MSc thesis in Civil Engineering and Management

RIVER DUNE PREDICTIONS

COMPARISON BETWEEN A PARAMETERIZED DUNE MODEL AND A CELLULAR AUTOMATON DUNE MODEL

Joost Seuren

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HR Wallingford
Working with water

ABSTRACT

River dunes are of great importance for the determination of water levels, especially during flood events. They have a large influence on the hydraulic roughness and thereby on water levels. In addition, dune formation could affect the navigability of rivers and propagation of dunes could uncover pipelines or other constructions beneath the river bed. Because fast calculations are essential during an upcoming flood event, there is a need for fast model predictions. The focus of this research is on a parameterized dune model and the cellular automaton dune model (CA model) HR Wallingford is experimenting with. Both models are relatively fast in their calculations but have a fundamentally different approach to predict river dunes. This research reveals the performance of these two models tested under various conditions. The main objective of this research is:

> *"To compare the performance of the cellular automaton dune model and the parameterized dune model for the prediction of dune dimensions, migration rates and sediment transport in equilibrium state, under flume conditions, similar to low-land river situations like the River Rhine (the Netherlands)."*

The first step in this research was the preparation of the CA model for comparison with the parameterized dune model. A sensitivity analysis provided insight in the behaviour of the input parameters used to adjust the model: A length scale was added by assuming a fixed domain and defining the model parameters in a unit of distance instead of a number of cells. Sediment transport was determined by counting all moving slabs and used to implement a time scale. Finally, the input parameters of the model were linked to the flow characteristics. After these adjustments, the model was calibrated using the same data as used for the calibration of the parameterized dune model.

The second step was the comparison of the parameterized dune model and the CA model using a data set containing sixteen experiments. Research has shown that the parameterized dune model is reliable for prediction of dune dimensions, although it seems limited to experiments with a slope between $11*10^{-4}$ and $22*10^{-4}$. The parameterized dune model overestimates migration with approximately a factor of three. The CA model is tested for the first time in the way as presented in this thesis, by adding time and length scales to the model. Results seem promising and show predictions that are reasonable for five experiments; however in general the predictions are slightly underestimated. The CA model underestimates the migration with approximately a factor of three.

In this research a non-dimensional CA model is made dimensional. The model has potential and recommended improvements are: a) linking the shear velocity to flow characteristics and b) adding an equilibrium state.

Preface

This thesis is a representation of the research I focused on for the last six months. It is the last step in finishing my master Civil Engineering and Management at the University of Twente. When I started this research I thought the focus was on the comparison of two river dune prediction models. Soon after the start I encountered a bigger challenge; model adjustments were necessary before I could start the actual comparison. I conducted my research at HR Wallingford in the United Kingdom.

First, I would like to thank Michiel for his hospitality during my first two weeks in Wallingford. More importantly, I am grateful for his guidance during my search for answers. He helped me think about ways to adjust the cellular automaton dune model and was always available when I struggled with adjusting the model code. Jord, thank you for your valuable feedback regarding my research approach and writing. I appreciated the Skype conversations we had; you gave me new insights and useful advice. Olav, you were always available for questions about model related problems, thank you for your input and the quick replies on my e-mails. Suzanne, I appreciate your critical questions and your broad perspective, it kept me focused.

In addition, I would like to thank Suleyman for providing his data set, which was very useful for the selection of suitable data sets. I would also like to thank Rolien van der Mark who sent me the code of the bedform tracking tool, which I used to determine the dune dimensions predicted by the cellular automaton dune model.

Last but not least, I would like to thank my friends and family, with special thanks to my parents Martin and Emmy for their unconditional support during my years in Enschede and my girlfriend Marlyn for her endless support, you are my buddy!

Joost Seuren

Enschede, March 2014

CONTENTS

List of symbols

C	Chézy coefficient	[$m^{1/2}$ s^{-1}]
C90	Chézy coefficient related to D90	[$m^{1/2}$ s^{-1}]
c1	Linear shear velocity coefficient	[-]
c2	Non-linear shear velocity coefficient	[-]
C_L	Constant (0.25)	[-]
D	Grain size of the sediment	[m]
D50	Median grain size	[m]
D90	Grain size for which 90% of the sediment is smaller	[m]
dx	Length of a single cell in x-direction	[m]
dy	Length of a single cell in y-direction	[m]
dz	Length of a single cell in z-direction	[m]
Fr	Froude number	[-]
g	Acceleration due to gravity	[m s^{-2}]
h	Average water depth	[m]
H	Dune height	[m]
H_b	Brink point height	[m]
H0	Initial water depth	[m]
i	Bed slope	[-]
L	Dune length	[m]
Lo	Step length in number of cells	[-]
Lo'	Step length	[m]
Lx	Length of the domain in x-direction	[m]
Ly	Length of the domain in y-direction	[m]
Lz	Length of the domain in z-direction	[m]
L_{st}	Flow separation zone length	[m]
L'_{st}	Non-dimensional flow separation zone length	[-]
M	Migration rate	[m h^{-1}]
nx	Number of cells in x-direction	[-]
ny	Number of cells in y-direction	[-]
nz	Number of cells in z-direction	[-]
pros	Grain size distribution	[-]
P	Pickup probability	[-]
P_d	Deposition probability	[-]
q	Discharge per meter width	[m^2 s^{-1}]
q_s	Sediment transport per unit width	[m^2 s^{-1}]
Rep	Angle of repose of the sediment (cellular automaton dune model)	[-]
sAng	Shadow angle in number of cells	[-]
sDist	Shadow distance in number of cells	[-]

sDist'	Shadow distance	[m]
slotp	Slot parameter	[-]
SD	Shadow distance	[m]
Slot	Number of slots	[-]
Slt	Total step length of all moved slabs in number of cells	[-]
ST	Sediment transported per unit width	[m^2]
u_*	Shear velocity	[$m\ s^{-1}$]
u_{*c}	Critical shear velocity	[$m\ s^{-1}$]
vol	Volume of a single cell	[m^3]
v_s	Settling velocity of the sediment	[$m\ s^{-1}$]
x_{len}	Number of cells in x-direction	[-]
y_{len}	Number of cells in y-direction	[-]
z_{len}	Number of cells in z-direction	[-]

α_2	Constant ($3.0*10^3$)	[-]
Δ	$(\rho_s - \rho_w) / \rho_w$	[-]
ε_p	Sediment porosity	[-]
θ	Shields parameter	[-]
θ_{cr}	Critical shields parameter	[-]
θ_{repose}	Angle of repose of the sediment (parameterized dune model)	[°]
λ	Dimensionless step length	[-]
Λ	Step length	[m]
ρ_s	Density of sediment	[$kg\ m^{-3}$]
ρ_w	Density of water	[$kg\ m^{-3}$]
φ	Angle of repose of the sediment	[°]
Φ	Non-dimensional transport parameter	[-]
Ψ	Non-dimensional flow parameter	[-]

CHAPTER 1

INTRODUCTION

River dunes are of great importance for the determination of water levels, especially during flood events. They have a large influence on the hydraulic roughness and thereby on water levels, due to their asymmetrical shape. Dune formation could affect the navigability of rivers and propagation of dunes could uncover pipelines or other constructions beneath the river bed. A better understanding and modelling of the evolution of these river dunes could be helpful for many water management purposes.

This chapter introduces the process that causes the development of river dunes and their influence on the river bed and flow. State of the art approaches in dune modelling are discussed in the context of these typical bedforms and compared with the two models used for this research. The objective of this research and related research questions are presented and the outline of this thesis is given.

1.1 DEVELOPMENT OF RIVER DUNES AND THEIR INFLUENCE

Rivers with a mild slope, most common in the lower part of a river basin, mainly have a sandy river bed that is continuously changing. In case water flows over a bed of erodible material like sand, regular patterns of sand waves form (Coleman and Melville, 1994). Sediment particles are being picked up and deposited elsewhere due to changes in flow velocity. A particle is set in motion when the shear stress exceeds a critical level. The shear stress is a result of the difference in flow velocity just below a particle and just above it that leads to a lifting force. When this lifting force is larger than the gravitational force, the particle is picked up and set in motion. This process is called sediment transport. The sediment transport often causes development of bedforms, regular undulations of the river bed. However, bedform evolution remains dynamic even in a case with a steady uniform flow (Jerolmack and Mohrig, 2005). The formation and evolution of bedforms is an important phenomenon that affects the hydraulic roughness of the river bed due to the turbulent flow and resistance created by their shapes (Best, 2005).

River dunes are a specific type of bed forms with a typical shape. The flow in rivers is unidirectional, resulting in an asymmetrical dune with a stoss and lee side as depicted in figure 1. Bed features, like river dunes, created by unidirectional flow in alluvial channels are seen to propagate downstream at speeds related to their heights (Raudviki and Witte, 1990). Sediment is eroded on the stoss side and deposited on the lee side of the dune, this process results in the downstream movement. Dune movement could uncover structures such as pipelines beneath the river bed. The downstream propagation of river dunes is reflected in the migration rate, this is the speed of the migrating dune. Dimensions of river dunes vary in time under changing conditions like water depth and flow velocity. This could affect the navigability of the river. River dunes, as classified by Simons and Richardson (1966), are the most common bed forms in lowland rivers with a sandy bed like the Lower-Rhine (Netherlands). In this type of rivers, flow velocity and grain size are most suitable to develop this typical bed form.

The typical asymmetric form of river dunes is important for the determination of hydraulic roughness of the river bed. Asymmetric dunes generated in a steady, uniform and unidirectional flow induce implications to the flow. Flow resistance, bed shear stress and sediment transport are affected by the shape of these dunes. Turbulence over such dunes is dominated by the flow separation zone and very important for dune formation (Best, 2005). Flow close to the bed follows the bed profile. However, when river dunes have an asymmetric form with steep lee sides, the flow will separate from this profile at the dune crest because the longitudinal flow velocity is larger than the vertical velocity caused by gravitational force. The flow separation results in rotational flow behind the dune crest with variations in the pressure gradient, as presented in figure 1. The rotational flow causes energy loss, a turbulent flow regime and a reverse flow near the bed that result in a zero net discharge through a vertical cross section between the bed and the separation zone (Paarlberg et al., 2007). This leads to a sudden increase in the hydraulic roughness and therefore to an increase of the water level.

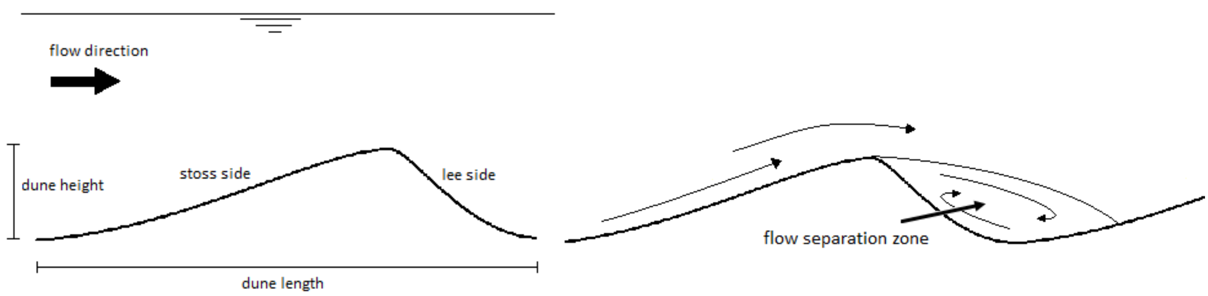


FIGURE 1: TYPICAL SHAPE OF A RIVER DUNE (LEFT), PRINCIPLE OF FLOW SEAPARATION (RIGHT)

The influence of river dunes on the river bed and flow is why many have tried and are still trying to model dimensions and propagation of dune models under various circumstances. Understanding the processes that induce dune formation and evolution is key when modelling river dunes. The question is which processes should be included and which should not be included. Assumptions have to be made because models are a simplification of reality and cannot capture all processes.

1.2 STATE OF THE ART APPROACHES IN DUNE MODELLING

There is a variety of approaches to capture the evolution of river dunes. In the early days of analysing dune evolution, equilibrium dune height predictors were used to estimate the dune dimensions (e.g. Yalin, 1964; Van Rijn, 1984). These dune height predictors are convenient for fast calculations of dune dimensions with almost no computational time; however results are limited to equilibrium state. To analyse whether dunes will form and what dimensions they would have in equilibrium state, linear stability analysis techniques were applied (e.g. Kennedy, 1963; Engelund, 1970; Richards, 1980). These models predict the initiation of dunes from a flat bed situation for certain flow conditions. To study the evolution of these dunes, nonlinear feedback mechanisms between flow and bed form amplitude were included (e.g. Ji and Mendoza, 1997; Zhou and Mendoza, 2005). These stability analysis techniques are also applicable in situations that are not in equilibrium. As a result of the improved calculation capacity of computers over the years, numerical codes to simulate dune evolution by solving linked systems of flow, sediment transport and bed morphology were introduced (e.g. Tjerry and Fredsøe, 2005; Giri and Shimizu, 2006). These models enable the prediction of time evolution of dune dimensions, dune shapes and dune migration in a two-dimensional way. Recently Nabi et al. (2013) presented a three-dimensional numerical model to simulate morphodynamics in a detailed way. The model provides insight into the physical transport phenomena. Disadvantage of the complex systems mentioned here, is that they are computationally intensive. River bed forms in the field show large dissimilarities over both space and time. Capturing these complex bottom features is still a challenge to researchers and modellers.

Because fast calculations are essential during an upcoming flood event, there is a need for fast model predictions with reliable outcomes. These requirements are not fulfilled by the models that are mentioned before. Their output is limited (e.g. Yalin, 1964; Van Rijn, 1984; Kennedy, 1963; Engelund, 1970; Richards, 1980, Ji and Mendoza, 1997; Zhou and Mendoza, 2005) or models are computationally intensive (e.g. Tjerry and Fredsøe, 2005; Giri and Shimizu, 2006; Nabi et al., 2013). Therefore the focus of this research is on the following two models: the cellular automaton dune model HR Wallingford is experimenting with (Knaapen et al., 2013) and the parameterized dune model of Paarlberg et al. (2009). Both models are relatively fast in their calculations and have a fundamentally different approach to predict river dunes.

Paarlberg et al. (2009) developed a process-based simulation model for river dune evolution that has limited computational effort and therefore is useful for operational water management. They extended the model of Németh et al. (2006) with a parameterization of flow separation (Paarlberg et al. 2007) to enable simulation of finite amplitude river dune evolution. The model is based on hydrostatic flow equations and predicts dune evolution in a two dimensional vertical plane.

HR Wallingford is experimenting with a so called cellular automaton dune model (CA model) to predict dune evolution. CA models are relatively unknown in the world of hydrodynamics, morphology and modelling river dunes. Fonstad (2006) described cellular automata as a class of numerical models based on a discrete space-time grid, each particle in the model is restricted to this grid. Interactions between cells are deterministic, probabilistic or rule based. CA models have been applied for modelling succession on aeolian sand dunes (Baas and Nield, 2010). Murray and Paola (1994) used cellular automata to model river braiding and Werner and Fink (1993) used a cellular automaton type of model to simulate beach cusps as self-organized patterns. Coco and Murray (2007) showed that cellular automata have been used for the simulation of different nearshore patterns. It is further shown that cellular automata are capable of capturing complex patterns of sand waves, ripple and dune formation (Bishop et al., 2002, Nield and Baas, 2008).

The basic CA model HR Wallingford is working on is based on the work of Bishop et al. (2002). The model is based on a three dimensional spatial grid, interactions between cells are based on stochastic rules. This innovative way of modelling is often more simple to initialize, understand and operate in comparison to mathematical deterministic models (Knaapen et al., 2013). In this way, model calculations are relatively short. Therefore this model could also be useful for operational water management. However, length and time scales were not present in the results because output was only presented in number of cells and interactions between cells were based on probabilities. Therefore conclusions on the performance of the model according to dune dimensions, migration rates and time to equilibrium could not be made.

The question for both models remains how accurate they are and what their predictive value is.

1.3 RESEARCH OBJECTIVES

The parameterized dune model and the CA model are two models with relatively fast calculations that could be useful for operational water management purposes such as water level predictions during an upcoming flood event. In this research both models are tested under various conditions to assess their performance and provide insight in their strengths and weaknesses. The main objective of this research is:

> *To compare the performance of the cellular automaton dune model and the parameterized dune model for the prediction of dune dimensions, migration rates and sediment transport in equilibrium state, under flume conditions, similar to low-land river situations like the River Rhine (the Netherlands).*

Because the CA model of HR Wallingford is missing essential length and time scales, adjustments are necessary before the model can be compared to data. The model should also be calibrated before the models can be compared. Consequently the following research questions are formulated to serve as a guideline for this research:

1. Which processes are modelled by the parameterized dune model and the cellular automaton dune model and which input data are necessary to calibrate and validate these models?
2. How to add length and time scales to the cellular automaton dune model and how to relate the input parameters of the model to the data?
3. How well do both models perform compared to flume data?
4. What are the strengths and weaknesses of the parameterized dune model and the cellular automaton dune model?

