SEDIMENT TRANSPORT PROCESSES IN DUNE MORPHOLOGY

AND THE TRANSITION TO UPPER-PLANE STAGE BED

OLAV J.M. VAN DUIN

Promotion committee:

prof. dr. ir. G.P.M.R. Dewulf	University of Twente, chairman and secretary
prof. dr. S.J.M.H. Hulscher	University of Twente, promotor
dr. ir. J.S. Ribberink	University of Twente, co-promotor
prof. dr. ir. W.S.J. Uijttewaal	University of Delft
prof. dr. ir. H.J. de Vriend	University of Twente
prof. dr. ir. C.H. Venner	University of Twente
dr. ir. A.J.F. Hoitink	Wageningen University
dr. ir. A. Crosato	UNESCO-IHE, Institute for Water Education
dr. K.M. Wijnberg	University of Twente
dr. E. Mosselman	Deltares, University of Delft

This study was carried out as part of the project 'BedFormFlood', supported by the Technology Foundation STW, the applied science division of NWO and the technology programme of the Ministry of Economic Affairs.

Cover: no name (by Elise Leusink)

Printed by: Gildeprint - Enschede, The Netherlands

ISBN: 978-90-365-3888-6
DOI: 10.3990/1.978903653888-6
URL: http://dx.doi.org/10.3990/1.9789036538886

SEDIMENT TRANSPORT PROCESSES IN DUNE MORPHOLOGY
AND THE TRANSITION TO UPPER-STAGE PLANE BED

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit Twente, op gezag van
de rector magnificus, prof.dr. H. Brinksma,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen op
donderdag 17 december 2015
om 14:45 uur

door

Olav Jacob Maarten van Duin
geboren op 9 februari 1984
te Delft

This thesis is approved by:

prof. dr. S.J.M.H. Hulscher promotor
dr. ir. J.S. Ribberink co-promotor

ISBN: 978-90-365-3888-6

CONTENTS

PREFACE 9

SUMMARY 11

SAMENVATTING 13

1 INTRODUCTION 17

1.1 THE IMPORTANCE OF BEDFORMS IN THE CONTEXT OF FLOOD MODELLING 17
1.2 DUNE EVOLUTION AND DUNE MODELLING 20
1.3 SEDIMENT DYNAMICS 24
1.4 RESEARCH METHODOLOGY 25
1.4.1 RESEARCH PROJECT 25
1.4.2 RESEARCH OBJECTIVES 26
1.4.3 RESEARCH QUESTIONS 26
1.4.4 RESEARCH APPROACH 27
1.5 THESIS OUTLINE 28

2 PARTICLE STEP LENGTH VARIATION ALONG RIVER DUNES 29

2.1 INTRODUCTION 31
2.2 STEP LENGTH 32
2.3 EXPERIMENTAL SET-UP 34
2.4 PARTICLE MOVEMENT OBSERVATIONS 38
2.5 STEP LENGTH MODEL VALIDATION 43
2.6 DISCUSSION 44
2.7 CONCLUSION 45

3 THE MODELLING OF SPATIAL LAG IN BED LOAD TRANSPORT PROCESSES AND ITS EFFECT ON DUNE MORPHOLOGY 47

3.1 INTRODUCTION 49
3.2 DUNE MODEL 52
3.2.1 GENERAL SET-UP 52
3.2.2 FLOW MODEL 54
3.2.3 SOLVING THE FLOW EQUATIONS 56
3.2.4 BED LOAD SEDIMENT TRANSPORT MODEL 56
3.2.5 STEP LENGTH 59
3.2.6 BED EVOLUTION 60
3.2.7 FLOW SEPARATION 60

3.3 RESULTS **61**
3.3.1 FLOW A WITH THE ORIGINAL BED LOAD MODEL 63
3.3.2 FLOW A WITH LINEAR RELAXATION 64
3.3.3 FLOW A WITH PICK-UP AND DEPOSITION 67
3.3.4 DUNE SHAPES 68
3.3.5 RESULTS WITH BEST-FITTING MODEL SETTINGS 70
3.3.6 POTENTIAL FOR PREDICTION OF UPPER-STAGE PLANE BED 71
3.4 DISCUSSION **73**
3.5 CONCLUSION **74**

4 MODELLING REGIME CHANGES OF DUNES TO UPPER-STAGE PLANE BED IN FLUMES AND IN RIVERS **77**

4.1 INTRODUCTION **79**
4.2 DUNE MODEL **82**
4.2.1 GENERAL SET-UP 82
4.2.2 FLOW MODEL 83
4.2.3 GOVERNING EQUATIONS 83
4.2.4 BED LOAD SEDIMENT TRANSPORT MODEL 85
4.2.5 STEP LENGTH 86
4.2.6 BED EVOLUTION 87
4.3 STEP LENGTH MODELS FROM LITERATURE **87**
4.3.1 SEKINE & KIKKAWA (1992) STEP LENGTH MODEL 87
4.3.2 SHIMIZU ET AL. (2009) STEP LENGTH MODEL 87
4.3.3 COMPARISON OF STEP LENGTH MODELS 88
4.4 NEW STEP LENGTH MODEL **90**
4.5 RESULTS WITH FLUME CONDITIONS **92**
4.6 RESULTS WITH RIVER CONDITIONS **96**
4.6.1 RESULTS FOR THE RIVER SCENARIO 97
4.6.2 RESULTS FOR THE MORE EXTREME RIVER SCENARIO 101
4.7 DISCUSSION **106**
4.8 CONCLUSION **109**

