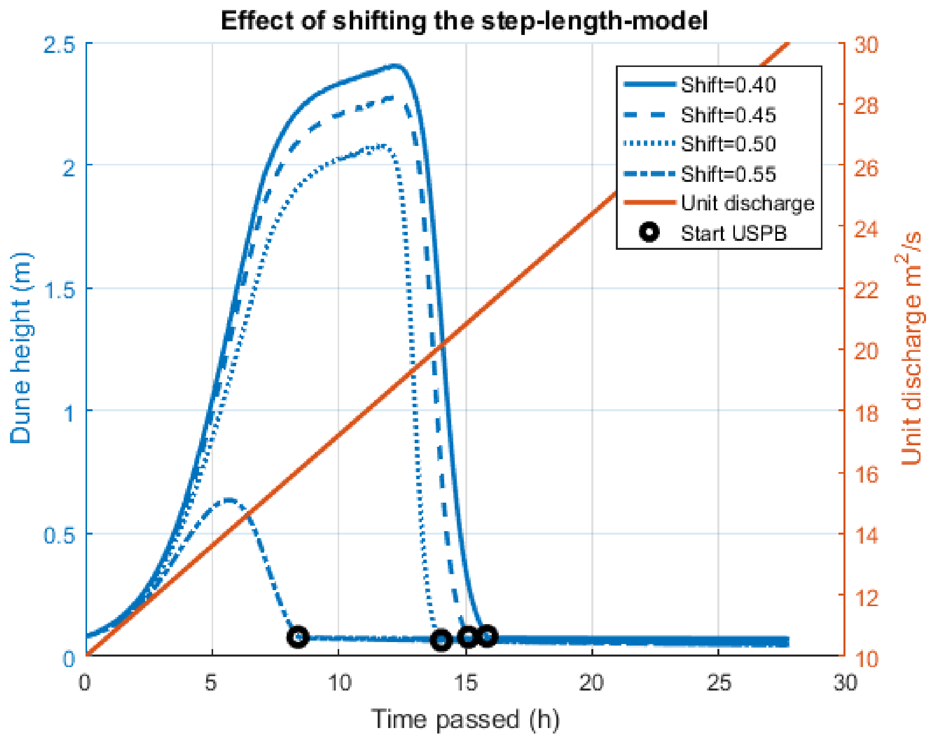

Figure 36 Effects of shifting the step-length-model with a grain size of 0.40 mm

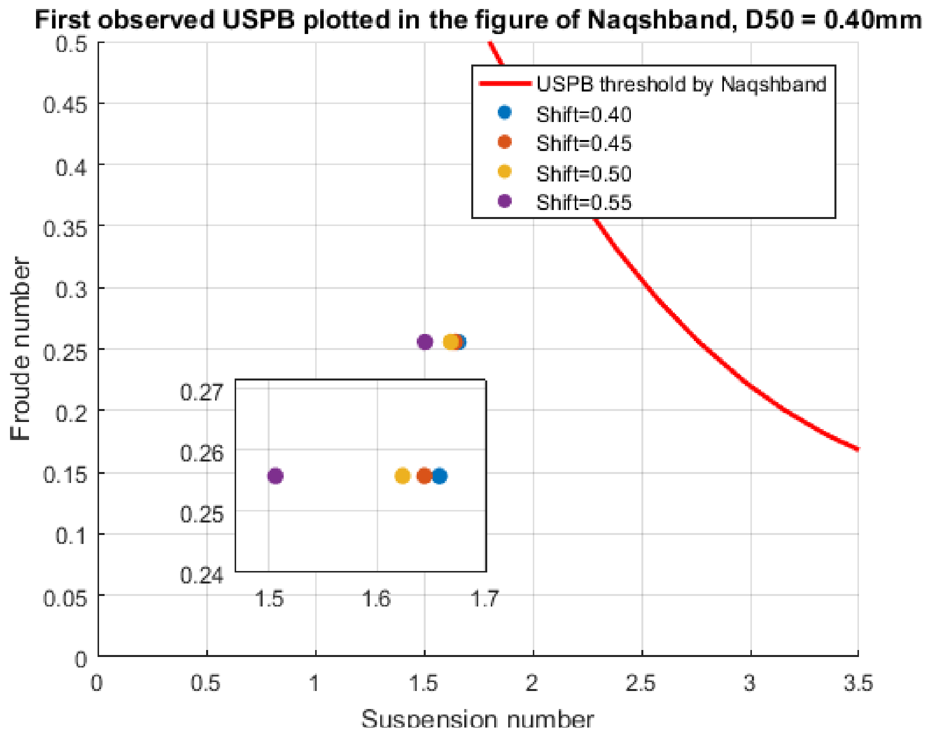

Figure 37 Results of shifting the step-length-model with a grain size of 0.40 mm