1.4 THESIS OUTLINE

Chapter 2 presents descriptions of the parameterized dune model and CA model, an outline of the modelled processes and necessary input data are presented. With these results, suitable data for the comparison between the models are selected (RQ 1). In chapter 3 the research methodology for the adjustments of the CA model and comparison of the model performances is described. The adjustments of the CA model are discussed in chapter 4. Methods used to add length and time scales to the CA model and the adjustments required to relate the input parameters with the data (RQ. 2) are presented. The chapter ends with the calibration phase, results are discussed. Chapter 5 describes the actual validation phase and the comparison of both models. Prediction results are presented (RQ3), and strengths and weaknesses of both models are discussed (RQ4). The performance of the models, possible improvements, research methodology and limitations and opportunities are discussed in chapter 6. Finally, chapter 7 presents the main conclusions of this research and recommendations for further research.

CHAPTER 2

MODEL DESCRIPTIONS AND EXPERIMENTAL DATA

This research starts with a description of the models to gain insight in the modelled processes and input parameters necessary to run these models. The parameterized dune model is analysed using the publications of Paarlberg et al. (2007 and 2009) and by running the model to discover the involved processes. The CA model is analysed by investigating the script and understanding the steps that lead to the output of the model. The publication of Knaapen et al. (2013) supports the understanding of the model and processes involved. Besides, an overview of the experimental data used for the comparison of the model performances is presented. This chapter provides an answer on research question 1.

2.1 THE PARAMETERIZED DUNE MODEL

The parameterized dune model used by Paarlberg et al. (2009) is based on the process-based morphodynamic model of Németh et al. (2006). This model is capable to simulate the evolution of dunes under unidirectional flows. Hydrostatic flow equations are the fundamentals of the used flow model, therefore separated flows cannot be analysed. However, Paarlberg et al. (2009) extended the model with a parameterization of flow separation. This parameterization is used to efficiently predict dune dimensions over the timescale of a flood wave instead of using complex hydrodynamic equations. Turbulence over dunes with a lee side angle of repose is dominated by the influence of the flow separation zone (Best, 2005 and references herein). The inclusion of flow separation is essential; without flow separation dunes saturate at an early stage of evolution, resulting in an incorrect dune shape without a slip face and an underestimation of dune height and time to equilibrium (Paarlberg et al., 2007).

The general setup of the parameterized dune model is depicted in figure 2. The model exists of a basic morphodynamic cycle (left side) and an extension for the parameterization of flow separation (right side). The basic cycle contains three modules, a flow module, a sediment transport module and a bed evolution module, that interact in a decoupled way. If the bed slope of the dune lee side exceeds a certain threshold, flow separation is assumed and the separation streamline is determined. The channel slope is the driving force for the flow, meaning that the specific discharge is not specified in the model, but inherently follows from the solution of the equations.

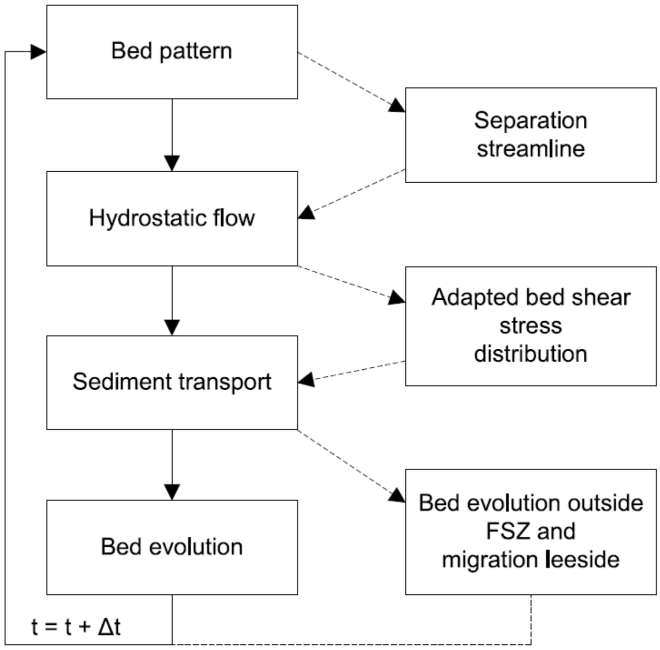


FIGURE 2: SETUP OF THE PARAMETERIZED DUNE MODEL (AFTER PAARLBERG ET AL., 2009)

2.1.1 PROCESSES MODELLED BY THE PARAMETERIZED DUNE MODEL

It is important to know which processes are modelled to compare the predictions of both models in the end. The processes involved in the parameterized dune model are described here.

Flow characteristics

The parameterized dune model is a process-based simulation model for river dune evolution, where flow characteristics are the driving force for sediment transport. The flow field is described by two-dimensional shallow water equations assuming hydrostatic pressure conditions. The essential input parameters can be measured or determined during flume experiments, this makes it straightforward to compare the model with datasets.

Flow separation

Essential for the parameterized dune model is the inclusion of flow separation. The flow is assumed to separate when the bed slope of the dune lee side exceeds a certain threshold. After establishing flow separation, the shape of the flow separation zone is determined. The separation streamline forms a virtual bed over which hydrostatic flow is computed (Paarlberg et al., 2007).

Sediment transport

The main purpose of the model is to predict dune evolution according to flow circumstances, where sediment transport is essential for the evolution of dunes. The model only incorporates bed load transport, suspended sediment transport is neglected. Suspended sediment transport is assumed to be not pertinent for the prediction of dune dimensions and migration rates under the proposed conditions. The sediment transport that causes dune evolution is computed using a formula like Meyer-Peter and Müller (1948). Adjustments have been made according to gravitational bed-slope effects and parameter settings. Sediment is transported in the flow direction and deposited along the dune and in the flow separation zone.

Avalanching
In case of flow separation, sediment passing the flow separation point is assumed to avalanche down the leeside of the dune. The sediment will distribute evenly and the leeside slope is assumed constant and equal to the angle of repose for natural sand (30°), which is valid according to Kleinhans (2003). This way the typical asymmetric form of a river dune under unidirectional flow develops.

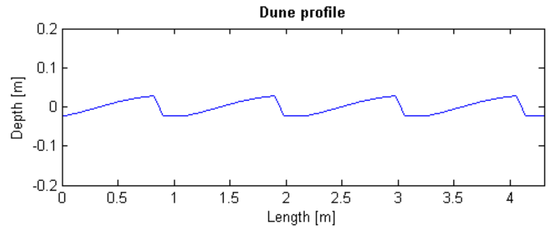
2.1.2 Input parameters of the parameterized dune model

To run the parameterized dune model it is essential to know the bed slope, which is the driving force for the flow. The domain for the simulation is set by two conditions: Water depth to determine the domain height and dune length to determine the domain length. The dune length is determined using a numerical linear stability analysis and is mainly controlled by the initial water depth. From this analysis the fastest growing dune length is found and adopted as domain length. The discharge is used to control the imposed water depth and is defined as the discharge per second per meter width. The initial water depth is used to help the model with a first estimation of the water depth. This will speed up the process at the start. The grain size is essential for calculation of the sediment transport.

Model parameters to check are the parameters defining the characteristics of the fluid, the characteristics of the sediment and the gravitational acceleration. The density of water needs to be set for the calculation of the influence of the characteristics of the fluid. The characteristics of the sediment are defined by the density of sediment, porosity and the angle of repose. Besides, the critical shields parameter is assumed to be constant as this was also adopted by Paarlberg et al (2009).

2.1.3 Output of the parameterized dune model

The main output of the parameterized dune model is the evolution of a two-dimensional bottom profile over time. Modelling of dune dimensions and migration rates is based on a single dune. Simulation of the development of the river dunes is based on one dune assumed to be in an infinite train of identical dunes (van Duin et al., 2013). The bottom profile for a given model run is presented in figure 3. The typical asymmetric dune profile is clearly visible, with a steep lee side where flow separation is assumed. The parameterized dune model is a process-based simulation model, where flow characteristics are the driving force for the sediment transport. That is why water depths can be predicted by the model as well. Results of the water depth (blue line), dune crest and trough heights (black lines) over time are presented in figure 4. The two-dimensional approach of the parameterized dune model results in two-dimensional output in the vertical plane only. Variations along the channel width cannot be determined using the parameterized dune model. The model is only capable to simulate the evolution of dunes under unidirectional flows.



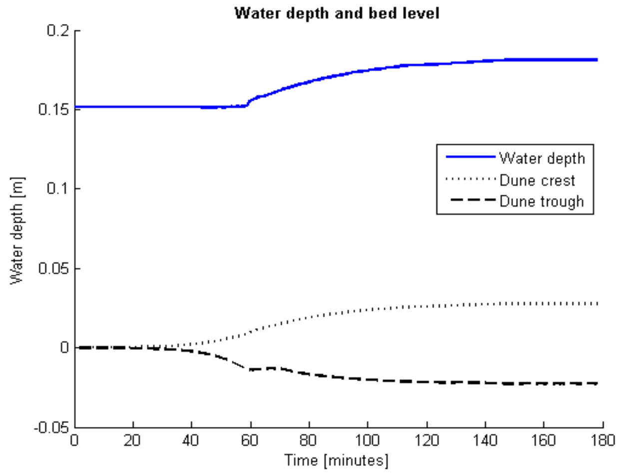


FIGURE 3: DUNE PROFILE OF FOUR IDENTICAL DUNES AS PREDICTED BY THE PARAMETERIZED DUNE MODEL, FLOW DIRECTION FROM LEFT TO RIGHT

FIGURE 4: WATER AND BED LEVEL AS PREDICTED BY THE PARAMETERIZED DUNE MODEL

2.2 THE CELLULAR AUTOMATON DUNE MODEL

The CA model of HR Wallingford is based on the study of Bishop et al. (2002). It is a model operating in a discrete three-dimensional space and simulating changes to the bottom profile. The model consists of a three-dimensional lattice that can be considered as a grid of stacked slabs. Sediment transport is simulated by the interaction between cells in the grid. Interactions are based on a stochastic set of rules that determine the chance on different events. Initially the model only focuses on uniform sediment, while Knaapen et al. (2013) modify the basic CA model by adding multiple grain types. In this way it becomes possible to model the principle of larger particles covering smaller particles and the sortation of sediment particles over bed forms. The critical difference between a model with specific grain types and the basic model is that each slab in the model needs to be identified and tracked which requires much more memory capacity.

The basic rules of the CA model are depicted in figure 6. First a cell is picked at random where the top slab is selected; a pickup probability distribution determines whether the slab will be picked up. When the selected slab is in shadow the chance to be picked is nil and another cell will be selected. A slab that will be picked up is shifted forward in the predefined direction of the current. The moved slab is deposited on top of the stack of slabs at the destination cell. At this cell it may 'stick' and remain there or 'bounce' and move again, which simulates the principle of saltation. When the slab sticks, a process of local avalanching is initiated. This process is also triggered at the origin cell when a slab is picked up. After this process a new cell is randomly selected, this process is repeated for a preset amount of slots. The amount of slots represents the number of random cell selections ('pick a random cell' in figure 6).

The model is based on stochastic rules, there is no direct relation to flow characteristics like flow velocity, water depth or slope. Dimensions are not defined in the model, only the amount of cells can be defined and probabilities according to the sediment distribution. Thus the model has no input parameters that could be compared to the data set or parameterized dune model. Therefore adjustments have to be made to provide the CA model with length and time scales.

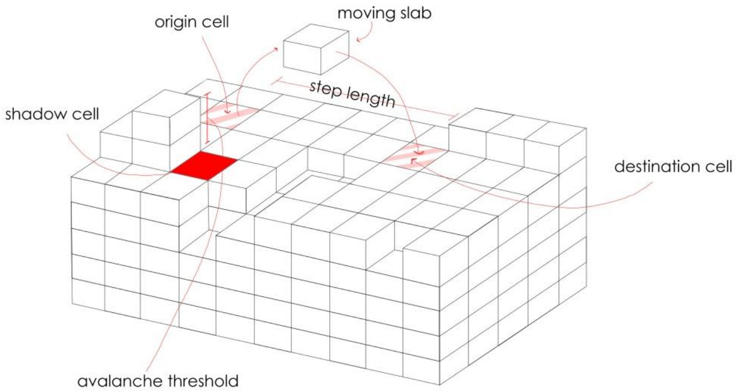


FIGURE 5: SCHEMATIC OVERVIEW OF THE PROCESSES INVOLVED IN THE CELLULAR AUTOMATON DUNE MODEL

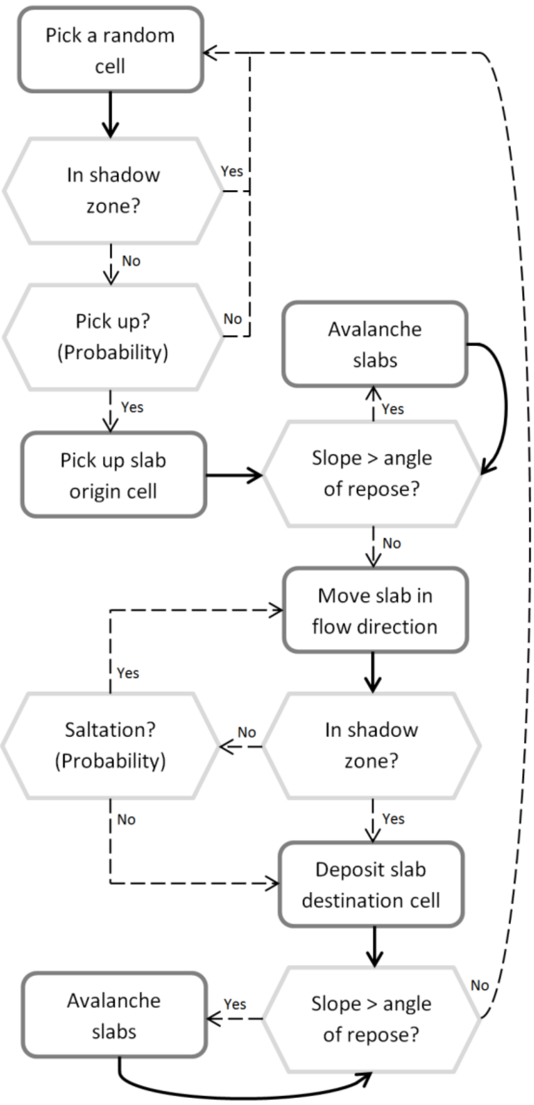


FIGURE 6: BASIC RULES OF THE CELLULAR AUTOMATON DUNE MODEL

2.2.1 PROCESSES MODELLED BY THE CELLULAR AUTOMATON DUNE MODEL

It is important to know which processes are modelled to compare the predictions of both models in the end. The processes involved in the CA model are described here.

Sediment transport

The model solely exists of sediment that forms the river bed or sediment that is moving in a predefined direction; the direction of the flow. Flow conditions, as incorporated in the parameterized dune model, are not present in the CA model. The simulated sediment transport concerns only bed load transport, suspended sediment is neglected. Sediment transport is simulated by moving slabs in the flow direction and depositing them on top of other slabs.

Shadow zone

The shadow zone reflects the areas in a flow where velocities are negligible and sediment will always be deposited, comparable with the flow separation zone of the parameterized dune model. A cell is picked at random where the top slab is selected, if the slab is in shadow it does not move, if it is not in shadow the slab is shifted forward in the direction of the current. When a destination cell is in shadow, the slab will always stick.

Saltation

A moved slab is deposited on top of the stack of slabs at the destination cell. At this cell it may 'stick' and remain there or 'bounce' and move again. This process is also observed in nature, where sediment particles in bed load transport touch the ground and move on before they deposit.

Avalanching

When a slab sticks on a destination cell a process of local avalanching is initiated. Avalanching involves a move to a neighbouring cell if the slope of the stack of slabs in that direction exceeds the angle of repose. Fill back is the opposite of this process that might occur when a slab is moved and the slope at the origin cell may exceed the angle of repose, this also causes avalanching.

Sediment sorting

The CA model is capable of capturing the sorting process of sediment due to different grain sizes. The grain size distribution is used to link sediment characteristics to probabilities; this reflects the sediment behaviour in real rivers (Blom et al., 2003). This process cannot be simulated by the parameterized dune model and is not included in this research.

2.2.2 INPUT PARAMETERS OF THE CELLULAR AUTOMATON DUNE MODEL

To run the CA model it is important to define the step length, which is the distance each slab can travel. The shear velocity increase consists of two components. The first (c1) is a linear shear stress component and the other (c2) is a non-linear component. They influence the distance travelled according to the height from where the slab is picked up. The higher the selected slab is in the column, the larger the travelled distance will be.

These shear velocity constants are indirectly related to the shape of the flow profile. The grain size distribution of the sediment enables one to add different grain sizes, their characteristics can be set by changing the pickup and deposition probability.

Model parameters to check are the number of cells in each direction to establish the grid, sediment characteristics and model characteristics. The angle of repose determines the difference in number of slabs between neighbours before an avalanche is triggered. The shadow distance determines how far to search for shadow zones. Also the number of slots have to be set once, this is the amount of slabs that will be selected during a model run.

2.2.3 OUTPUT OF THE CELLULAR AUTOMATON DUNE MODEL

The main output of the CA model is the evolution of the bed in a three-dimensional way. Bed formations can be presented restricted to differences in number of cells only. Dune dimensions can be counted in number of cells. There is no relation with length or time scales so migration rate and sediment transport are not present. Adjustments have to be made before comparing the model with the parameterized dune model or experimental data.