5 SYNTHESIS **111**

5.1 DISCUSSION **111**
5.1.1 THE ROLE OF SUSPENDED LOAD COMBINED WITH BED LOAD 111
5.1.2 HYDRAULIC ROUGHNESS IN FLOOD MODELLING 112
5.1.3 THE INFLUENCE OF THE LATERAL VARIATION OF DUNES, SUPERIMPOSED BEDFORMS AND OTHER FORMS OF IRREGULARITY ON ROUGHNESS 113
5.2 CONCLUSIONS **114**
5.3 RECOMMENDATIONS **117**

REFERENCES **123**

PUBLICATIONS **131**

ABOUT THE AUTHOR **133**

PREFACE

Finally the work is done, and the preface can be written! Completing this work could not have been possible without the help and support of various people. So, time for some thanks, here goes!

First of all, I am grateful for my supervisors. Suzanne and Jan, over the years we've had a lot of discussions and both of you have helped me with navigating the scientific field, with Jan mostly focusing on the fine details of my research, and Suzanne on the broader scope and implications thereof. Also your help with finishing this thesis has been invaluable. The countless notes of Jan (literally) on my thesis have improved it greatly, and as an aside enabled me to train my handwriting deciphering skills very thoroughly. Suzanne taught me many things, but the idea that the science is most convincing when you tell a strong and clear story may be the most important lesson. Thank you both for your help and encouragement during my research. It has been a pleasure.

This research would not have been possible without you, Marjolein. Not only did you secure the funding for the research project, but you most importantly guided us through the first years of the project as our project leader. Your knowledge and guidance helped me a lot, and I have warm memories of our pleasant meetings, thank you. Within our project team, Fenneke and Ralph guided us as well. Thank you both for your insights and discussions over the years.

Not only did the project team have supervisors, it had other researchers as well. Jord and Suleyman, I have enjoyed working with and alongside you greatly. It was fruitful with regard to sharing knowledge and generally helping each other out, but most of all it was fun and I have always enjoyed hanging out with you at the university, laboratory and conferences. Thank you for all of that.

During and before the experimental work in Braunschweig we were supported by René, Arjan, David, Peter, Uwe, and Joe. Thank you all for your support. Andries, thank you for your help getting us started working with your model, as well as the discussions over the years in various settings. Working in a research project means arranging all kinds of things, and luckily Anke, Joke and Brigitte were there to help me with that. Thank you for your support, and pleasant talks.

I have spent a lot of time with Jolanthe and Erik in W-100 and outside of it, and the latter often included Ronald and Anne as well. Thank you for making those times fun, and the mental support you have given me. I hope to you see many times more, to share stories and laughs (and drinks and burgers). Conferences are an important part of research, for the knowledge shared and maybe also a tiny bit because of the enormous amounts of fun you have with your colleagues. Bas, Suleyman, Erik, Jord, Freek, Arjan, thank you for your various adventures abroad. Especially China with Bas (skipping 'class' to rush through the Forbidden City), Suleyman and Erik (vacation afterwards) I will never forget.

With the risk of still forgetting some people, thanks for the following colleagues are in order: Blanca, Pieter (x2), Rolien, Jebbe, Joanne, Lisette, Wenlong, Abebe, Nicholas, Kurt, Mehmet, Kathelijne, Arjen, René, Denie, Martijn, Winnie, Maarten, Michiel, Ruth, Guoping, Leonardo, Ertug, Markus, Thaiënne, Marcela, Koen, Wouter, Joep, Mesfin, Geert, Lianne, Juan Pablo, La, Rick, Mireia, Hero, Andry, and Hatem,

This page is fast running out of space, so: various other friends, study buddies, band members, family members, you know who you are and thank you for being there!

Papa and mama, thank you for support from 31 years ago up until now. Your support has encouraged me to do all these things, and I am forever grateful for that and your love. Elin, thank you for being such a kind and generous sister. It has been great seeing you grow into the person you have become. I love you all.

And now for the most important person of all, who is carrying a second person (maybe even on your shoulder by the time you read this). Nicole, thank you for love, patience and pretty much keeping me alive this past year. I couldn't have done it without your support and reminders to not only drink coffee during my working at home, but also to eat and drink other things. We already have had a lot of fun, and we will have many more adventures in the future. I am completely looking forward to spending the rest of my life with you. Ik hou van jou!