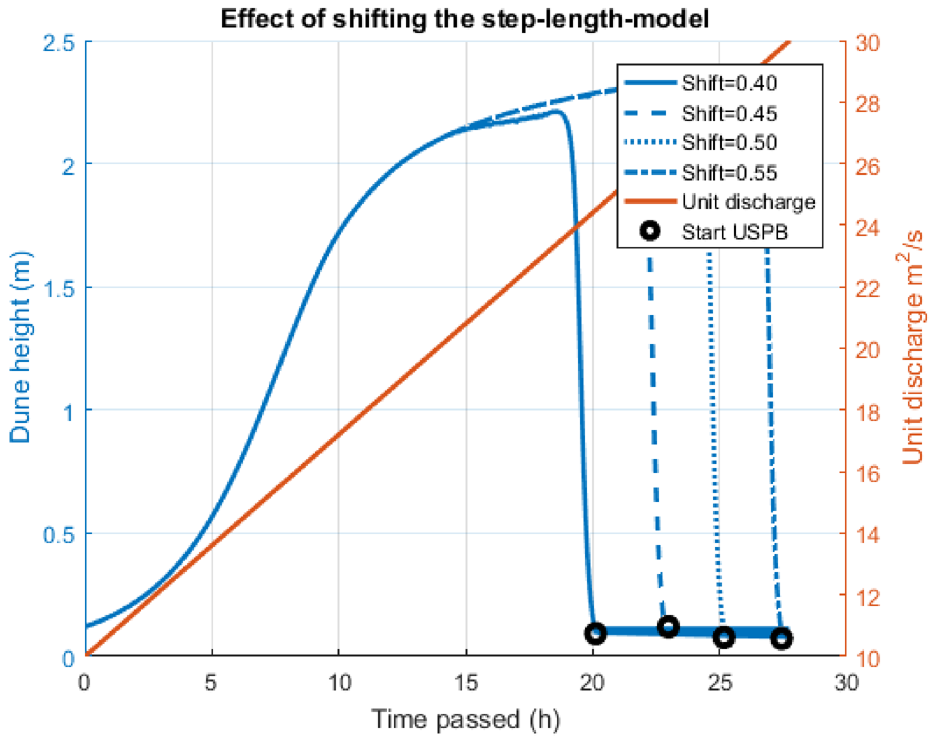

Figure 38 Effects of shifting the step-length-model with a grain size of 0.60 mm

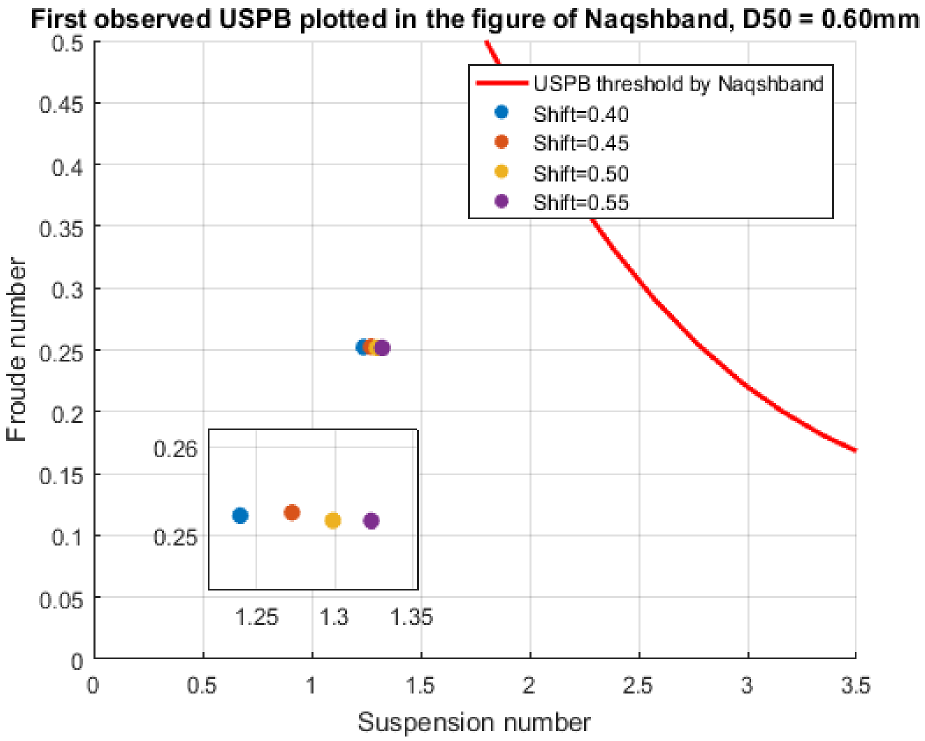

Figure 39 Results of shifting the step-length-model with a grain size of 0.60 mm