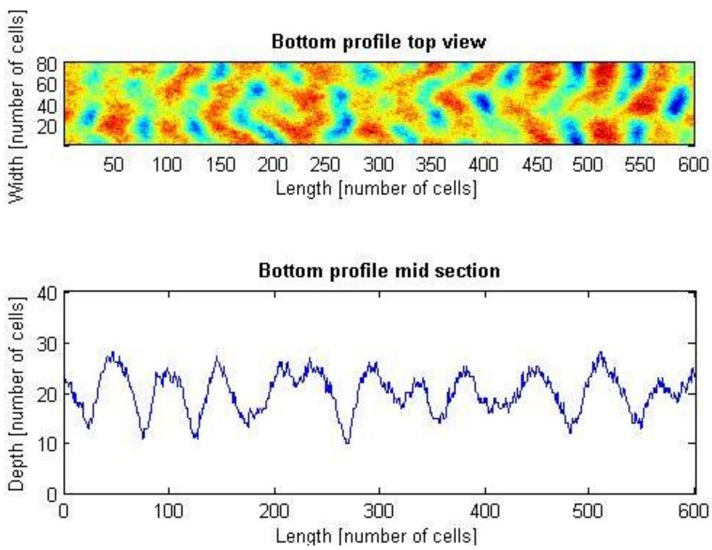


FIGURE 7: DUNE FIELD AND PROFILE AS PREDICTED BY THE CELLULAR AUTOMATON DUNE MODEL, FLOW DIRECTION FROM LEFT TO RIGHT

In contrast to the parameterized dune model, the CA model shows a field of dunes that varies in height and length over the domain. A bottom profile predicted by the model is presented in figure 7. The mid section of the bed profile shows variations in dune height, length and shape of the dunes. The driving force for sediment transport in the CA model is the step length. Although output seems promising, results cannot be compared with field observations in a quantitative manner. This is due to the absence of length and time scales. The question is how to adjust the CA model in a way it can be compared with flume experiments and the parameterized dune model?

2.3 Overview of processes and model input

The difference in approach of modelling is reflected in the modelled processes and input parameters required to run both models. Overviews are presented and discussed in this section.

2.3.1 Modelled processes

An overview of the modelled processes is presented in table 1 to gain insight in the similarities and dissimilarities of the model approaches.

TABLE 1: PROCESSES MODELLED BY EACH MODEL

Processes that are represented by the models		
Process	**Parameterized dune model**	**Cellular automaton dune model**
Flow characteristics	Present	Only flow direction and shear velocity increase
Flow separation	Present	Reflected by shadow zone
Sediment transport	Present	Reflected by slabs
Avalanching	Present	Present
Shadow zone	Reflected by flow separation zone	Present
Saltation	Implied in bed load (MPM)	Present
Sediment sorting	Absent	Present

Predictions of the parameterized dune model are based on the flow characteristics, whereas in the CA model only flow direction and shear velocity increase are included to determine the shape of the flow profile. Sediment transport is simulated in two different ways. The parameterized dune model uses a sediment transport formula to calculate the dune development, while the sediment transport in the CA model is represented by moving slabs of sediment based on stochastic rules. The process of saltation is explicitly incorporated in the CA model, whereas in the parameterized dune model it is implied by bed load transport. The presented overview of processes is useful for the comparison of both models to declare the differences in outcomes.

2.3.2 Input parameters

Overviews of the model input and parameters are presented in tables 2 and 3 that serve as guideline to select appropriate data sets.

Model input

Input of the parameterized dune model is straightforward and measurable during experiments, while input of the CA model is hard to relate to physical properties. More information about linking the model input of the CA model to flow characteristics can be found in chapter 4.

TABLE 2: MODEL INPUT FOR EACH MODEL

Model input: to be checked every run			
Parameterized dune model			
Parameter	**Symbol**	**Dimension**	**Function**
Bed slope	i	[-]	Driving force
Initial water depth	H0	[m]	First estimation of water depth
Discharge	q	[m^2 s^{-1}]	Control imposed water depth
Grain size	D50	[m]	Sediment characteristics
Cellular automaton dune model			
Parameter	**Symbol**	**Dimension**	**Function**
Step length	Lo	[-]	Travel distance of slab
Shear velocity increase	c1 and c2	[-]	Shear stress
Grain size distribution	pros	[-]	Sediment distribution (SD)
Pickup probability	P	[-]	Related to Shields parameter
Deposition probability	P_d	[-]	According to SD

Model parameters

Besides the model input that depend on the experiments and have to be checked each run, the models also include parameters that are independent of the experiments and therefore should be checked before starting the validation phase.

TABLE 3: MODEL PARAMETERS FOR EACH MODEL

Model parameters: to be checked once			
Parameterized dune model			
Parameter	**Symbol**	**Dimension**	**Function**
Density of water	ρ_w	[kg m^{-3}]	Water characteristics
Density of sediment	ρ_s	[kg m^{-3}]	Sediment characteristics
Porosity	ε_p	[-]	Sediment characteristics
Angle of repose	θ_{repose}	[°]	Sediment characteristics
Gravitational acceleration	G	[m s^{-2}]	Acceleration due to gravity
Critical shields parameter	θ_{cr}	[-]	Critical shear stress
Cellular automaton dune model			
Parameter	**Symbol**	**Dimension**	**Function**
Number of cells	x_{len}, y_{len} and z_{len}	[-]	Grid dimensions
Angle of repose	Rep	[-]	Avalanche trigger
Shadow distance	sDist	[-]	Distance to search for shadows
Shadow angle	sAng	[-]	Shadow zone
Number of slots	Slot	[-]	Amount of selected slabs

The overviews of model input and parameters provide the starting point for the selection of suitable experiments. Important to mention is that the parameters needed for the CA model are not related to flume experiments and therefore the focus of the data selection is on the parameters of the parameterized dune model. The input parameters of the CA model are adjusted to match with the selected data as described in chapter 4.

2.4 DATA SELECTION OF FLUME EXPERIMENTS

The focus of this research is on river dunes which are dominant in low-land rivers with a sandy bed such as the River Rhine (the Netherlands). Therefore, conditions of the experiments should be comparable to this type of rivers. Flow in this type of rivers is always subcritical (Fr << 1)[1]. Under subcritical flow conditions bed load transport is dominant. The influence of suspended sediment transport can be safely neglected when Froude numbers are small (Fr < 0.5) (Paarlberg et al., 2009). The selected data have to contain the required input parameters described in section 2.3. However, not only input values are important in this research, because model output of dune dimensions and migration rates will be compared. Also the flume experiments have to show the values of dune height, dune length and migration rates to compare the model predictions with measures of the flume experiments. Data of flume experiments requires the information presented in table 4. A variety of circumstances is selected, resulting in a dataset containing 17 experiments; a single experiment for calibration and 16 experiments for validation.

TABLE 4: PARAMETERS WHERE DATA SELECTION IS BASED ON

Input	Output
Bed slope	Measured dune height
Water depth	Measured dune length
Discharge	Measured migration speed
Grain size	

2.4.1 DATA USED FOR CALIBRATION

To ensure that the comparison of model results is based on the same conditions, both models should be calibrated using the same data. The parameterized dune model is already calibrated. Paarlberg et al. (2009) calibrated the model using flow A as reported by Venditti (2003). The value of each parameter and the results according to flow A are presented in table 5. These values are also used to calibrate the CA model.

TABLE 5: DATA USED FOR CALIBRATION (AFTER VENDITTI, 2003)

	Input parameters				Dune characteristics			
Experiment	i (10^{-3}) [-]	h [m]	q [m^2 s^{-1}]	D50 [mm]	H [m]	L [m]	M [m h^{-1}]	Fr [-]
Flow A	1.20	0.152	0.0759	0.50	0.048	1.17	2.34	0.411

2.4.2 DATA USED FOR VALIDATION

The data set used for the validation phase is a small selection of the data set used by Naqshband et al. (2014). The final data set used for validation contains sixteen experiments, consisting of four equal sets of four experiments. The first selection is based on four experiments of Venditti (2003) partly used by Paarlberg et al. (2009) as well, although input and output values are used slightly different in the research of

[1] Fr denotes the Froude number

Paarlberg et al. (2009). The expectation is that predictions of the models are closest to the observed characteristics for these experiments. As circumstances of these experiments are close to conditions of flow A that is used for calibration. The data have a varying Froude number and a constant median grain size of 0.5 mm. The second set used for validation is data set II: Fixed layer experiments large flume (DS-II) of Tuijnder (2010). Although the main purpose of the research is on supply limited conditions, six experiments were executed without a limitation in sediment supply (alluvial conditions). The validation on data of Tuijnder (2010) will be based on four experiments with a varying Froude number, comparable to the data of Venditti (2003) and a larger median grain size of 0.8 mm to discover the effects of a changing grain size. The third set used is the data set of the flume experiments of Termes (1986). The validation on data of Termes (1986) will be based on four experiments with slightly higher Froude numbers in comparison to the data of Tuijnder (2010) and Venditti (2003) and a smaller median grain size of 0.39 mm. The last set used is derived from case 2 of the flume experiments of Iseya (1984). The data set of Iseya (1984) contains four experiments with a combination of two different discharges and two different slopes. The experiments were conducted in a larger flume compared to the other experiments; however Froude number and grain size are comparable to the data of Venditti (2003). Table 6 represents the data of Venditti (2003), Tuijnder (2010), Termes (1986) and Iseya (1984) that will be used for the validation phase. Additional information about the experimental conditions and measurement methods can be found in appendix A.

TABLE 6: DATA USED FOR VALIDATION (AFTER VENDITTI, 2003; TUIJNDER, 2010; TERMES, 1986 AND ISEYA, 1984)

	Input parameters				Dune characteristics			
Venditti	i (10^{-3}) [-]	h [m]	q [$m^2 s^{-1}$]	D50 [mm]	H [m]	L [m]	M [$m h^{-1}$]	Fr [-]
Flow B	1.10	0.152	0.0723	0.50	0.042	0.86	1.34	0.391
Flow C	0.70	0.153	0.0696	0.50	0.036	0.95	1.20	0.370
Flow D	0.55	0.153	0.0611	0.50	0.022	0.84	0.62	0.326
Flow E	0.55	0.153	0.0546	0.50	0.020	0.30	0.35	0.290
Tuijnder	i (10^{-3}) [-]	h [m]	q [$m^2 s^{-1}$]	D50 [mm]	H [m]	L [m]	M [$m h^{-1}$]	Fr [-]
Nr.5-7	1.50	0.200	0.0940	0.80	0.070	1.39	1.00	0.336
Nr.1-10	2.20	0.200	0.1050	0.80	0.077	1.44	1.90	0.375
Nr.6-1	1.70	0.250	0.1300	0.80	0.083	1.47	1.60	0.332
Nr.6-3	2.20	0.260	0.1500	0.80	0.095	1.49	2.50	0.361
Termes	i (10^{-3}) [-]	h [m]	q [$m^2 s^{-1}$]	D50 [mm]	H [m]	L [m]	M [$m h^{-1}$]	Fr [-]
T1-A	2.79	0.168	0.1010	0.39	0.081	1.56	3.43	0.468
T1-B	2.85	0.229	0.1730	0.39	0.093	2.08	6.55	0.504
T1-C	2.70	0.280	0.2350	0.39	0.103	2.67	6.89	0.506
T1-D	2.83	0.335	0.2950	0.39	0.129	2.71	6.99	0.486
Iseya	i (10^{-3}) [-]	h [m]	q [$m^2 s^{-1}$]	D50 [mm]	H [m]	L [m]	M [$m h^{-1}$]	Fr [-]
R3 St.8	2.45	0.345	0.2490	0.57	0.136	2.51	4.55	0.392
R4 St.8	2.37	0.395	0.3675	0.57	0.180	3.42	5.04	0.473
R6 St.4	1.01	0.388	0.2600	0.57	0.043	1.00	1.58	0.343
R7 St.5	1.07	0.477	0.3725	0.57	0.103	1.72	2.55	0.361

Besides the data selection for validation, all fixed parameters as discussed in section 2.3 need a value before starting with the model runs. As mentioned earlier, it is assumed they will be constant and will not change during the model runs. The density of water and sediment are assumed to be common used values, respectively 1000 kg m^{-3} and 2650 kg m^{-3}. The porosity of the sediment is assumed to be 40%, this is also the default value for porosity in the parameterized dune model. The angle of repose is set for the characteristic value of sand which is 30°. The gravitational acceleration parameter g is set on 9,81 m s^{-2}. An overview of these parameters is provided in table 7.

TABLE 7: VALUES FIXED PARAMETERS

Parameters to be checked once			
Parameter	**Symbol**	**Value**	**Dimension**
Density of water	ρ_w	1000	[kg m^{-3}]
Density of sediment	ρ_s	2650	[kg m^{-3}]
Porosity	ε_p	0.4	[-]
Angle of repose	θ_{repose}	30	[°]
Gravitational acceleration	g	9.81	[m s^{-2}]
Critical shields parameter	θ_{cr}	0.05	[-]

CHAPTER 3

RESEARCH METHODOLOGY

This research consists of two steps to reach the final goal. Each step is described in a separate chapter. The first step is the preparation of the CA model for the validation phase. To do so, a sensitivity analysis reveals the behaviour of the model, length and time scales are added to the model and the input parameters of the model are linked to the flow characteristics. The CA model is calibrated after these adjustments. Research question 2 is answered by finishing the first step. The second step is the comparison of the parameterized dune model and the CA model with the prepared data sets. Output of the models is analysed and both models are discussed which leads to the answers on research questions 3 and 4. The used methods are described in this chapter.

3.1 ADJUSTMENTS OF THE CELLULAR AUTOMATON DUNE MODEL

The initial CA model is based on stochastic rules; there is no link between sediment transport and flow characteristics within the model. It is not possible to relate experimental data to the model without making adjustments to the model.

3.1.1 SENSITIVITY ANALYSIS

A sensitivity analysis is performed to determine the influence of fluctuations of model parameters. The initial conditions for this sensitivity analysis are assumed to be the default settings of the model. Slots, grid cells, step length, shear velocity and shadow distance are tested to describe the effects on the predicted results. The results of the sensitivity analysis are presented in chapter 4. The model is tested first by varying the amount of slots. Results for conditions with 25%, 75% and 200% of the initial slots are discussed and an extremely long run reveals a limitation of the model. For the analysis of the other parameters default settings are used, with the exception of the amount of slots. The other parameters are analysed using 200% of the initial slots because dunes show more regular patterns for this amount of slots. Grid cells in both flow direction and height are changed; 50% and 150% of the initial amount of cells are used. The step length is tested for many values; the most important observations are discussed. The shear velocity components are tested separately. One component is held constant (default value), while the other component is varied. The outcomes are plotted in figures and presented in tables. Better understanding of the model behaviour and the influence of the parameters on the predictions is useful for the calibration process. Based on this sensitivity analysis, choices are made about the usefulness of the parameters for calibration.

3.1.2 PREPARATION OF THE CELLULAR AUTOMATON DUNE MODEL

The CA model is adapted before the model is calibrated. The model has not been used for dune evolution predictions under flume conditions before. Therefore adjustments to the model are made before comparing it with the parameterized dune model. A length scale is added by linking the model parameters to a distance instead of a number of cells and assuming a fixed domain. In this way parameters and the domain itself are defined in meters and no longer in number of cells. The moved sediment within the model is determined by counting the number of slabs and the distance travelled. The amount of moved sediment is used to add a time scale to the model by relating it to the sediment transport according to Meyer-Peter and Müller (1948). Additionally model parameters of the CA model are linked to the characteristics of the experimental data by using theories to relate flow characteristics with input parameters of the CA model. The adjustments lead to new input parameters for the model; these are the step length, pickup probability, shadow distance and sediment transport.

3.1.3 CALIBRATION OF THE CELLULAR AUTOMATON DUNE MODEL

After the CA model is adjusted it needs to be calibrated before the actual comparison with the parameterized dune model. Predictions are compared to the observed data of experiment flow A (Venditti, 2003). Differences between the model output and the observed data are minimized by adjusting model parameters. The parameters not defined by input characteristics are used for the calibration of the CA model; these are the amount of cells, shear stress velocity and run time of the model. The sensitivity analysis provides insight in the behaviour of those parameters and therefore facilitates the calibration process. Because of the long runtime of the CA model, calibration is done manually by trial and error. The model is calibrated by running the model and changing each calibration parameter separately for a wide range (± 25-400%). The best approximations are combined and small changes in the parameters are tested to further improve the predictions of the model (± 1-10%).

The dimensions are determined using the bedform tracking tool of van der Mark et al. (2008). The average of three sections parallel to the flow direction determines the dimensions. Transects are selected at the first quarter, midsection and third quarter of the domain. Dune height is defined as the distance between the top of a crest and the consecutive downstream trough. Dune length is defined as the distance between two consecutive troughs. The migration rates are determined by selecting five dune troughs at random and compare the output of the final result with the result of 19/20 of the total runtime. The mean difference between the troughs is assumed to be the displacement of the dunes. The time is known; therefore the migration rate can be determined for each experiment.