Olav van Duin, Utrecht, 25th of November 2015

SUMMARY

Delta areas around the world are densely populated, and feature an incredible amount of economic activity. Especially with regard to changing climate, it is vital to protect these areas from flooding by rivers. For flood modelling of lowland rivers specifically it is important to understand the interaction between river flow and bedforms. Bedforms arise when sediment (e.g. sand) that is transported downstream, organizes itself in (rhythmic) patterns on the river bed. Dunes are common bedforms in the sandy rivers found in low-lying land, and affect the water depth in the river strongly, especially under flood conditions. This is because under increasing discharge and flow strength, they grow rapidly and become more asymmetric and steeper. Due to this, water is slowed down more and more by the dunes (the dunes impose hydraulic roughness) during increasing discharge. However, if the discharge increases enough, dunes eventually degrade due to processes that dampen the bedform. Eventually a transition to the upper-stage plane bed regime can occur; the flow is so powerful that the dunes are completely washed away and the hydraulic roughness and water depth decrease sharply. It is valuable to be able to describe the aforementioned processes with models that are accurate but also computationally cheap.

This thesis aims to i) better understand the sediment transport processes along dunes and which processes control the transition from a dune regime to an upper-stage plane bed regime, and, ii) based on this understanding, to investigate the possibilities of an idealized dune evolution model to represent a wide range of dune shapes including upper-stage plane bed.

An important property of how sand particles move along the bed (as so-called bed load) is the step length of individual particles, which controls the distance between where the flow is most able to move sediment and where the maximum bed load occurs. The step length is the distance between where a particle is picked up, and where it is deposited. Studies under *flat bed conditions* have shown that it varies due to varying flow, and generally increases when flow strength increases. For this research, a new laboratory experiment has been undertaken to measure step lengths under *dune conditions*. For a series of dunes the motion of particles was captured with a high-speed camera. The experiment showed that the variation of step length distribution along a dune is small, which is different from what is expected from the flat bed conditions. It is hypothesized that this is due to the specific variations in the flow field (turbulence) as present along dune surfaces.

In dune evolution models, commonly transport models are applied where the flow properties are directly linked to sediment transport. However, this disregards the influence of step length, which causes a spatial lag between flow properties and sediment transport. This is an import driver for the transition between regimes. Other types of bed load models, like a pick-up and deposition model, do include this lag. For this research, two of those models have been tested in an existing idealized dune model (which originally did not allow for this lag). The original model has been compared with a version that uses a relaxation equation, and with a version that includes pick-up and deposition processes. Both new model versions rely on the mean particle step length, which has a strong influence on the resulting dune shape. The comparison has shown that the results are best with the pick-up and deposition model, combined with a step length of 25 times the particle diameter. It has also been shown that in principle the model is also able to wash out fully grown dunes, by increasing the step length parameter manually to mimic the real life behaviour of step length under increasing flow strength.

To better approximate this behaviour, the model has been further adjusted. Firstly, step length has been made to depend on the mean bed shear stress (which arises from water flowing over the bed). This model lets the step length increase with increasing flow strength, in line with previous experimental results. To also account for sediment which is transported high above the bed (as so-called suspended load) and the large scale turbulence seen in rivers, the step length has also been made dependent on water depth. This model approach has been tested successfully with a synthetic data set corresponding to laboratory conditions, and has produced results similar to a more advanced model. It has been shown that with increasing discharge the flow strength increased, which led to higher step length and the washing out of dunes. Although this model version overestimated the dune height for a river situation, it was shown the model concept describes dynamic river dune processes including the transition to upper-stage plane bed. Furthermore, it was shown that if a transition to upper-stage plane bed occurs in a realistic river scenario, a significant drop of the water depth can occur.

SAMENVATTING

De dichtstbevolkte delen van de wereld zijn deltagebieden, en deze gebieden zijn ook economisch zeer actief. Het is daarom van uiterst belang om deze gebieden tegen overstromingen te beschermen, zeker met het oog op klimaatverandering. Het is belangrijk om de wisselwerking tussen rivierstroming en de vormen op de bodem te begrijpen om overstromingsberekeningen beter te maken, zeker in laaggelegen land. Beddingvormen ontstaan wanneer sediment (bv. zand) wat door de rivier verplaatst wordt zich in (ritmische) patronen organiseert. Rivierduinen zijn veel voorkomende beddingvormen in de zandige rivier van laaggeleden land, en hebben een sterk effect op de waterstanden in de rivier. Dit komt omdat ze sterk groeien, en meer asymmetrisch en steiler worden, als de afvoer en kracht van de stroming in de rivier toeneemt. Hierdoor remmen de duinen het water telkens meer af; hun hydraulische ruwheid neemt toe. Echter, als de kracht van het water genoeg toeneemt worden de duinen afgevlakt. Uiteindelijk kan dan een overgang naar vlak bed in het hoge regime plaatsvinden; de stroming is zo krachtig dat the duinen compleet weggespoeld worden waardoor de hydraulische ruwheid en waterdiepte sterk afnemen. Het is belangrijk om deze processen te kunnen beschrijven met modellen die accuraat zijn en snel kunnen rekenen.

Deze thesis heeft als doel om i) beter te begrijpen hoe zand over een rivierduin beweegt en wat dat betekent voor de overgang tussen regimes, en ii) om met deze kennis te onderzoeken hoe een geïdealiseerd duinevolutiemodel een breed bereik van mogelijke duinvormen, inclusief de overgang naar vlak bed, weer kan geven.

Een belangrijke eigenschap van hoe zandkorrels over de bodem bewegen (als zogenoemd bodemtransport) is de staplengte, die invloed heeft op de afstand tussen waar de stroming het best in staat is zand te verplaatsen en waar het bodemtransport het hoogste is. De staplengte is de afstand tussen waar een deeltje wordt opgepikt en waar het weer wordt neergelegd. Studies *met vlakke bodem* hebben aangetoond dat staplengte varieert als de stroming varieert, en in het algemeen toeneemt als de stroming sterker wordt. Voor het huidige onderzoek is een nieuw laboratoriumexperiment ondernomen, om staplengtes te meten *op duinen*. De beweging van deeltjes was met een hogesnelheidscamera opgenomen bij verschillende duinen. Het experiment heeft laten zien dat de variatie in staplengte langs de duin klein was, wat niet overeenstemt met de situatie bij vlak bed. Dit komt vermoedelijk door de variatie in het stromingsveld langs het oppervlakte van duinen (turbulentie).

In duinevolutiemodellen worden vaak transportmodellen gebruikt die de stroming direct koppelen aan het sedimenttransport. Deze aanpak houdt echter geen rekening met het effect van staplengte, wat een afstand tussen stromingseigenschappen en sedimenttransport veroorzaakt. Dit effect is een belangrijke katalysator voor regimeovergangen. Voor dit onderzoek zijn twee transportmodellen getest in een reeds bestaand geïdealiseerd duinevolutiemodel (welke origineel deze afstand niet kende). Het originele model is vergeleken met een versie met een relaxatievergelijking, en een versie die het oppikken en neerleggen van deeltjes apart beschrijft. Beiden modellen gebruiken de gemiddelde staplengte als belangrijke parameter, welke een sterk effect op de duinvorm heeft. Het vergelijk heeft laten zien dat de resultaten het best zijn met de versie die het oppikken en neerleggen van deeltjes apart beschrijft, gecombineerd met een staplengte van 50 keer de korreldiameter. Het is ook aangetoond dat het model volgroeide duinen kan wegspoelen, door de staplengte handmatig te laten oplopen om het gedrag van staplengte onder toenemende kracht van stroming te benaderen.

Om dit gedrag beter te beschrijven, is het model verder aangepast. De staplengte is afhankelijk gemaakt van de bodemschuifspanning (veroorzaakt door het stromen van water over de bodem). Dit model laat, net als in experimenten beschreven, de staplengte toenemen als de kracht van de stroming toeneemt. Om ook het effect van zand wat hoog boven het water vervoerd wordt en het effect van grootschalige turbulentie mee te nemen, is de staplengte ook afhankelijk gemaakt van de waterdiepte. Deze modelaanpak benadert de resultaten van een geavanceerder model goed voor een synthetische situatie die het laboratorium benadert. Met toenemende kracht van stroming nam staplengte toe, werd de staplengte groter, en werden de duinen weggespoeld. Voor een riviersituatie overschatte het model de afmetingen van de duin, maar beschreef het wel dynamische rivierduin-processen, waaronder de overgang naar vlak bed. Verder heeft het model laten zien dat als zo’n overgang plaats vindt de waterdiepte sterk af kan nemen.

1 INTRODUCTION

1.1 THE IMPORTANCE OF BEDFORMS IN THE CONTEXT OF FLOOD MODELLING

The Netherlands is a low-lying country that for a large part covers the Rhine-Meuse-Scheldt delta (see Figure 1). Economic activity is dependent on these rivers, as they offer a navigable pathway into the European continent. The delta is protected from the sea by the Delta Works, which started construction after the North Sea Flood of 1953. Besides the threat from the sea, economic activity in the Netherlands is mostly concentrated in areas near the river, which is protected from flooding by a system of among others dikes, weirs and locks. Due to changing climate and increasing population and economic activity in the delta area, the question has risen whether the Netherlands is adequately protected against flooding. Therefore, the government appointed a commission to re-evaluate the current safety levels and safety practices (and other water related issues). This commission was named after the commission that advised the government regarding the Delta Works; *de Deltacommissie* (Delta Commission). After a period of research the commission presented a report with extensive advice and 12 main recommendations to protect the Netherlands in the future (Deltacommissie, 2008).

Two of the main recommendations are to increase the design discharge of the Rhine branches from 16000 m^3/s to 18000 m^3/s and to decrease the probability of flooding in all protected areas by a factor of 10. In other words, the rivers must be able to accommodate higher discharges with more water than before. This means that, more than ever before, it is vital to have an idea what actually happens in the Rhine branches during such extreme flood waves; reducing uncertainty leads to better predictions and the possibility to decrease safety margins (thereby reducing costs). The problem is that these flood waves have not been observed in the modern configuration of the delta. So, there is no reliable historical data to derive water levels from. Of course, with hydraulic modelling water levels can be predicted for situations that have not occurred yet. However, there is an important complicating factor in this context: the uncertain hydraulic roughness.