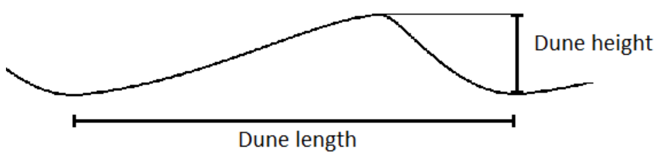


FIGURE 8: DETERMINATION OF DUNE DIMENSIONS

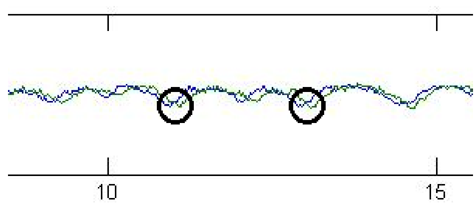


FIGURE 9: DETERMINATION OF THE MIGRATION RATE (ONLY A SMALL SECTION PRESENTED)

3.2 COMPARISON OF THE MODEL PERFORMANCES

The performance of the parameterized dune model and the CA model is tested using sixteen experiments (as described in chapter 2) to determine their predictive value for prediction of dune dimensions and migration rates. An overview of the input parameters can be found in appendix B (table A). The focus of the validation phase is on the performance of both models compared to the experimental results. The first runs are performed using the data of Venditti (2003) to examine the performance of both models under conditions close to the calibration experiment. Runs for data of Tuijnder (2010), Termes (1986) and Iseya (1984) are performed to examine the models for conditions with various grain sizes, Froude numbers and flume widths.

The output of the parameterized dune model is generated by running the model until equilibrium state is reached. The time to run a single experiment varied between 50 minutes and 3.5 hour. There is no equilibrium state in the CA model, therefore runtime of the model is used as a calibration parameter and assumed to be independent of the input parameters during the validation phase. Runtime of the CA model varied between 10 minutes and 25 minutes. Dune height and length for the predictions of the CA model were provided using the bedform tracking tool of van der Mark et al. (2008) and migration rates are determined by selecting five dune troughs at random and determining the displacement, as described in section 3.1.3.

Results are presented in a table B (appendix C) to get an overview of the predicted dune characteristics of both models and the observed values. The predicted values of dune dimensions and migration rates are plotted against the observed values to get better insight in the performance of the models and a better feeling for possible trends in the predictions. This is done in the same way as Paarlberg et al. (2009) did to compare their output results. Results are acceptable when predictions are within a 25% range of the observed values. Therefore a 25% accuracy band is plotted together with the results. This reveals the performance of the models that is reflected by the root-mean-square error (RMSE) and possible trends become visible.

CHAPTER 4

ADJUSTMENTS OF THE CELLULAR AUTOMATON DUNE MODEL

4.1 SENSITIVITY ANALYSIS

Default settings of the model are presented in table 8. A bottom profile with dunes develops under these conditions as visible in figure 10. This situation is the initial condition that is used in this sensitivity analysis.

TABLE 8: DEFAULT SETTINGS CA MODEL

Default settings	
Parameter	**Value**
Slots (number of cells)	50.000
Cells x-direction	10
Cells y-direction	500
Cells z-direction	200
Step length (Lo, number of cells)	12
Linear shear velocity parameter (c1)	0.3
Non-linear shear velocity parameter (c2)	0.004
Shadow distance (sDist, number of cells)	5

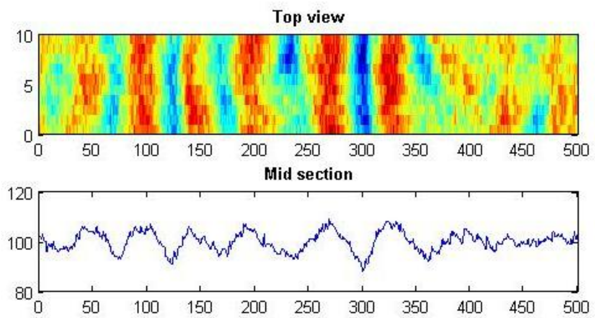


FIGURE 10: BOTTOM PROFILE CA MODEL USING DEFAULT SETTINGS, FLOW DIRECTION FROM LEFT TO RIGHT

Slots

Changing the amount of slots influences the dimensions of the resulting dunes. When the number of slots is set too low, no regular bedform patterns form (top view figures 11 and 12). The bottom profile shows only random patterns, this is likely to be the result of a lack in sediment transport. Increasing the number of slots leads to patterns that start to look like dunes (second view figures 11 and 12). Further increase of slots leads to a regular pattern of bedforms (third view figures 11 and 12). The larger the number of slots, the longer, higher and more asymmetrical the dunes will grow and thus, the number of dunes in the domain will decrease (last view figures 11 and 12). An extremely long run is presented; dunes are merged into a large dune and three smaller dunes. A further increase of slots will finally result in a single dune that covers the whole domain. This is a problem within the model because dunes keep growing; an equilibrium state is not reached.

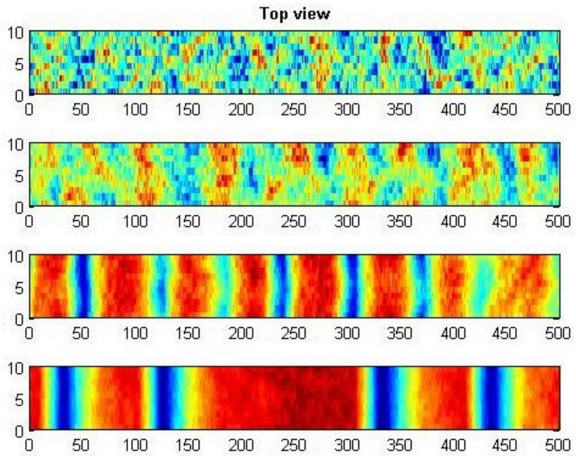


FIGURE 11: TOP VIEW BOTTOM PROFILE CHANGING SLOTS, (IN ORDER 12.5, 37.5, 100 AND 5000 (*10^3)) VALUES ON AXIS IN NUMBER OF CELLS, FLOW DIRECTION FROM LEFT TO RIGHT

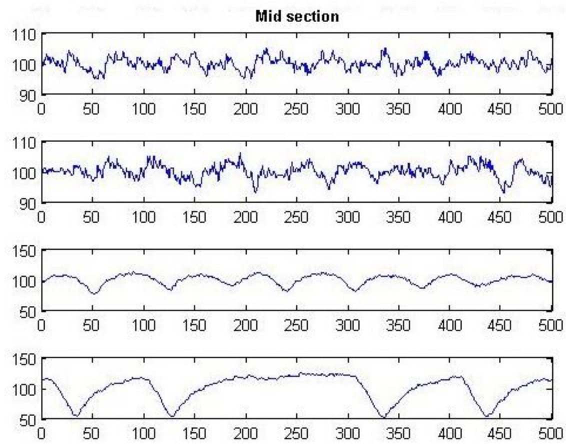


FIGURE 12: MID SECTION BOTTOM PROFILE CHANGING SLOTS, (IN ORDER 12.5, 37.5, 100 AND 5000 (*10^3)) VALUES ON AXIS IN NUMBER OF CELLS, FLOW DIRECTION FROM LEFT TO RIGHT

TABLE 9: RESULTS SENSITIVITY ANALYSIS SLOTS

Sensitivity analysis slots			
Figures 11 and 12	**Slots (*10^3)**	**Dunes**	**Height**
A	12.5	-	-
B	37.5	± 9	± 12
C	100	8	± 40
D	5000	4	± 75

Grid cells

Changing the number of grid cells shows that dune formations are directly related to the grid size. Doubling the number of cells in z-direction (height of the domain) does not affect the amount of cells within the dune. Changing the number of cells in the direction of the flow (y-direction) shows the same relation, the amount of cells in a single dune does not change. More dunes will develop in the fixed domain with a larger amount of cells in y-direction. Thus dune dimensions depend on the grid size, assuming that the domain has dimensions; however this should not be the case.

TABLE 10: RESULTS SENSITIVITY ANALYSIS GRID CELLS

Sensitivity analysis grid cells					
z-direction			**y-direction**		
Cells in z-direction	Dunes in domain	Height in cells	Cells in y-direction	Dunes in domain	Height in cells
100	8	± 40	250	5	± 40
200	8	± 40	500	8	± 40
300	8	± 40	750	11	± 40

Step length

Changing the step length shows a relation between dune length and step length, although there are some transition zones. In general, an increasing step length leads to an increase in dune length; fewer dunes will develop. Between step lengths of 20 to 25 cells something strange happens, the developed patterns become irregular. After increasing the step length further, regular patterns are formed again with an increase in number of dunes and thus a decreasing dune length. Further increase of the step length leads to a further decrease of number of dunes, until a new transition zone is reached (around a step length of 60). It seems that dunes developed at larger step lengths show more constant forms with less variations than dunes developed at smaller step lengths. There is no observed relation between step length and dune height.

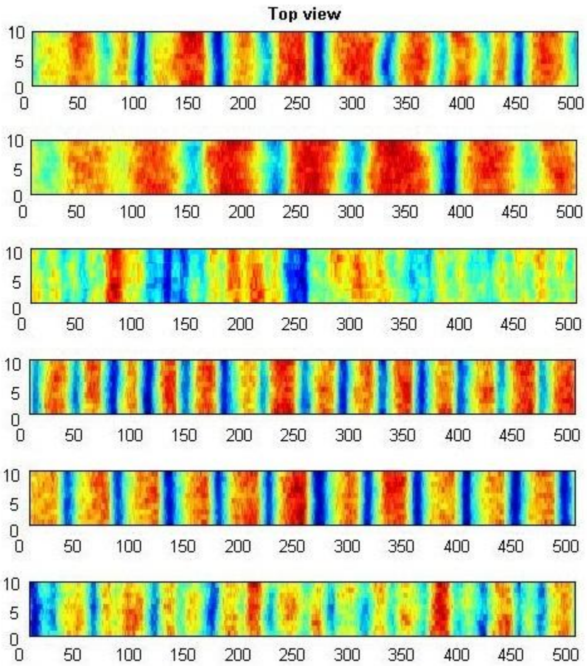


FIGURE 13: TOP VIEW BOTTOM PROFILE CHANGING STEP LENGTH, (IN ORDER: 8, 15, 20, 40, 50 AND 60) VALUES ON AXIS IN NUMBER OF CELLS, FLOW DIRECTION FROM LEFT TO RIGHT

TABLE 11: RESULTS SENSITIVITY ANALYSIS STEP LENGTH

Sensitivity analysis step length			
Figure 13	**Step length**	**Dunes**	**Height**
A	8	10	± 20
B	15	7	± 21
C	20	-	-
D	40	14	± 19
E	50	11	± 21
F	60	17	± 21

Shear velocity

Changing the linear shear stress component (c1) has influence on the dune height. Decreasing the component leads to an increasing dune height, while increasing the component leads to a decreasing dune height. Dune length is not influenced by changing the component, although the form seems to be more asymmetric when the component is getting lower. Changing the non-linear component (c2) results in a change in dune form; with a decreasing non-linear component, dunes develop more asymmetrically with steeper lee sides and stoss sides that are more flattened. Also dune height is affected by changes; decreasing the component leads to an increase in dune height. Both components show similar behaviour according to dune form and dimensions, although the first component seems to have more effect on the dune height, while the second component has the largest influence on the asymmetrical shape of the dune.

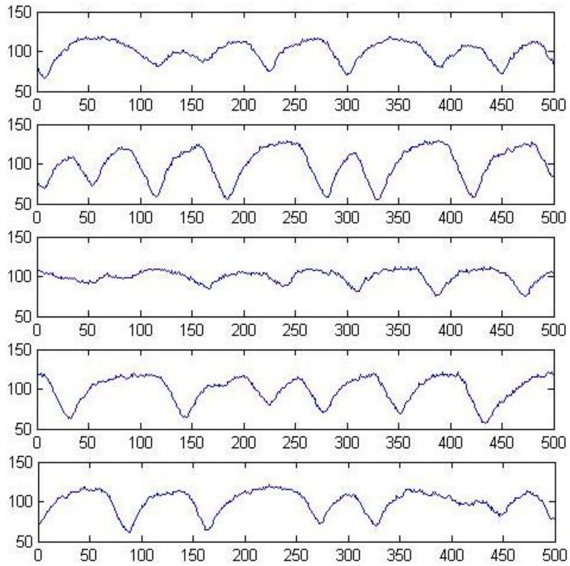


FIGURE 14: MIDSECTION BOTTOM PROFILE CHANGING SHEAR VELOCITY, VALUES ON AXIS IN NUMBER OF CELLS, FLOW DIRECTION FROM LEFT TO RIGHT

TABLE 12: RESULTS SENSITIVITY ANALYSIS SHEAR VELOCITY

Sensitivity analysis shear velocity				
Fig. 14	**c1**	**c2**	**Dunes**	**Height**
A	0.3	0.004	7	± 50
B	0.2	0.004	7	± 70
C	0.4	0.004	7	± 25
D	0.3	0.003	7	± 52
E	0.3	0.005	7	± 48

Shadow distance

Shadow distance is tested under various conditions. Changing the shadow distance seems to have almost no influence on the dune dimensions. Number of dunes and dune height remain approximately the same. It is important to ensure this parameter is set large enough to search for the former dune crest.

Conclusions

The sensitivity analysis provides insight in the behaviour of the input parameters. Relations between individual cells according to angle of repose, step length, shadow distance and so on are all based on a number of cells. Increasing the number of cells leads to decreasing dune dimensions. It is important to separate this relation in a way that the amount of grid cells determines the level of detail of the dune instead of the number of dunes in the domain. The step length can be seen as the driving force for sediment transport in the CA model. In reality flow velocity is responsible for sediment transport. This parameter should be linked to the flow velocity of the experimental data to make comparison of both models and the data possible. The shear velocity is important for the fine tuning of the model and can be an important parameter for the calibration process.

4.2 PREPARATION OF THE CELLULAR AUTOMATON DUNE MODEL

A length scale is added to the CA model by linking the model parameters to a distance instead of a number of cells and assuming a fixed domain. The sediment transport within the model is determined and a time scale is added. Additionally model parameters of the CA model are linked to the characteristics of the experimental data.

4.2.1 LENGTH SCALE

The first step to add a length scale to the CA model is assuming a fixed domain and defining the dimensions of that domain. In this way increasing the number of cells lead to a more detailed grid with smaller cells, while the domain dimensions remain the same. The predefined domain is divided into the number of determined cells, where each cell has dimensions of:

$$dx = \frac{Lx}{nx}\,, \tag{1}$$

$$dy = \frac{Ly}{ny}, \tag{2}$$

$$dz = \frac{Lz}{nz}, \tag{3}$$

where dx, dy, dz is the length of one cell in x-, y- or z-direction, Lx, Ly, Lz is the length of the domain in the corresponding direction and nx, ny, nz is the number of cells in the corresponding direction. In this way the dimensions of the domain are fixed and the dimensions of a single cell can be determined. Each cell has the same dimensions; therefore distances and thus dune dimensions can be easily determined. Also the volume of sediment transported within the model can be calculated. The next step is relating the model parameters to a distance instead of a number of cells. The parameters are adjusted to create model parameters defined in a length scale.

Angle of repose

The angle of repose in the CA model was defined as a number of slabs in z-direction. When the slab difference between neighbours exceeds this amount of slabs, an avalanche is triggered. Adjusting this parameter to link the amount of slabs to the angle of repose is necessary. To do so, the dimensions of each cell in both height (z-direction) and length (y-direction) are used. The ratio between these dimensions determines the amount of slabs (Rep) in the z-direction needed to create the angle of repose (φ). In formula:

$$Rep = \frac{tan(\varphi)}{dz/dy}\,. \tag{4}$$

Implementing this formula in the code can lead to a non-integer number of slabs. The result needs to be an integer, because the model only counts cells. Therefore the closest number of cells is selected which leads to an approximation of the angle of repose. The real angle of repose for this research is 32,6° within the CA model.

Step length
The step length in the CA model was defined as a number of slabs. Increasing the number of cells in the domain leads to a decrease in step length. The step length is linked to the grid to overcome this problem. Step length defined in cells (Lo) is determined as follows:

$$Lo = \frac{Lo\prime}{dy}, \qquad (5)$$

where Lo' is the parameter that defines the step length in meters and dy is the length of a single cell in the flow direction. The result needs to be an integer, because the model only counts cells. Therefore the closest number of cells is selected which leads to an approximation of the step length that varies between 3 and 18 cells for this research.

Shadow distance
The shadow distance was also defined as a number of slabs to search for the shadow zone. Thus the problem for the step length also applied for shadow distance. The shadow distance defined in cells (sDist) is linked to the grid in the following way:

$$sDist = \frac{sDist\prime}{dy}, \qquad (6)$$

where sDist' is the parameter that defines the shadow distance in meters and dy is the length of one cell in the flow direction. The result needs to be an integer, because the model only counts cells. Therefore the closest number of cells is selected which leads to an approximation of the shadow distance that varies between 4 and 35 cells for this research.

Slots
The number of slots determines how many cells will be selected each model run. This number is set in a way that the amount of sediment that could be transported is the same for each run. Therefore the number of slots is chosen in a way that it is a multiplicity of the number of cells on the surface:

$$Slot = slotp(nx * ny), \qquad (7)$$

where slotp is the slot parameter that determines how many times the total surface will be selected each run and nx and ny are the number of cells in x- and y-direction respectively.

Now that the relation between parameters and grid size is separated, a length scale is added. The input for the CA model consists of a domain length and a number of cells to set up the grid. The input parameters that were defined in number of cells are now translated to a distance in meters.