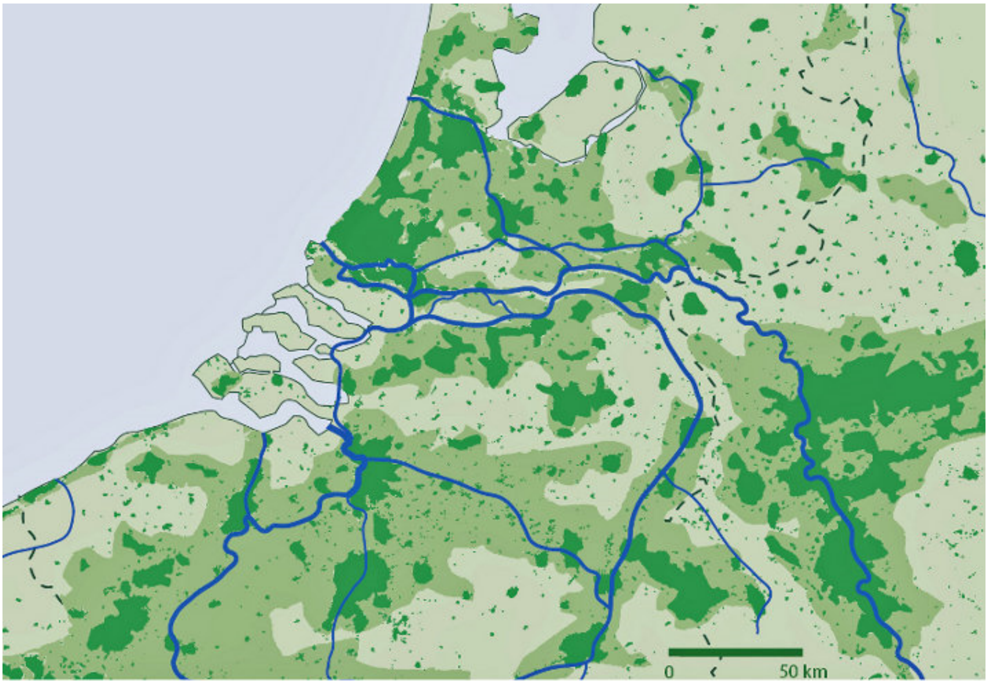

Figure 1: The Dutch-Belgian Rhine-Meuse-Scheldt delta (from: Deltanet, 2014).

Hydraulic roughness values play an important role in correctly determining water levels (Casas et al., 2006; Vidal et al., 2007; Morvan et al., 2008), which is critical for flood management purposes. While a lot of improvements have been made in the field of hydraulic modelling, the roughness values of the main channel and floodplains are still largely uncertain (Warmink et al., 2007, 2012. 2013). For this research the focus is on the hydraulic roughness of the main river channel, which is largely determined by the bed morphology. Under normal conditions and during flood, bedforms can develop and evolve on the river bed. River dunes are the dominant bedforms in many rivers, and form in beds with sediment sizes ranging from silt to gravel (Kostaschuck 2000; Wilbers and Ten Brinke, 2003; Best, 2005; Jerolmack and Mohrig, 2005; Kleinhans et al., 2007) so also in the lowland river channels consisting of sand and gravel in the Netherlands. They have heights of 10-30% of the water depth and lengths of 5 to 10 times their height. They migrate in downstream direction and are of asymmetrical shape with mild stoss side slopes and steep lee side slopes, up until the angle of repose (about 30°). See the figure below for a schematization of a dune.

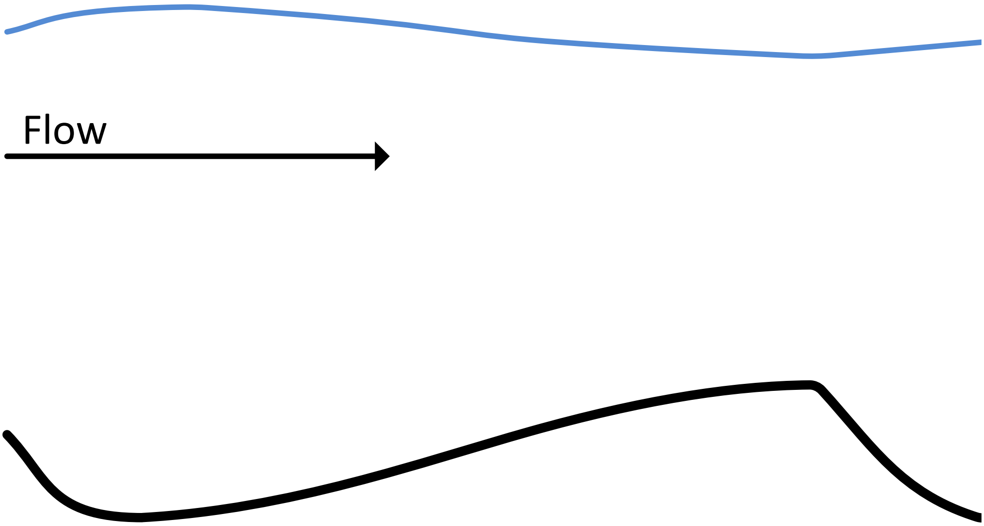

Figure 2: Schematization of a dune.

River bedforms influence water levels significantly because they impose roughness on the flow. In general, increasing flow strength leads to increasing bedform dimensions, which in turn lead to increasing water levels. Due to practical reasons the main channel roughness of a river reach is often used as a calibration parameter to match observed and modelled water levels. This is also the case in models of the Rhine branches in the Netherlands (Wasantha Lal, 1995; Werner, 2004; Van den Brink et al., 2006). The hydraulic roughness is generally calibrated as *a constant parameter*, though sometimes it is calibrated as *a function of discharge*. With both methods the described effect of the changing bed morphology and its interaction with the flow is not directly taken into account and that can lead to inaccurate results. This is because, during a discharge wave, bedforms do not immediately adjust to the changing discharge, which can lead to significantly different bedform heights, for the same discharge, between the rising and falling limb (see Figure 3). Bedform dimensions also depend on their past values, and this hysteresis effect is of course also seen in the development of roughness height (see Figure 4). This means that calibrated roughness values can be unreliable, especially when the modelled scenario is significantly different from the calibration scenario (e.g. broad-peaked versus sharp-peaked flood waves). This signifies the need for a better implementation of dune evolution modelling within the context of flood modelling.

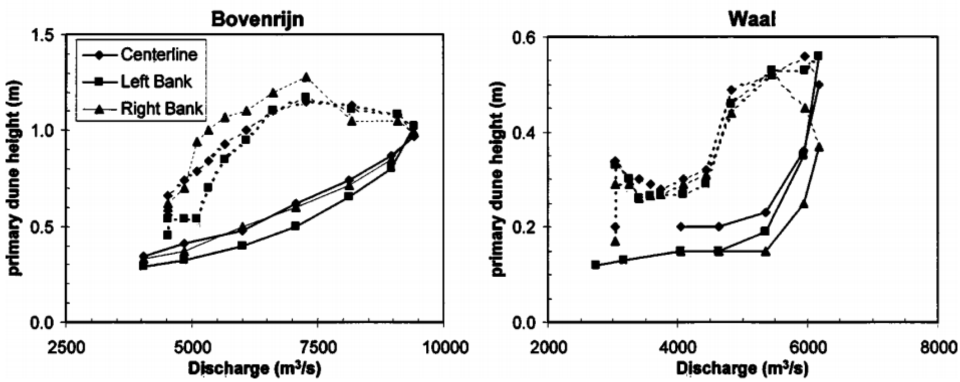

Figure 3: Dune height in the Bovenrijn (Upper Rhine) and Waal during the 1998 flood wave (from Julien et al., 2002). Dashed lines represent the falling limb of the hydrograph.

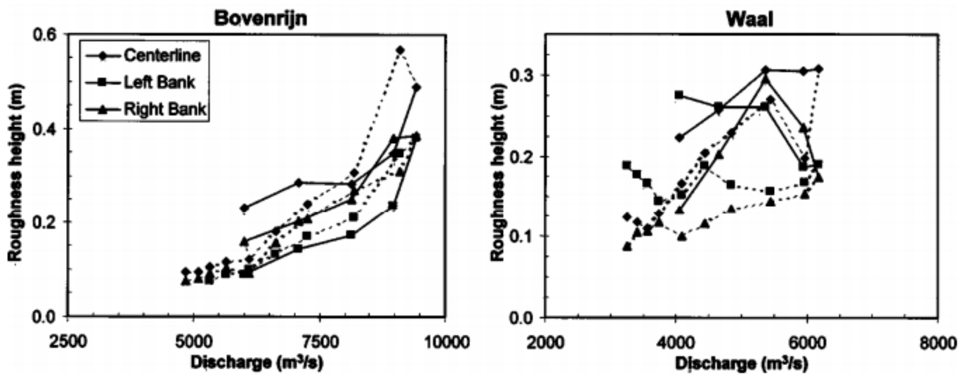

Figure 4: Nikuradse roughness height in the Bovenrijn (Upper Rhine) and Waal during the 1998 flood wave (from Julien et al., 2002). Dashed lines represent the falling limb of the hydrograph.

Because of the importance of bedforms it has been a topic of research for decades. We have a basic understanding of the processes involved, and can model the behaviour of dunes to some extent. However, there are still important knowledge gaps and hurdles to overcome in modelling. One of these hurdles, which is very important in the modelling of extreme flood events, is the prediction of the transition to upper-stage plane bed. In such an event, the flow is so powerful that bedforms are completely washed out and the bed becomes flat.