4.2.2 TIME SCALE

A time scale is added to the CA model by using the sediment transport for both the model and the experiments. The sediment transport of the experiments is determined using the sediment transport formula of Meyer-Peter and Müller (1948) with a correction according to Wong & Parker (2006). The value for the empirical coefficient m is 4 instead of 8 and the critical Shields number θ_{cr} is 0.05 instead of 0.047 as proposed by Meyer-Peter and Müller (1948). These values are also used for the parameterized dune model (Paarlberg et al. 2009). The initial sediment transport is calculated using the data of the experiments and the corrected formula of Meyer-Peter Müller (1948). The sediment transport is determined using the following equations.

$$\Phi = 4(\Psi - 0.05)^{\frac{3}{2}}, \tag{8}$$

where Φ is the non-dimensional transport parameter and Ψ the non-dimensional flow parameter defined in the following way:

$$\Phi = \frac{q_s}{\sqrt{g\Delta D^3}}, \tag{9}$$

$$\Psi = \left(\frac{C}{C_{90}}\right)^{\frac{3}{2}} * \theta, \tag{10}$$

where q_s is the sediment transport volume of solid material per unit width. This is the volume without porosity; the initial sediment transport is adjusted to include the porosity. The acceleration due to gravity is denoted by g and Δ is the mass of sediment minus the mass of water divided by the mass of water ($(\rho_s - \rho_w) / \rho_w$). D is the grain diameter of the sediment; C denotes the Chézy coefficient and C_{90} is related to D_{90} in the following way:

$$C_{90} = 18 log \frac{12h}{3D_{90}}. \tag{11}$$

The transported sediment in the model is determined by using the total step length of all moved slabs and multiplying the result with the volume of one cell. This leads to the total distance travelled by a single slab, dividing this by the domain length will result in the total amount of sediment transported. In formula:

$$ST = \frac{Slt * dy * vol}{Lx * Ly}, \tag{12}$$

where ST is the total sediment transport per unit width, Slt is the total step length of all the moved slabs in number of cells, dy is the length of an individual cell in meters, vol is the volume of one cell in m^3, Lx is the length of the domain in the x-direction in meter and Ly is the length of the domain in y-direction in meter.

Knowing the sediment transport according to the sediment transport formula and the total transport in the CA model, results in the opportunity to determine the time it takes to develop the dunes in the model. The duration of a model run can be determined by dividing the total transport in the model (ST) by the sediment transport (q_s) including the porosity (ε_p), in formula:

$$Time\ of\ a\ run = \frac{ST}{q_s * (1+\varepsilon_p)}, \tag{13}$$

In this way a time scale is added and migration rates and time to equilibrium of dunes can be predicted. Together with the dune dimensions, these are the most important characteristics to compare, because they influence the roughness and changes to the riverbed.

A disadvantage of the presented method is that sediment transport in the model is assumed to be equal to the calculated sediment transport according to the sediment transport formula. In other words, the sediment transport in the CA model is based on measurements during the experiments instead of a modelled sediment transport. In this way it is impossible to compare predicted sediment transport rates of both models with the data, because the sediment transport rate in the CA model will be exactly the same as the outcome of the sediment transport formula.

4.2.3 LINKING PARAMETER INPUT TO EXPERIMENTAL DATA

After implementing time and length scales to the CA model, it is possible to link the model to the experimental data. Pickup probability, deposition probability, step length and shadow distance are related to the results of the experiments. To do so, a couple of assumptions are made. The used methods and theories to link the input parameters to the experimental data are described here.

Pickup probability

The pickup probability in the CA model is a measure for the ability of the sediment to be set in motion. This pickup probability depends on the grain size of the sediment and the flow characteristics such as flow velocity. To link the pickup probability to the circumstances of the experiments there should be a relation between the sediment, flow characteristics and pickup probability.

Cheng & Chiew (1998) proposed a method to relate the pickup probability with the shields parameter, a measure for the initiation of motion of sediment in a fluid flow. They based their formula on earlier studies of Engelund and Fredsoe (1976) and Fredsoe and Deigaard (1992).

$$P = 1 - 0.5\frac{0.21-\sqrt{\theta C_L}}{\left|0.21-\sqrt{\theta C_L}\right|}\sqrt{1-exp\left[-\left(\frac{0.46}{\sqrt{\theta C_L}}-2.2\right)^2\right]} - 0.5\sqrt{1-exp\left[-\left(\frac{0.46}{\sqrt{\theta C_L}}+2.2\right)^2\right]}, \tag{14}$$

where θ is the shields parameter, the dimensionless shear stress and C_L denotes a constant that is assumed to be 0.25 (Cheng & Chiew, 1998).

The CA model is linked to the flow circumstances and grain size of the sediment by using this formula. Important to mention is that the method of Cheng & Chiew (1998) is designed for single sediment particles and the CA model is calculating with slabs of sediment. This method only holds, when the assumption is made that the behaviour of single particles and the slabs in the model are the same. Further research on the application of this method is necessary to determine whether this assumption is reliable or not.

Deposition probability
Besides the pickup probability as described above, there is also a deposition probability in the CA model. Heavier particles and lower flow velocities result in lower values of the shields parameter and therefore a lower pickup probability. This principle should also be reflected in the deposition probability. Therefore it is assumed that the deposition probability is denoted as:

$$P_d = 1 - P/1.5\,, \qquad (15)$$

where P_d is the deposition probability and P is the pickup probability.

Step length
Flow velocity is an important parameter in dune evolution and affects dune dimensions. The travel distance of sediment in transport is influenced by the flow velocity. No flow velocity is present in the CA model; however the step length determines the travel distance of the slabs. Therefore these two parameters should be linked in a way to represent the flow velocity in the CA model.

Sekine & Kikkawa (1992) proposed a relation between the shear and settling velocity and the step length of saltating grains. The shear and settling velocity can be derived from the experiments and the step length of saltating grains is included in the CA model as step length of slabs. The resulting relation is denoted by the following formula:

$$\lambda = \alpha_2 \left(\frac{u_*}{v_s}\right)^{\frac{3}{2}} * \left[1 - \frac{\left(\frac{u_{*c}}{v_s}\right)}{\left(\frac{u_*}{v_s}\right)}\right]\,, \qquad (16)$$

where λ is the dimensionless step length, α_2 is a constant with value 3.0*10^3, u_* is the shear velocity [m s^{-1}], v_s denotes the settling velocity of the sediment [m s^{-1}] and u_{*c} is the critical shear velocity [m s^{-1}]. The dimensionless step length is related to the step length in [m] in the following way:

$$\lambda = \frac{\Lambda}{D}\,, \qquad (17)$$

where Λ is the step length in [m] and D the grain size in [m].

Important to consider is the difference in interpretation of step length. The theory of Sekine and Kikkawa (1992) describes the total trajectory of a saltating grain, while the step length in the CA model is defined as a single step and saltation is simulated separately. The step length theory as proposed by Sekine and Kikkawa (1992) is adjusted to overcome this discrepancy. The expected number of cells a slab will travel is determined using the pickup and deposition probabilities.

$$S_c = \frac{\sum n*P*(1-P_d)^{n-1}*P_d}{\sum P*(1-P_d)^{n-1}*P_d} , \qquad (18)$$

where S_c is the expected number of cells a slab will travel, n the number of cells, P the pickup probability and P_d the deposition probability. In this way the step length according to Sekine & Kikkawa (1992) can be adjusted to a step length that is used in the CA model.

$$S_l = \frac{\Lambda}{S_c} , \qquad (19)$$

where S_l is the step length used in the CA model, Λ is the step length according to the theory of Sekine and Kikkawa (1992) and S_c is the expected number of cells a slab will travel.

Tests with this formula show outcomes that seem reliable, however the method of Sekine & Kikkawa (1992) is designed for single sediment particles and the CA model is calculating with slabs of sediment. This method only holds, assuming the behaviour of single particles and the slabs in the model is the same. Further research on the application of this method is necessary to determine if this assumption is indeed reliable.

Shadow distance

The shadow distance in the CA model is used to determine the maximum distance to search for shadows. The shadow distance defined in meter can be related to the flow separation zone, assuming the separation zone length is the same length as the shadow distance. This means that the shadow distance depends on the dune height. To link the shadow distance to the field data there should be a relation between the developed dunes and the length of the flow separation zone.

Paarlberg et al. (2007) described the flow separation zone length as the distance between the brink point where the flow starts to separate and the flow reattachment point.

$$L'_{st} = L_{st}/H_b , \qquad (20)$$

where L'_{st} is the non-dimensional flow separation zone length, L_{st} the flow separation zone length in [m] and H_b the brink point height [m]. Schatz & Herrmann (2006) found a relation for dunes with a horizontal bed at the flow separation point and the non-dimensional flow separation zone length that is denoted by:

$$L'_{st} \approx 4.85 . \qquad (21)$$

In this way the shadow distance (SD) is linked to the length of the flow separation zone as follows:

$$SD = 4.85 * H_b \ . \qquad (22)$$

The only problem here is that shadow distance is based on a predefined single value instead of a changing variable, whereas dunes develop over time. This development is not included using this method. Besides, dune dimensions are determined after a model run, while the shadow zone needs to be determined upfront. Therefore, the shadow zone will be based on the dune dimensions as observed during the experiments as a first estimate.

After these adjustments data of the Shields parameter, shear velocity, settling velocity, brink point height, grain size and Chézy coefficient are required to run the model. In addition it is important to determine the dimensions of the domain.

TABLE 13: INPUT PARAMETERS CELLULAR AUTOMATON DUNE MODEL

Input parameters		
Input	Data	Method
Pickup probability (P)	Shields parameter	Cheng & Chiew (1998)
Step length (S_l)	Shear velocity, settling velocity and grain size	Sekine & Kikkawa (1992)
Shadow distance (SD)	Brink point height	Paarlberg et al. (2007) and Schatz & Herrmann (2006)
Sediment transport (q_s)	Grain size, Shields parameter and Chézy coefficient	Meyer-Peter and Müller (1948) and Wong & Parker (2006)

4.2.4 INPUT PARAMETERS CELLULAR AUTOMATON DUNE MODEL

The model adjustments of the CA model results in a relation between the flow characteristics and the input parameters of the model. The values of these parameters are calculated using the formulas of Sekine & Kikkawa (1992), Cheng & Chiew (1998) and the by Wong & Parker (2006) corrected formula of Meyer-Peter & Müller (1948) as described in section 4.2.2. The used input values are presented in table 14.

TABLE 14: VALUES OF THE INPUT PARAMETERS

	Exp.	P [-]	S_l [m]	SD [m]	q_s [m^2 s^{-1}]
Venditti	**Flow A**	0.568	0.141	0.231	6.93E-06
	Flow B	0.522	0.140	0.202	5.52E-06
	Flow C	0.249	0.077	0.174	3.05E-06
	Flow D	0.128	0.072	0.104	1.28E-06
	Flow E	0.139	0.152	0.095	6.39E-07
	Exp.	P [-]	S_l [m]	SD [m]	q_s [m^2 s^{-1}]
Tuijnder	**Nr.5-7**	0.596	0.272	0.340	6.66E-06
	Nr.1-10	0.756	0.324	0.373	1.34E-05
	Nr.6-1	0.740	0.323	0.403	1.23E-05
	Nr.6-3	0.827	0.372	0.461	2.10E-05
	Exp.	P [-]	S_l [m]	SD [m]	q_s [m^2 s^{-1}]
Termes	**T1-A**	0.916	0.298	0.393	2.55E-05
	T1-B	0.944	0.345	0.451	5.05E-05
	T1-C	0.952	0.365	0.500	6.81E-05
	T1-D	0.963	0.458	0.626	8.54E-05
	Exp.	P [-]	S_l [m]	SD [m]	q_s [m^2 s^{-1}]
Iseya	**R3 St.8**	0.940	0.218	0.660	3.56E-05
	R4 St.8	0.946	0.199	0.873	6.95E-05
	R6 St.4	0.826	0.112	0.207	1.89E-05
	R7 St.5	0.877	0.125	0.500	3.17E-05

4.3 CALIBRATION OF THE CELLULAR AUTOMATON DUNE MODEL

Adjustments are made to the CA model as described in section 4.2. Now the model contains length and time scales and model parameters are linked to these scales. Relations were found between the input parameters and the experimental data to link the model to the available data sets.

4.3.1 PARAMETERS USED FOR CALIBRATION

After the adjustments and assumptions only three input parameters are left for calibration, assuming the other parameters are defined correctly. These are the dimensions of the domain, the amount of cells in the domain and the shear stress velocity. The dimensions of the domain should be set in a way that the modelled area corresponds to the area where data is measured. As a result only two variables can be used for calibration. (1) The amount of cells in the domain, changing this parameter leads to a change in detail of the predicted dune dimensions. (2) The shear stress velocity should be defined related to the flow, although there is no relation defined for this parameter yet. In addition the run time of the model is used for calibration because an equilibrium state is not reached and somehow the run time should be defined. The run time of the model is changed by varying the amount of slots for each run, which will lead to varying dune dimensions. Thus the amount of cells, shear stress velocity and the run time are the parameters used for calibration.

4.3.2 CALIBRATION PROCESS

The dimensions of the domain are chosen in a way that the model represents the flume conditions where experiments were conducted. The dimensions are set for a width of 1 meter and a length of 25 meter. The depth is set at 0.5 meter and is assumed to be the maximum variation of the bed. The optimal values of the calibration parameters are presented in table 15. The number of cells is chosen in a way that the xy-plane would always be a square. The surface area of a single cell is 6.25 cm^2, with dimensions in both x- and y-direction of 2.5 cm and the volume of a single cell is 2.5 cm^3 where the cell height is 0.4 cm.

TABLE 15: VALUES OF CALIBRATED PARAMETERS

Calibration parameters			
Parameter	Symbol	Value	Unit
Cells x-direction	xlen	40	Number of cells [-]
Cells y-direction	ylen	1000	Number of cells [-]
Cells z-direction	zlen	125	Number of cells [-]
Linear shear velocity	c1	0.31	Coefficient [-]
Non-linear shear velocity	c2	0.002	Coefficient [-]
Slots	slotp	20	Parameter [-]

4.3.3 PERFORMANCE AFTER CALIBRATION

Results of the calibration process are presented here. The predicted values of the dune dimensions and migration rate are presented in table 16. Results are depicted in figure 15, where the top view of the bottom profile is reflected in the top figure. The bottom figure shows a slice of the bottom profile over the midsection of the simulated domain.

TABLE 16: PREDICTED VERSUS OBSERVED DUNE CHARACTERISTICS

Dune characteristics		
Parameter	Model prediction	Flow A (Venditti)
Dune length [m]	1.14	1.17
Dune height [m]	0.054	0.048
Migration rate [$m\ h^{-1}$]	0.71	2.34

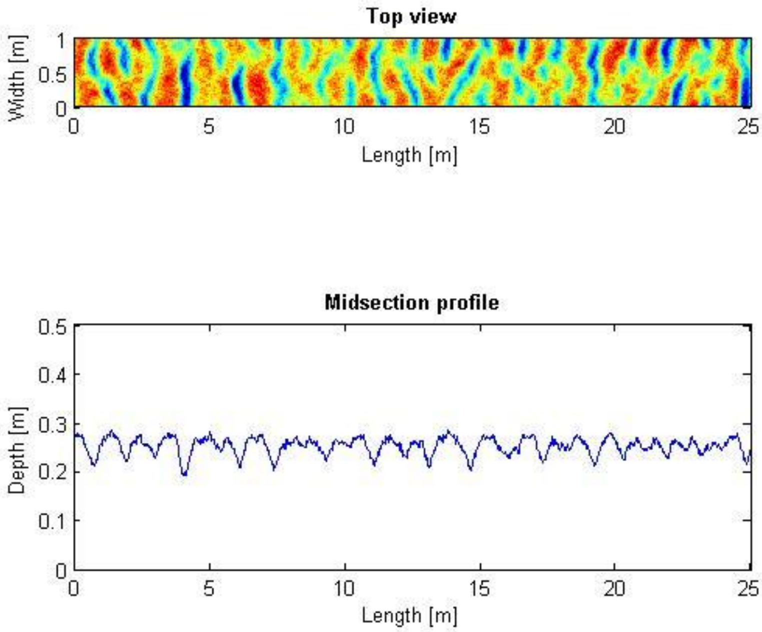


FIGURE 15: PERFORMANCE OF THE CELLULAR AUTOMATON DUNE MODEL AFTER CALIBRATION, FLOW DIRECTION FROM LEFT TO RIGHT

The dune heights are slightly overestimated (6 mm, ± 12 %), while the dune lengths are slightly underestimated (3 cm, ± 3 %). However, the results seem promising, predicted dune dimensions are close to the observed dimensions from the experiment of flow A. Important now is the validation process. How will the model perform when it is applied to other experiments?

CHAPTER 5

COMPARISON OF THE MODEL PERFORMANCES

5.1 MODEL RESULTS

An overview of the outcomes of the validation process is given by tables 17 and 18. In table 17 predicted sediment transport for both models and the observed data are presented, only data of Tuijnder (2010) and Termes (1986) was available. The overview in table 18 contains the observed dune dimensions and migration rates for each experiment and the predicted values of both models.

The parameterized dune model overestimates the sediment transport for experiments of Tuijnder and Termes as presented in table 17. The sediment transport is two to four times higher than the observed sediment transport. The predicted migration rates are also overestimated as clearly visible in figure 16. In general the model overestimates dune migration approximately with a factor of three compared to the observed migration rates. Only 3 predictions of Venditti are within the 25% accuracy bands (VC, VD and VE). The root-mean-square error (RMSE) of the predicted migration rate is 7.05 m h^{-1}. Looking at the dune height most of the experiments are under- and overestimated. Only experiments flow B and T5-7 are within the 25% accuracy bands (figure 16). The RMSE of the predicted dune height is 0.044 m. With 5 experiments in the 25% accuracy bands, dune length is predicted better than dune height. Deviations in the dune length predictions are similar to the dune height prediction for each experiment, although the variety is less; dune length predictions are relatively closer to the observed values (figure 16). The RMSE of the predicted dune length is 0.77 m.

The CA model predicts a sediment transport close to the observed sediment transport (± 25%) for experiments of Tuijnder and Termes as presented in table 17. Migration rates are underestimated in general, except for three experiments of Iseya (I4s8, I6s4 and I7s5) that are predicted reasonably well as depicted in figure 17. The RMSE of the predicted migration rate is 2.03 m h^{-1}. Figure 17 shows that dune height of 6 experiments is predicted within the 25% accuracy bands, the other experiments are underestimated, except for experiment I6s4 which is overestimated by the model. The RMSE of the predicted dune height is 0.036 m. Dune length predictions are closer to the observed values as depicted in figure 17; results of 9 experiments are within the accuracy bands. The RMSE of the predicted dune length is 0.82 m.

TABLE 17: OVERVIEW OF SEDIMENT TRANSPORT

	Sediment transport [$m^2\ s^{-1}$] $*10^{-5}$							
	Tuijnder (2010)				Termes (1986)			
	T5-7	T1-10	T6-1	T6-3	T1-A	T1-B	T1-C	T1-D
PMD	2.24	4.24	3.82	6.36	5.95	10.78	14.23	18.40
CA	0.67	1.34	1.23	2.10	2.55	5.05	6.81	8.54
Exp	0.55	1.20	0.95	1.71	2.34	6.04	8.73	10.72

TABLE 18: OVERVIEW OF DUNE DIMENSIONS AND MIGRATION RATES

		Output results								
		Dune height [m]			Dune length [m]			Migration rate [$m\ h^{-1}$]		
	Exp.	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
Venditti	**Flow B**	0.050	0.049	0.042	1.08	1.05	0.86	2.25	0.52	1.34
	Flow C	0.054	0.017	0.036	1.09	0.41	0.95	1.09	0.44	1.20
	Flow D	0.053	0.015	0.022	1.24	0.39	0.84	0.57	0.22	0.62
	Flow E	0.050	0.015	0.020	1.24	0.43	0.30	0.47	0.07	0.35
	Exp.	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
Tuijnder	**Nr.5-7**	0.053	0.036	0.070	1.22	1.06	1.39	3.52	0.38	1.00
	Nr.1-10	0.042	0.075	0.077	1.02	1.77	1.44	8.01	0.65	1.90
	Nr.6-1	0.058	0.060	0.083	1.28	1.63	1.47	5.84	0.60	1.60
	Nr.6-3	0.058	0.067	0.095	1.33	1.70	1.49	9.41	0.85	2.50
	Exp.	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
Termes	**T1-A**	0.037	0.096	0.081	0.86	1.52	1.56	13.29	1.47	3.43
	T1-B	0.051	0.092	0.093	1.17	1.73	2.08	17.13	2.60	6.55
	T1-C	0.073	0.079	0.103	1.71	1.61	2.67	16.20	3.14	6.89
	T1-D	0.073	0.061	0.129	1.71	1.35	2.71	21.10	2.56	6.99
	Exp.	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
Iseya	**R3 St.8**	0.078	0.092	0.136	1.76	1.33	2.51	13.93	2.29	4.55
	R4 St.8	0.106	0.087	0.180	2.41	1.23	3.42	14.83	4.88	5.04
	R6 St.4	0.122	0.071	0.043	2.37	0.86	1.00	3.47	1.86	1.58
	R7 St.5	0.154	0.072	0.103	2.91	0.97	1.72	4.47	3.15	2.55

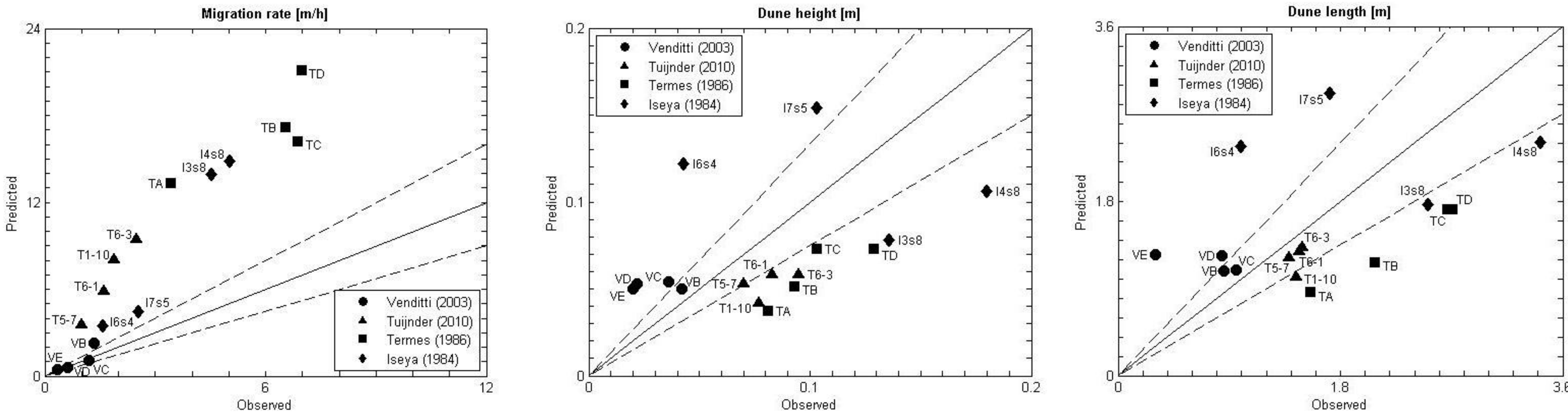


FIGURE 16: OBSERVED MIGRATION RATE (LEFT), DUNE HEIGHT (MIDDLE) AND DUNE LENGTH (RIGHT) VERSUS OBSERVED VALUES (PARAMETERIZED DUNE MODEL)

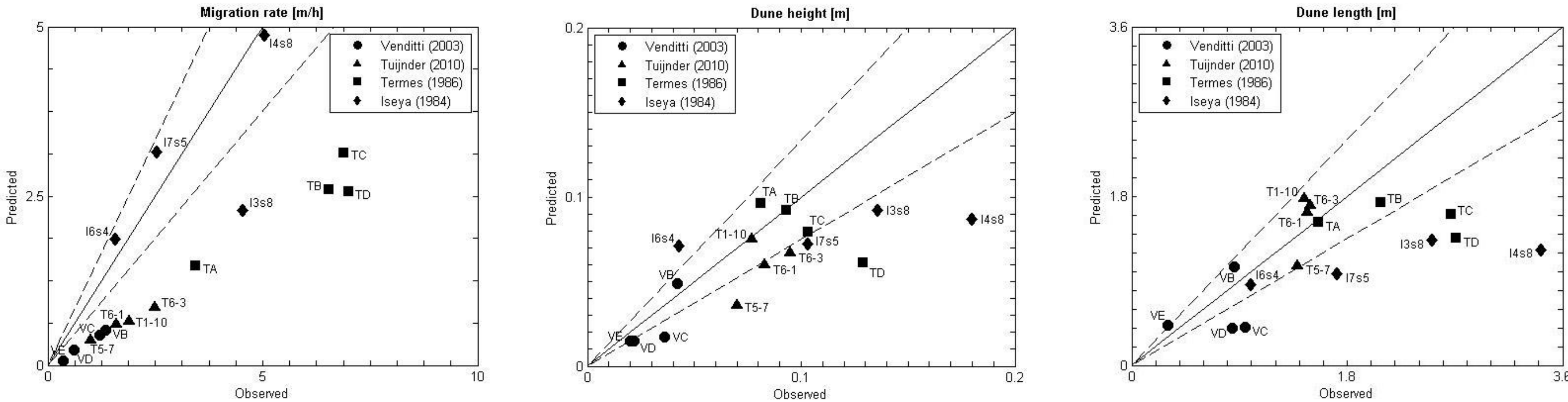


FIGURE 17: OBSERVED MIGRATION RATE (LEFT), DUNE HEIGHT (MIDDLE) AND DUNE LENGTH (RIGHT) VERSUS OBSERVED VALUES (CA MODEL)

5.2 ANALYSIS OF MODEL RESULTS

Sediment transport overestimation is a well-known problem of the parameterized dune model as stated by Warmink (Personal communication, 2014). This overestimation in sediment transport is also reflected in the predicted migration rates. The overestimation of the parameterized dune model can partly be attributed to the absence of the ripple factor. The ripple factor corrects the sediment transport for the Meyer-Peter Müller transport equation. The ripple factor reduces the sediment transport by a factor between 0.9 and 0.5 (Warmink, Personal communication, 2014). In addition, dune dimensions affect migration rates, smaller dimensions lead to a larger migration rate. The underestimation of dune dimensions for most experiments could contribute to the overestimation of the migration rates. Looking at the dune height and length predictions of the parameterized dune model it is clear the model overestimates dune dimensions for experiments with a small slope. The bed slope is the driving force in the parameterized dune model. The experiments where the parameterized dune model underestimates the dune dimensions are the experiments where the bed slope is about a factor two to three times larger than the experiments where the results are close to the observed dimensions, for example Venditti and Iseya, where slope varies between $5.5*10^{-4}$ and $10.7*10^{-4}$. For other experiments of Venditti and Tuijnder, slope varies between $11*10^{-4}$ and $22*10^{-4}$, results are reasonably (within the 25% accuracy band). For experiments with a larger slope, varying between $22*10^{-4}$ and $28.5*10^{-4}$, observed dune dimensions are larger than the predicted values. According to these observations the predictions of the parameterized dune model could depend on the slope. In figure 12 of the paper of Paarlberg et al. (2009) dune height and length predictions showed similar results (corresponding slope conditions presented in table 2 of that paper). Most of the predictions are within the 25% accuracy band; however the experiments that showed larger observed dunes dimensions than the predicted values are those experiments where the slope is larger than the experiments within the accuracy band. This could mean that the parameterized dune model is limited in applicability according to a band width for the bed slope, which is the driving force of the model.

The CA model predicts the sediment transport reasonably well, as expected since sediment transport is used as input according to Meyer-Peter Müller (1948). It is remarkable that dune migration is underestimated for most experiments, as a result the relation between sediment transport and migration does not hold for the CA model. A reason for this could be the way in which sediment transport is incorporated in the CA model; sediment transport in the CA model can differ from the used transport formula. The model calculates with slabs of sediment, instead of sediment particles. The development of dunes in the model might be more sediment consuming; it might be easier for individual sediment particles to compile dune formations compared to sediment slabs. Resulting in slower migrating dunes in the CA model than observed in the field, even though the sediment transport is assumed to be the same.

Looking at the dune height and length predictions of the CA model it is clear that the model underestimates the dune dimensions on average. However predictions of the dune dimensions for experiments VB, VE, T1-10, TA and TB are all within the 25% accuracy bands. It is hard to define specific conditions in which the CA model is performing reasonably, because there is dispersion in the input parameters for the experiments within the accuracy bands while experiments with comparable input parameters are not predicted within the limits (T6-1 is similar to T1-10 and TC is similar to TB). Although based on the transition zones in the step length, as observed earlier during the sensitivity analysis in chapter 4, one might say that the prediction results of the CA model could depend on the step length. Examination of the step length has led to better insight in the behaviour of the CA model. The transition zones are based on the amount of cells, as observed during the sensitivity analysis in chapter 4 and confirmed by a test after the validation phase. The range for reliable outcomes lies between step lengths of 0.1 to 0.375 meter, which corresponds to step lengths of 4 to 15 cells in the model. The step length for experiments VC and VD are 0.077 and 0.072 respectively and the step length of experiment T1-D is 0.458. Predictions of these experiments are all outside the 25% accuracy bands. This observation confirms the presumed transition zones in the step length.

5.3 EVALUATION OF BOTH MODELS

Both models show problems for predicting migration rates. The parameterized dune model is performing reasonably for experiments VC, VD and VE as presented in figure 19, however in general the model overestimates the dune migration. The CA model on the other hand underestimates the dune migration under all circumstances as visible in figure 19. Looking at the RMSE of the migration rate for both models one could say that the predictions of the CA model (2.03 m h^{-1}) are closer to the observed values in general than the predictions of the parameterized dune model (7.05 m h^{-1}). However, the deviation in relative terms is comparable. The overestimation of the parameterized dune model is about three times the observed migration rates, while the predictions of the CA model for Venditti, Tuijnder and Termes are about three times smaller than the observed migration rates.

On average, predictions of dune dimensions are lower than observed for both models. The CA model is performing better, looking at the number of predictions within the 25% accuracy band (15 against 8), although predictions of the parameterized dune model are very close to these accuracy bands. Therefore, looking at the RMSE of the predicted dune dimensions gives better insight in the performance of both models. The RMSE of the dune height shows that the CA model is performing better (0.036 m) than the parameterized dune model (0.044 m), whereas the RMSE of the dune length shows that the parameterized dune model is performing better (0.77 m) than the CA model (0.82 m). The performance of both models for dune dimension prediction is comparable according to the RMSE. Dune height for experiments of Venditti is predicted best by the CA model (figure 19). Results of the experiments of Iseya, conducted in a flume of four meter instead of one meter with a similar grain size and comparable Froude numbers to the experiments of Venditti, show an underestimation of the first two experiments (I3s8 and I4s8). Interesting is experiment I6s4, this is the only experiment that is seriously overestimated by both models. No clear explanation of this overestimation can be found, although the sudden decrease in observed dune height is remarkable because input parameters of that experiment does not differ in a great extend from the other experiments. For experiments of Tuijnder, with Froude numbers similar to Venditti and a larger grain size (0.8 instead of 0.5 mm), dune length is predicted close to the observed dune length by the models (± 30%) (figure 19). For the experiments of Termes, with higher Froude numbers and a smaller grain size, predicted dune dimensions are lower than observed in general. The trend of predictions of the parameterized dune model is similar to the observed dimensions (figure 19).

The dune dimensions of experiment VB are predicted within the 25% accuracy bands by both models. A part of the midsection of the CA model is plotted against the predicted dune profile of the parameterized dune model; results are presented in figure 18 to show the differences in dune profiles. Although dimensions are comparable, the results are completely different. The skew shape of the dune profile predicted by the parameterized dune model is not clearly represented in the profile of the CA model. The predicted troughs of the CA model are narrow and steep, while the dune crests are wide and flat. Runs with longer simulation times have shown that the predicted dune shape in the CA model becomes more asymmetric like the dunes predicted by the parameterized dune model. This indicates that longer run times are required to simulate equilibrium dunes as predicted by the parameterized dune model and observed in the field.