1.2 DUNE EVOLUTION AND DUNE MODELLING

The bed of a river goes through various stages of development (regimes) as the flow strength increases (e.g. due to increasing discharge). Starting from a plane bed, first ripples will appear, followed by dunes, a transition stage and then an upper-stage plane bed (Richards, 1982). After these regimes, the bed can evolve further, starting with antidunes. For lowland rivers, with Froude numbers smaller than 1 antidunes do not occur. In Figure 5 data and a schematic representation of the occurrence of these bedforms for various combinations of sediment size and flow velocity is shown.

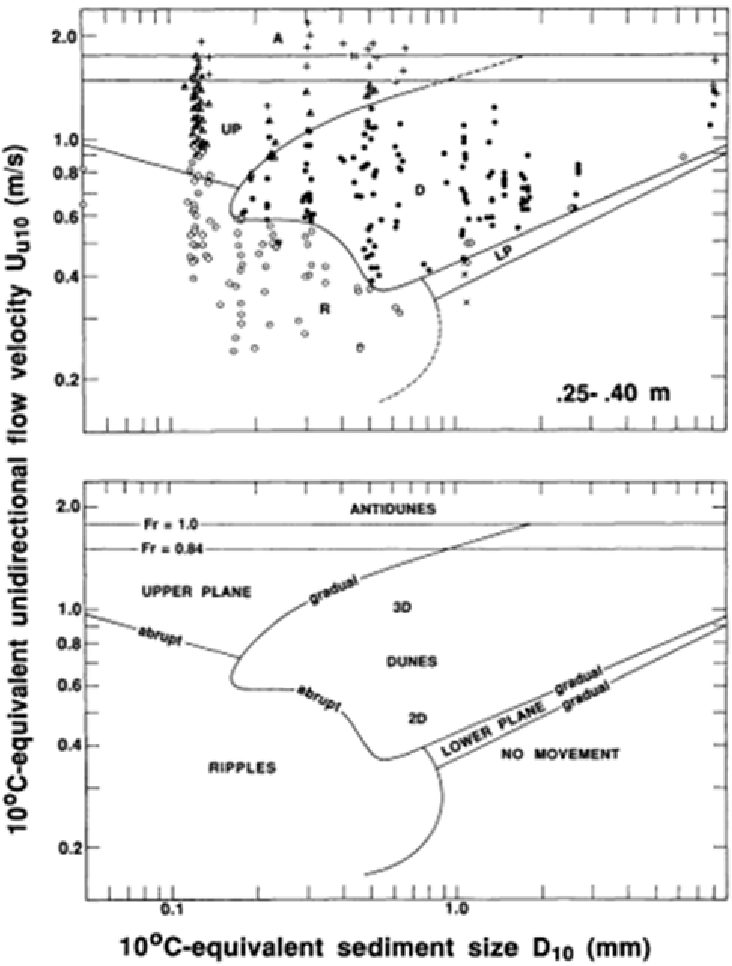

Figure 5: Bed-phase stability fields (source: Southard, 1991; original: Southard & Boguchwal, 1990). The upper graph shows data, with ripples (open circles), dunes (solid circles), ripples/dunes (half open circles), lower-regime plane beds (open diamonds), upper-regime plane beds (half-open triangles) and antidunes (plus signs). The water depth of the data sets ranged from 0.25 to 0.40m. Because fluid density and fluid viscosity vary with temperature, the data, which is derived from scenarios with different temperatures, has been normalized to account for these variations. See Southard & Boguchwal (1990) for details. The lower graph shows a schematic representation of the stability fields and the transitions between them.

Venditti et al. (2005a) have shown that initiation of bedforms at high flow strength is spontaneous, and occurs across the bed more or less simultaneously. Their experiments have shown that this starts with cross-hatch patterns across the bed, followed by a field of narrow chevron-shaped forms which finally merge to form wide crest lines. At low flow strength bedforms could only occur by creating defects in the bed (Venditti et al, 2005a). The experiments of Venditti et al. (2005b) show that under certain conditions superimposed bedforms may form on and migrate along the stoss side of a dune. The authors state that besides imposing additional roughness on the flow, these superimposed migration forms control the bed load transport along the dune. Finally, the experiments of Venditti et al. (2005c) have shown that for certain conditions where 2D dunes are expected according to the phase diagram above, eventually the 2D dunes transition to 3D dunes. The authors therefore suggested that crestline shape may not be a good discriminator in such diagrams.

Besides the previously mentioned work many experiments have been carried out regarding the occurrence of various types of bedforms and transition stages. Many approaches have been used to model dune dimensions, varying from equilibrium dune height predictors (e.g. Yalin, 1964; Allen, 1968, 1978; Van Rijn, 1984b) which show that for certain combination of parameters the various bedform regimes can be predicted fairly well.