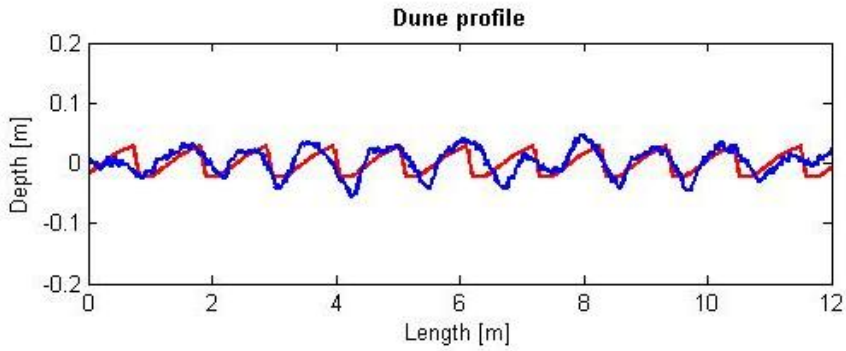


FIGURE 18: PREDICTED DUNE PROFILES FOR FLOW B. RED LINE REPRESENTS THE PARAMETERIZED DUNE MODEL, BLUE LINE THE CELLULAR AUTOMATON DUNE MODEL, FLOW DIRECTION FROM LEFT TO RIGHT

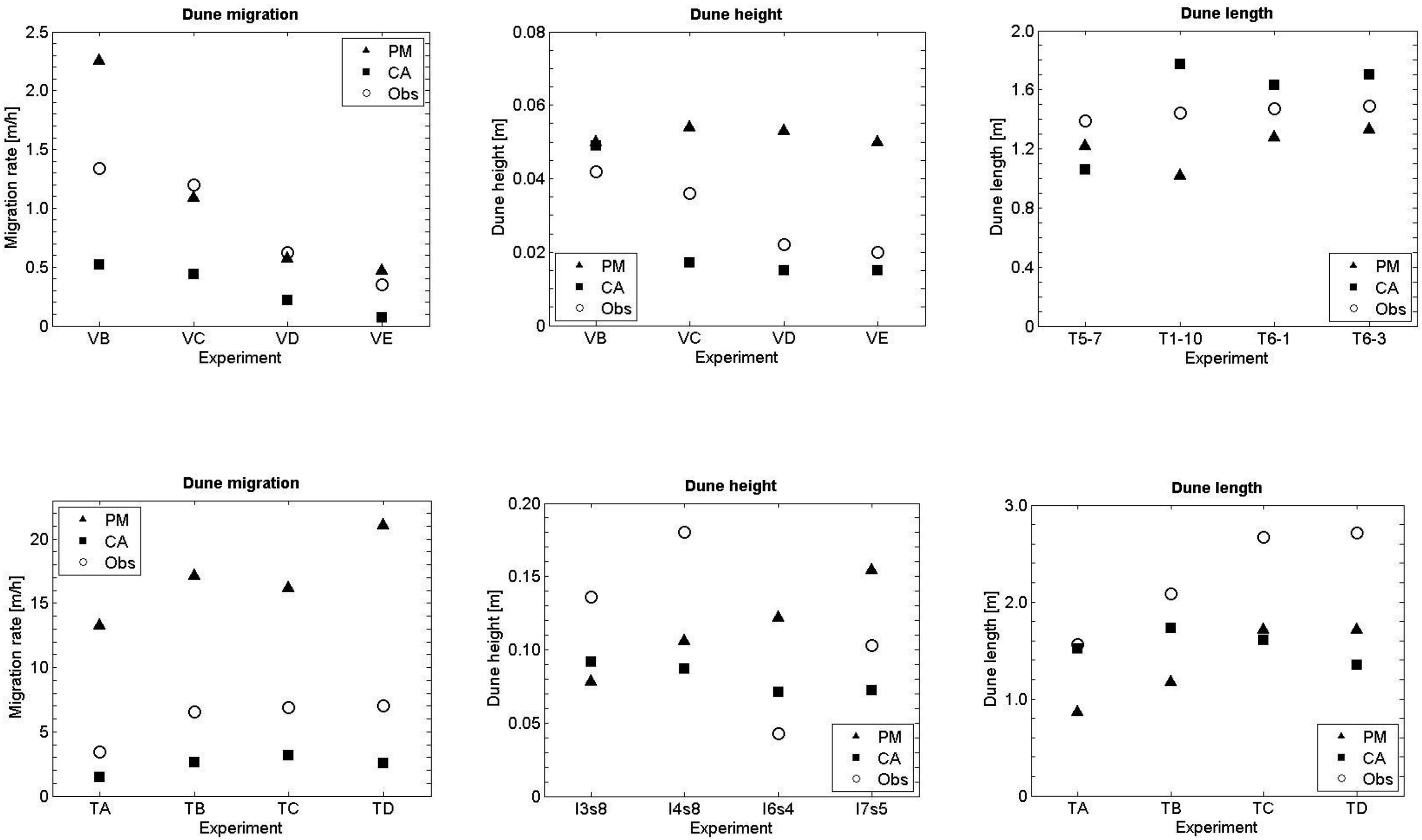


FIGURE 19: PERFORMANCE OF BOTH MODELS AGAINST THE OBSERVED VALUES. DUNE MIGRATION FOR VENDITTI (2003) AND TERMES (1986) (LEFT), DUNE HEIGHT FOR VENDITTI (2003) AND ISEYA (1984) (MIDDLE), DUNE LENGTH FOR TUIJNDER (2010) AND DUNE LENGTH TERMES (1986) (RIGHT)

5.4 MODEL SCALING

The CA model produces output in a three-dimensional way. It is interesting to check the performance of the model under scaled conditions. Therefore the experiments of Iseya (1984) are used. The experiments were conducted in a four meter width flume. To check the performance of the CA model, these experiments were simulated with a domain width of a single cell, one and four meter. The results of dune dimensions and migration are presented in figure 20. The predicted values are roughly the same for all conditions and thus the results are not influenced by the width of the domain. However the model run with a single cell shows a slight underestimation compared to the other results. This underestimation could be caused by the limitation of a single cell; no exchange is possible in lateral direction.

Important to mention is the difference in output for all conditions as depicted in figure 21. Because the CA model is capable of predicting variations in both length and width, a dune field can be simulated. The simulation with a width of a single cell only shows variation in the direction of the flow. The simulation with a width of one meter shows successive dunes along the direction of the flow and the simulation with a width of four meter shows more variation along the width of the domain. A predicted dune field with varying dunes in both length and width can be useful for many water management purposes. Although until now simulations are not tested for predictions along the width of the domain.

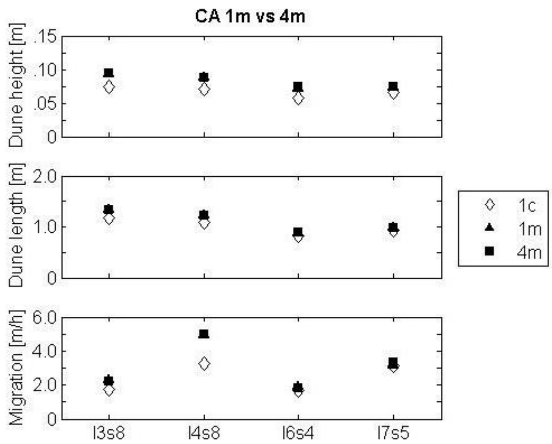


FIGURE 20: PREDICTED DUNE CHARACTERISTICS OF THE CELLULAR AUTOMATON DUNE MODEL FOR EXPERIMENTS OF ISEYA (1984)

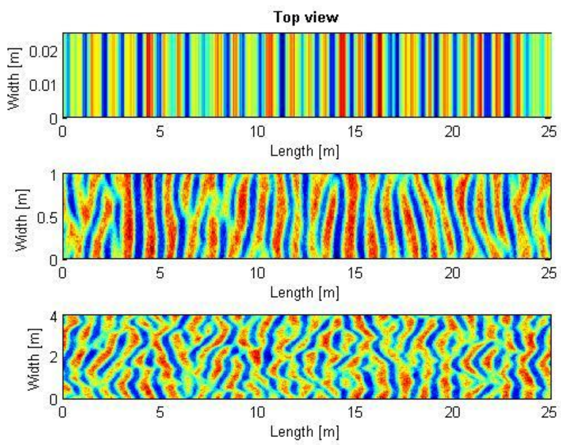


FIGURE 21: DUNE FIELD PREDICTED BY OF THE CELLULAR AUTOMATON DUNE MODEL FOR A FLUME WIDTH OF A SINGLE CELL, 1 AND 4 METER, FLOW DIRECTION FROM LEFT TO RIGHT

5.5 STRENGTHS AND WEAKNESSES

The parameterized dune model is directly related to the flow characteristics; the model is process-based. In this way, calculations of the model are closely related to the processes observed in the field. Paarlberg et al. (2009) have proven that the model is working for various experiments; this is also reflected in this experiment albeit in a limited extent. It is proved that the model is reliable for the prediction of dune dimensions for experiments with a slope between $11*10^{-4}$ and $22*10^{-4}$. Predictions of other experiments show results that are close to the 25% accuracy band and therefore the overall performance of the model is acceptable for the prediction of dune dimensions. On the other hand migration rates are overestimated consistently except for the experiments of Venditti (2003). The two-dimensional approach of the parameterized dune model focuses on dune evolution parallel to the flow direction, resulting in two-dimensional output in the vertical plane. The output of the model shows the typical asymmetrical shape of river dunes in equilibrium state. However variations along the channel width cannot be determined using the parameterized dune model, although these three dimensional dunes are present in nature. Best (2005) showed (several studies) that flow over three dimensional dunes is very different from two dimensional dunes. The three dimensionality affects the flow over dunes in a completely different way as also been stated by Venditti (2003). A fastest growing wavelength is determined using a numerical linear stability analysis, before the model starts calculating the dune evolution. This means the wavelength of the dune is already set and does not change over time. Thus, wave length evolution over time cannot be determined using the parameterized dune model.

The output of the CA model is three-dimensional; the model predicts bottom profiles in both length and width of the river bed. This results in the opportunity to predict dune fields as observed in the field. Tests with scaling of the domain showed there is almost no influence on the output. This means the model is reliable for a varying domain length and width. Calculations of the model are relatively fast compared to the parameterized dune model. Predicted dune dimensions are reasonably and frequently within the 25% accuracy bands, however migration rates are consistently underestimated. The probabilistic approach of the model creates a dune field with random varieties in dune characteristics. However, the probabilistic approach has a downside, which is the variation in output. Dune dimensions and their location vary also between different model runs. Influences of shear stresses due to the side wall are not incorporated. Another problem is that there is no equilibrium state so dunes keep growing. The model has a lot of potential because the flow direction can be adjusted during a run and a sediment distribution can be added as shown by Knaapen et al. (2013). Dunes developed under unidirectional flow will often show a vertical sorting process, whereas coarser material is deposited on the lower part of the bedform and finer grades are predominantly deposited in the upper part (Blom et al., 2003). However, the three-dimensional approach is limited to the grid because a bed slope is not present in the model.

CHAPTER 6

DISCUSSION

6.1 PERFORMANCE OF THE MODELS

The research presented in this thesis compares the performance of a parameterized dune model and a CA model. Although, to a large extent the focus of this research was on adjusting the CA model by adding time and length scales. Output has shown that the model predictions are not in the same range as the observed values. Many predictions are outside the 25% accuracy bands as presented in chapter 5. Therefore the conclusion of this research might be that both models are not reliable for the prediction of river dunes under various flume conditions. Nabi et al. (2014) for instance, showed predictions of dune heights with an error between 2% and 17%. However the used model in that research was more complex than the models used in this research and thus not suitable for fast predictions required for operational water management.

Paarlberg et al. (2009) proved that the parameterized dune model is working for various experiments. Although it seems that the parameterized dune model is limited in applicability according to the slope and Froude number. Research has shown that the model is reliable for prediction of dune dimensions limited to experiments with a slope between $11*10^{-4}$ and $22*10^{-4}$. Predictions of dune dimensions in this research are often not in the same range as the observed dimensions and migration rates are overestimated most of the time. The difference between the research of Paarlberg et al. (2009) and the research presented here is the range of chosen flow conditions. On average the water depth, slope and discharge are slightly higher for this research.

The CA model is tested for the first time in the way as presented in this thesis, by adding time and length scales to the model. There is no other research to compare results with. Results seem promising and show predictions that are reasonable for five experiments; however in general the predictions are slightly underestimated. Based on the results one could say the model is not reliable for the prediction of dune dimensions and migration rates, because there are significant deviations present in the predictions of the model compared to the observations. Nevertheless, I am convinced that the CA model could be a valuable tool to predict river dunes.

6.2 IMPROVEMENTS OF THE CELLULAR AUTOMATON DUNE MODEL

This research has shown that the model is able to predict dune dimensions and migration rates, however improvements are needed before the results are reliable. The methods presented in this research are based on assumptions and choices to adjust the CA model in a way that the model could be compared with the parameterized dune model within the time span of this research. There are ways to improve the model and most likely the predictions of the model, therefore further research is advised.

Interesting is the method used to add a time scale to the model. The sediment transport was used to determine the time scale of the CA model, by calculating the initial sediment transport according to the formula of Meyer-Peter Müller (1948). The weakness of this method is that the sediment transport in the model is assumed to be equal to the result of Meyer-Peter Müller. Consequently a comparison of the sediment transport in both models is actually a comparison between the sediment transport of the parameterized dune model and the formula of Meyer-Peter Müller. It might be interesting to implement a time scale according to the migration rate of the CA model and the observed time scales to overcome this problem. A downside of this method is the relation of migration rates, which will lead to predicted migration rates similar to the observed migration rates.

Initially the CA model only counted number of cells. Therefore input parameters were translated to a distance and the domain was fixed. In this way a length scale was added to the model. A couple of formulas where used to relate the input parameters of the model to the flow characteristics. The step length was used to link flow velocity to the travel distance of a single slab, therefore the formula of Sekine & Kikkawa (1992) was used. The problem here is that the formula was designed for single sediment particles and the CA model is calculating with slabs of sediment. This method only holds, when the assumption is made that the behaviour of single particles and the slabs is the same. Besides linking the step length to the flow characteristics, pickup probability is linked to the flow characteristics as well. This is done by using the formula of Cheng & Chiew (1998). The same problem as for the method of the step length holds for this method, as the formula is based on single particles while the CA model counts with sediment slabs. Further research on the application of these methods is necessary to determine if the assumptions are reliable. The presented methods are a first attempt to quantify the outcomes of the model; however there might be other ways to link the flow characteristics to the input parameters.

Prediction results for experiments with relatively small step lengths (< 0.1 m) or relatively large step lengths (> 0.375 m) could be improved by solving the problem with the transition zones of the step length by changing the amount of cells in the domain. Initial tests showed results that are promising; dune dimensions are closer to the observed values. However, the model should be tested extensively before drawing conclusions on these results. Therefore, the model probably needs to be re-calibrated for predictions within another transition zone. This will lead to a model version for each transition zone and the correct version should be selected depending on the flow characteristics of the experiments. Another way to overcome the problem with the step length could be to investigate the reason for the transition zones and correct the script.

6.3 LIMITATIONS AND OPPORTUNITIES

Input of the CA model is related to flow characteristics using formulas and therefore output of the model only contains a bottom profile. There is no relation with water depths, flow velocities and other flow characteristics. Because the lack of these characteristics, only bed load transport can be determined. Influence of the developed dunes on the flow is not represented in the model. Narteau et al. (2009) used a model where a cellular automaton model for sediment transport is linked to a lattice gas cellular automaton model to simulate the interactions between bed form dynamics, the fluid flow and the bed shear stress. This combination of two CA models could be an approach to relate the flow characteristics with the input parameters of the cellular automaton dune model. In this way flow characteristics will be represented by the lattice gas cellular automaton model.

A major problem within the CA model is that no equilibrium state is reached; dunes merge until only a single dune is left in the domain. The runtime of the model is used as calibration parameter in this research. However, time to equilibrium could be an important parameter to determine during flood events to see whether the predicted dunes develop or do not develop. This depends on the duration of the flood event and the time it takes to develop the predicted dunes. One approach to solve this problem might be to replace the recirculation of sediment by a constant sediment supply. First investigations with this method seem promising, dunes saturate after hours. However, the runtime has increased considerably, a single run will take hours and dune dimensions are heavily overestimated. Further research on this approach is advised and the model should be recalibrated to improve predictions. Another solution to the problem could be the simulation of river dune splitting as described by Warmink et al. (accepted). He proposed a method to implement dune splitting to reach equilibrium state in a dune evolution model.

Although the CA model generates a three-dimensional output, the displacement of slabs is carried out in the direction of the flow. In this way the model transports all the slabs in the same direction; however sediment is facing turbulent flow in reality and therefore can be transported in both lateral and longitudinal directions. Within the CA model only the process of avalanching allows slabs to move in a lateral direction. This complicates the applicability of the model in cases where flow is changing within the domain, caused by bends in a river for instance.

6.4 REFLECTION ON THE RESEARCH METHODOLOGY

The strength of this research is the adjustment of the CA model to make it suitable for a comparison with the parameterized dune model. The presented extensions of the CA model, have led to a model that can be compared with other dune predictors and field observations in a quantitative manner. This is a step forward in dune modelling using cellular automata. Where other studies only showed patterns without quantifying the results, this model can be used for predictions of dune dimensions and migration rates. The CA model is tested under various conditions against the parameterized dune model; this has led to insight in the processes that are included and the strengths and weaknesses of both models. Besides the improvements of the CA model, this research also gained better insight in the behaviour of the parameterized dune model. The comparison of two completely different models under various conditions has shown that there is still a lot to improve in the field of dune modelling.

The research also has some drawbacks, since time was limited choices had to be made that should be mentioned. The process of adjusting the CA model has some limitations. The assumptions made to link input parameters of the model to flow characteristics might be theoretical incorrect, as the used methods where designed for single particles only. On the other hand, results seem promising. Calibration of the CA model is based on the parameters left after the model adjustments. However, these parameters should better not be used for calibration; solving the problem of equilibrium state and linking the shear velocity increase to the flow characteristics presumably lead to better results. Therefore the calibration process should be extended using other parameters within the model. Various experiments were used to test both models. The probabilistic approach of the CA model results in varying outcomes for different runs. These variations seem to be small, although the uncertainty in outcomes is not tested extensively and therefore could not be quantified.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research was: "*To compare the performance of the cellular automaton dune model and the parameterized dune model for the prediction of dune dimensions, migration rates and sediment transport in equilibrium state, under flume conditions, similar to low-land river situations like the River Rhine (the Netherlands).*" Four research questions were used as a guideline to reach the goal. This chapter recaps the answers to these questions in the same order as they were answered throughout this thesis.

7.1 CONCLUSIONS

1. Which processes are modelled by the parameterized dune model and the cellular automaton dune model and which input data are necessary to calibrate and validate these models?

The processes modelled by the parameterized dune model are: a) flow separation to simulate the turbulent flow behind the dune crest, b) sediment transport using a sediment transport formula like the formula of Meyer-Peter Müller, c) avalanching in the flow separation zone when the leeside angle exceeds a certain threshold. The parameterized dune model is directly related to the flow characteristics. This is also reflected in the input parameters necessary to run the model; these are the bed slope, water depth, discharge and grain size.

The processes modelled by the CA model as used in the comparison of this research are: a) sediment transport that is reflected by moving slabs, b) shadow zones where sediment always deposits c) saltation of grains when being picked up d) avalanching when the angle between cells exceeds a certain threshold. The input parameters necessary for the CA model are changed after the adjustments. The input parameters necessary to run the improved CA model are the step length, pickup probability, shadow distance and sediment transport according to Meyer-Peter Müller (1948).

To ensure that the comparison of model results is based on the same conditions, both models are calibrated using flow A as reported by Venditti (2003). The data set used for the validation phase is a small selection of the data set that was used by Naqshband et al. (2014). The final data set that is used for validation contains sixteen experiments, consisting of four equal sets of four experiments from Venditti (2003), Tuijnder (2010), Termes (1986) and Iseya (1984). These experiments were selected to create a dataset containing various conditions.

2. How to add length and time scales to the cellular automaton dune model and how to relate the input parameters of the model to the data?

The length scale is added to the CA model by assuming a fixed domain with predefined dimensions. In this way dimensions of each cell can be determined. The model parameters are linked to this distance instead of a number of cells. Now, a length scale is added because both cells and parameters are no longer defined in numbers but in distances. The time scale is added to the model by assuming that the sediment transport within the model is equal to the sediment transport calculated by the formula of Meyer-Peter Müller. In this way it becomes possible to determine the time of a model run and thus every single slab movement can be linked to a time step.

Besides the introduction of length and time scales, the CA model needed a link to the flow characteristics. There was no relation with the parameters presented in the data sets. Therefore the step length in the CA model is linked to the flow characteristics using the theory of Sekine & Kikkawa (1992). The shadow distance is defined assuming the length is equal to the flow separation zone using theories of Paarlberg et al (2007) and Schatz & Herrmann (2006). The pickup probability is linked to the flow characteristics using the theory of Cheng & Chiew (1998) and the deposition probability is related to this pickup probability in a reversed way. After the adjustments data of the Shields parameter, shear velocity, settling velocity, brink point height, grain size and Chézy coefficient are required to run the CA model. In addition it is important to determine the dimensions of the domain.

3. How well do both models perform compared to flume data?

The parameterized dune model overestimates the sediment transport about a factor of two to four and migration rates are overestimated about a factor of three compared to the flume data. Looking at the dune height most of the experiments are under- and overestimated. The RMSE of the predicted dune height is 0.044 m. Deviations in the dune length predictions are similar to the dune height prediction for each experiment, although the variety is less; dune length predictions are relatively closer to the observed values. The RMSE of the predicted dune length is 0.77 m.

The CA model predicts a sediment transport close to the flume data (± 25%). Migration rates are underestimated in general. Looking at the dune height is underestimated in general with an RMSE of 0.036 m. Dune length predictions are relatively closer to the observed values as also observed for the parameterized dune model. The RMSE of the predicted dune length is 0.82 m.

Both models are performing quite well based on the results as presented in chapter 5. The CA model is performing better looking at the number of predictions within the 25% accuracy band (15 against 8), although predictions of the parameterized dune model are very close to these accuracy bands. Performance of both models for dune dimension prediction is comparable according to the RMSE.

4. What are the strengths and weaknesses of the parameterized dune model and the cellular automaton dune model?

The parameterized dune model is directly related to the flow characteristics; the model is process-based. In this way, calculations of the model are closely related to the processes observed in the field. Paarlberg et al. (2009) have proven that the model is working for various experiments; this is also reflected in this experiment albeit in a limited extent. The overall performance of the model is acceptable for the prediction of dune dimensions. The output of the model shows the typical asymmetrical shape of river dunes in equilibrium state. Although the two-dimensional approach limits the output, variations along the channel width cannot be determined. The wavelength of the dune does not change over time, thus wave length evolution over time cannot be determined using the parameterized dune model.

The CA model is three-dimensional and predicts bottom profiles in both length and width of the river bed. However the three-dimensional approach is limited to the grid; a bed slope is not present in the model. The model has potential because the flow direction can be adjusted during a run and a sediment distribution can be added as shown by Knaapen et al. (2013). The probabilistic approach leads to random varieties in dune characteristics, which is also observed in the field. However, this approach has a downside because dune dimensions and their location vary also between different model runs. Influences of shear stresses due to the side wall are not incorporated. No equilibrium state is reached and dunes keep growing.

Reflection on research objectives

Length and time scales are added to the CA model; this allows the model to produce quantified output. The model is calibrated using the same data as the parameterized dune model. Comparison of both models has led to insight in the performance of the CA model and the parameterized dune model for the prediction of dune characteristics under flume conditions. Possible causes for the differences in predictions are mentioned and strengths and weaknesses of both models are discussed.

The presented CA model is able to predict dune dimensions when pickup probability, step length, shadow distance and sediment transport are known. These parameters can be determined using the formulas presented in this thesis. Results are promising for flume conditions similar to low-land river situations like the River Rhine (the Netherlands) and performance of the CA model is comparable to the performance of the parameterized dune model for tested conditions.

7.2 Recommendations

The extension of the CA model with length and time scales and the linking to flow characteristics as presented in this thesis are a first attempt to gain quantitative output of the CA model. The presented methods to adjust the CA model are based on many assumptions, the question remains which approaches could be improved. In addition, there are problems with the CA model that should be solved. The applicability of the models could be tested in a broader perspective.

Methods for model adjustments
The implementation of a time scale should be analysed and improved. The weakness of the method used is that the sediment transport in the CA model is assumed to be the same as the result of Meyer-Peter Müller. It would be valuable to implement a time scale according to other relations between time and model parameters in a way that also sediment transport is predicted by the model itself. Questions to be answered might be: What relations between time and model parameters are included in the CA model? How to link the model to these time dependent parameters?

Further research on the application of the methods used to link the input parameters to flow characteristics is necessary to determine if the assumptions are reliable. Problem is that the used formulas are based on single particles while the CA model counts with sediment slabs. To improve the linking of flow characteristics to input parameters important questions might be: Are the used methods of Sekine & Kikkawa (1992) and Cheng & Chiew (1998) applicable for sediment slabs as present in the CA model? What other methods can be used to link flow characteristics to input parameters of the model?

Improvements for an ideal cellular automaton dune model
The problem with the equilibrium state of the CA model is important to investigate. Time to equilibrium could be an important parameter to determine during flood events to see whether the predicted dunes develop or not. Options to consider when solving this problem might be the approach of replacing the recirculation of sediment by a constant sediment supply or implementing a method to simulate dune splitting.

An opportunity to improve the relation of the CA model with the flow characteristics is the linking of the shear velocity parameters to flow characteristics. The shear velocity parameters c1 and c2 are used for calibration in this research; however the values of these parameters should depend on the flow characteristics of the experiments. They influence the distance travelled according to the height from where a slab is picked. The higher the picked slab is in the column, the larger the travelled distance will be. These shear velocity constants should be related to the shape of the flow profile in a more direct way.

The shadow distance is based on dune dimensions as observed during the experiments. Problem here is that the shadow distance is based on a predefined single value instead of a changing variable, whereas dunes develop over time. A better way to determine the shadow distance would be to relate the shadow distance with the actual dune dimensions predicted by the model.

Further investigation of the transition zones present in the CA model could help improve the predictions. Therefore, the model could be calibrated again for predictions within another transition zone or one could investigate the reason for the transition zones. Questions to be answered might be: What causes the transition zones within the model for changing step lengths? Is there a solution to solve this problem?

Calibration of the model is performed using only the parameters left after the adjustments. In this way the assumption is made that the other parameters are predict correctly. This is probably not the case, because a lot of assumptions were made. Besides, calibration is based on runtime which influence should be eliminated after solving the problem of equilibrium state.

Broader perspective

There are many possible improvements of the CA model, before testing the model in a broader perspective. However the focus of this research was moreover on the comparison of the CA model with the parameterized dune model. The research focused on flume conditions similar to low land rivers, it might be interesting to test the models in a broader perspective. One could think of flume experiments with coarser bed materials, larger flow velocities or different bed slopes. Besides, the models could be tested for field data to investigate their value for real river predictions.

In this research the focus was limited to situations with unidirectional flow and homogeneous sediment only. There is still a lot of work to do for these situations as described earlier. However, the CA model initially could operate for varying flow directions and varying grain sizes (Knaapen et al. 2013). This is important to consider, since the model could be widely implemented when it is adjusted correctly. In this research, focus was on uniform sediment. However, implementing a sediment distribution could lead to better insight in the sorting of sediment along dunes. Including the varying flow direction could lead to an applicability of the model in a broad perspective. The model might be applicable for tidal rivers, estuaries and probably for evolution of sand waves in seas and oceans in a quantitative way.

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Appendices

A. Background information about used experiments

Additional information about the selected data sets is presented here. The focus of the researches, flume characteristics, the experimental setup, and methods to measure the results are described briefly.

A.1 Experiments of Venditti (2003)

Focus of the study of Venditti (2003) is on the initiation of bedforms from a flat sand bed. The experiments were conducted in a 15.2 m long, 1 m wide flume that recirculates both sediment and water. The used sediment is a narrowly graded sand (D50 = 0.5 mm). Runs were about 12 hours, although equilibrium state for dune dimensions and migration rates was reached after about 1.5 hours. The bed topography is monitored using acoustic echo-sounders and a Super-VHS video camera. Corresponding dune dimensions were averaged according to all measures in equilibrium state. The experimental conditions like flow velocity, flow depth and grain size, were comparable to sand-bedded channels. Therefore, observations in the flume are assumed to have a 1:1 scaling with 'real' river channels Venditti (2003).

A.2 Experiments of Tuijnder (2010)

The focus of the research of Tuijnder (2010) is on supply limited conditions in the lower-flow regime as occurs in the lower reaches of many rivers like the River Rhine in the Netherlands. Although the main purpose of the research is on supply limited conditions, six experiments were executed with unlimited sediment supply (alluvial conditions). The experiments were conducted in a 30 m long, 1 m wide flume that recirculates both sediment and water. The bed and water level were measured over a length of 17.45 m using echo sensors. Bed level is measured at three transects parallel to the flow direction, dimensions were determined using a 'zero-crossing' method (van der Mark et al., 2008).

A.3 Experiments of Termes (1986)

The focus of the research of Termes (1986) is on testing bedform dimensions under varying conditions and to link those dimensions to resistance parameters. The experiments were conducted in a 30 m long, 1 m wide flume that recirculates both sediment and water. Dune profiles were measured in the middle and 33 cm left and right of the middle of the flume after reaching equilibrium state. Averaged values of these profiles determine the bedform dimensions as used in this research.

A.4 EXPERIMENTS OF ISEYA (1984)

The focus of the research of Iseya (1984) is on the behaviour of bedforms, changes of flow characteristics and the change of suspended sediment transport under varying flow conditions. The experiments were conducted in a 160 m long, 4 m wide recirculating flume. Conditions during the experiment were set in a way that dunes in the lower flow regime developed on an initially flat bed. Profiles of the river bed were measured using a sonic sounder. The dune data are based on two longitudinal profiles of the bed surface, each located one-third of the width from both walls. Each time measures were taken the experiment was paused.

B. Table A: Input parameters

Experiment		q [m2/s]	h [m]	i [-]	D50 [m]	θ cr [-]	Λ [m]	P [-]	SD [m]	qs [m2/s]
		Input parameters								
		PDM					CA			
Flow A	Venditti (2003)	0.0759	0.1516	0.00120	0.0005	0.0500	0.141	0.568	0.231	6.932656E-06
Flow B		0.0723	0.1517	0.00110	0.0005	0.0500	0.140	0.522	0.202	5.518951E-06
Flow C		0.0696	0.1533	0.00070	0.0005	0.0500	0.077	0.249	0.174	3.048282E-06
Flow D		0.0611	0.1530	0.00055	0.0005	0.0500	0.072	0.128	0.104	1.282792E-06
Flow E		0.0546	0.1534	0.00055	0.0005	0.0500	0.152	0.139	0.095	6.388581E-07
		q [m2/s]	h [m]	i [-]	D50 [m]	θ cr [-]	Λ [m]	P [-]	SD [m]	qs [m2/s]
DS-II Exp nr 5-7	Tuijnder (2010)	0.0940	0.2000	0.00150	0.0008	0.0500	0.272	0.596	0.340	6.660701E-06
DS-II Exp nr 1-10		0.1050	0.2000	0.00220	0.0008	0.0500	0.324	0.756	0.373	1.344616E-05
DS-II Exp nr 6-1		0.1300	0.2500	0.00170	0.0008	0.0500	0.323	0.740	0.403	1.231998E-05
DS-II Exp nr 6-3		0.1500	0.2600	0.00220	0.0008	0.0500	0.372	0.827	0.461	2.097931E-05
		q [m2/s]	h [m]	i [-]	D50 [m]	θ cr [-]	Λ [m]	P [-]	SD [m]	qs [m2/s]
T1-A	Termes (1986)	0.1010	0.1680	0.00279	0.0004	0.0500	0.298	0.916	0.393	2.553966E-05
T1-B		0.1730	0.2290	0.00285	0.0004	0.0500	0.345	0.944	0.451	5.051185E-05
T1-C		0.2350	0.2800	0.00270	0.0004	0.0500	0.365	0.952	0.500	6.809310E-05
T1-D		0.2950	0.3350	0.00283	0.0004	0.0500	0.458	0.963	0.626	8.539340E-05
		q [m2/s]	h [m]	i [-]	D50 [m]	θ cr [-]	Λ [m]	P [-]	SD [m]	qs [m2/s]
Run 3 step 8	Iseya (1984)	0.2490	0.3450	0.00245	0.00057	0.0500	0.218	0.940	0.660	3.557158E-05
Run 4 step 8		0.3675	0.3950	0.00237	0.00057	0.0500	0.199	0.946	0.873	6.954959E-05
Run 6 step 4		0.2600	0.3880	0.00101	0.00057	0.0500	0.112	0.826	0.207	1.887633E-05
Run 7 step 5		0.3725	0.4770	0.00107	0.00057	0.0500	0.125	0.877	0.500	3.170249E-05

C. Table B: Prediction results against observations

		Output results														
		Dune height [m]			Dune length [m]			Migration [m/h]			Time [h]			qs eq. [m2/s]		
Experiment		PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
Flow A	Venditti (2003)	0.050	0.054	0.048	1.08	1.14	1.17	2.60	0.71	2.34	2.43	5.35	1.50	1.51E-05	6.93E-06	n/a
Flow B		0.050	0.049	0.042	1.08	1.05	0.86	2.25	0.52	1.34	2.87	6.44	1.50	1.24E-05	5.52E-06	n/a
Flow C		0.054	0.017	0.036	1.09	0.41	0.95	1.09	0.44	1.20	6.96	4.08	1.50	6.46E-06	3.05E-06	n/a
Flow D		0.053	0.015	0.022	1.24	0.39	0.84	0.57	0.22	0.62	11.92	6.11	1.50	3.78E-06	1.28E-06	n/a
Flow E		0.050	0.015	0.020	1.24	0.43	0.30	0.47	0.07	0.35	9.49	26.24	1.50	3.36E-06	6.39E-07	n/a
		PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
DS-II Exp nr 5-7	Tuijnder (2010)	0.053	0.036	0.070	1.22	1.06	1.39	3.52	0.38	1.00	1.88	10.23	n/a	2.24E-05	6.66E-06	5.47E-06
DS-II Exp nr 1-10		0.042	0.075	0.077	1.02	1.77	1.44	8.01	0.65	1.90	0.80	6.66	n/a	4.24E-05	1.34E-05	1.20E-05
DS-II Exp nr 6-1		0.058	0.060	0.083	1.28	1.63	1.47	5.84	0.60	1.60	1.83	7.21	n/a	3.82E-05	1.23E-05	9.51E-06
DS-II Exp nr 6-3		0.058	0.067	0.095	1.33	1.70	1.49	9.41	0.85	2.50	1.03	5.10	n/a	6.36E-05	2.10E-05	1.71E-05
		PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
T1-A	Termes (1986)	0.037	0.096	0.081	0.86	1.52	1.56	13.29	1.47	3.43	0.66	3.51	n/a	5.95E-05	2.55E-05	2.34E-05
T1-B		0.051	0.092	0.093	1.17	1.73	2.08	17.13	2.60	6.55	0.66	2.09	n/a	1.08E-04	5.05E-05	6.04E-05
T1-C		0.073	0.079	0.103	1.71	1.61	2.67	16.20	3.14	6.89	0.87	1.67	n/a	1.42E-04	6.81E-05	8.73E-05
T1-D		0.073	0.061	0.129	1.71	1.35	2.71	21.10	2.56	6.99	1.80	1.58	n/a	1.84E-04	8.54E-05	1.07E-04
		PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp	PDM	CA	Exp
Run 3 step 8	Iseya (1984)	0.078	0.092	0.136	1.76	1.33	2.51	13.93	2.29	4.55	0.91	1.92	3.67	1.31E-04	3.56E-05	n/a
Run 4 step 8		0.106	0.087	0.180	2.41	1.23	3.42	14.83	4.88	5.04	1.17	0.88	4.83	1.91E-04	6.95E-05	n/a
Run 6 step 4		0.122	0.071	0.043	2.37	0.86	1.00	3.47	1.86	1.58	6.30	1.66	1.33	4.84E-05	1.89E-05	n/a
Run 7 step 5		0.154	0.072	0.103	2.91	0.97	1.72	4.47	3.15	2.55	6.01	1.21	4.58	7.37E-05	3.17E-05	n/a