Furthermore, stability analyses (e.g. Kennedy, 1963; Engelund, 1970; Fredsøe, 1974; Yamaguchi & Izumi, 2002; Colombini, 2004) can be applied to describe amplitude evolution. These analyses show that equilibrium dunes in the flume can be represented well by the fastest-growing wavelength for a certain combination of flow and sediment properties (Colombini, 2004). Colombini (2004) shows that a phase-lag between local bed elevation and sediment transport leads to growth of a bedform. This lag can arise in a stability analysis theory if the flow model allows bed shear to reach its maximum downstream of the maximum bed elevation. Also the inclusion of suspension of sediment and/or particle inertia in the sediment transport model can result in a destabilizing lag between flow properties and sediment transport (Colombini, 2004). Colombini & Stocchino (2012) have carried out a linear stability analysis that is able to identify the various parameter combinations that lead to various bedforms (2D and 3D). They show that for low Shields numbers dunes are dominant, with larger depths leading to 2D dunes and smaller depths to 3D dunes.

Coleman et al. (2005) have investigated how the time from plane bed to equilibrium dunes depends on flow and sediment parameters. Most importantly, the authors have shown that the time to equilibrium decreases if the ratio of shear stress over critical shear stress increases. Furthermore, the temporal development of bedform length and height can be predicted fairly well with exponential functions if the equilibrium dimensions are known (Coleman et al., 2005). Warmink & Schielen (2014) use the Coleman et al. (2005) time-lag approach with the equilibrium dune predictor of Allen (1968) to predict bedform evolution. With the bedform dimensions a part of the hydraulic roughness is predicted using Van Rijn (1993), and this method is implemented in a SOBEK model for a part of the river Rhine. This approach predicts the water levels fairly well, and yields similar results as a SOBEK model with calibrated roughness values (Warmink & Schielen, 2014).

In recent years, in line with increasing computational power, the focus has shifted towards complex numerical modelling. The 2DV model of Shimizu et al. (2009) is a prime example, incorporating a k-ε turbulence model, pick-up and deposition bed load processes and suspended transport. This model has been shown to be able to predict a transition to upper-stage plane bed, as well as hysteresis effect with regard to dune dimensions and hydraulic roughness during a flood wave. Nabi et al. (2010, 2012a, 2012b, 2013a, 2013b) have developed a highly complex 3D dune evolution model that uses, among other aspects, Large Eddy Simulation and grouped particle modelling to capture very fine details of the hydraulic and sediment behaviour processes involved.

To predict evolution of dune dimensions over the time-scale of a flood wave, computation time should be limited. This means that certain physical processes will have to be left out or parameterized in a solid way, while preserving the essential characteristics and valid outcomes. The types of models described above either leave out aspects necessary to describe the full range of dune evolution (from the lower stage plane bed through the upper-stage plane bed), or are too computationally intensive to be implemented in (operational) flood forecasting models.

To fill that gap Paarlberg et al. (2007, 2009) developed a dune evolution model which has shown promising results in predicting dune length and height. This model is based on the work done on sand wave modelling by Hulscher (1996), Nemeth (2003), Van Den Berg (2007) and Sterlini (2009). It is a 2DV-model with only bed load transport and assumes constant eddy-viscosity. This model is able to predict the evolution of dunes from small initial disturbances up to equilibrium dimensions with limited computational time. If the dune length in the model is fixed (fastest growing mode determined using numerical stability analysis), the dune dimensions predicted by the model are in good agreement with measurements. The model has been used to predict a part of the hydraulic roughness used in a hydrodynamic model in various studies. This approach showed the expected hysteresis effects in dune roughness and water levels during flood waves, different behaviour of sharp-peaked versus broad-peaked flood waves within the dune regime and in general a reasonable agreement with observed water levels (Paarlberg et al., 2010; Paarlberg, 2012; Paarlberg & Schielen, 2012).

The model of Paarlberg et al. (2006; 2007; 2009) still lacks certain important aspects of dune evolution. For example, the evolution of low-angle dunes cannot be described. Best (2005) has highlighted the influence of leeside angle on flow (and thereby roughness) as an important future research direction. Also, the transition to lower-stage plane beds and upper-stage plane beds cannot be described, while it is very important to know when and how these transitions occur. The processes leading to the low angle dune shapes have been investigated in the past but results are often contradictory (an overview of relevant work is found in Best, 2005).

1.3 SEDIMENT DYNAMICS

Dunes grow, decay and are shaped by the movement of the sediment that comprises the bottom of a river. Particles on the bed surface experience drag from flow, and can be transported near the bed by first rolling and sliding, and then saltation before again colliding with the bed. Einstein (1950) stated that saltation only occurs sometimes compared to rolling and sliding, but it has later been shown that saltation is in fact the dominant mode of bed-load transport over immobile beds (Francis, 1973; Abbot & Frances, 1997) and mobile beds (Fernandez Luque & Van Beek, 1976; Sekine & Kikkawa, 1984; Van Rijn, 1984a; Niño & Garcia, 1994; Charru et al., 2004; Lajeunesse et al., 2010).

Saltation was described by Bagnold (1956) as the process of particles making small jumps from/to the bed without becoming entrained in the water column. These jumps can occur consecutively due to the collision with the bed after a jump, when forward momentum is partly lost to the bed and partly converted to upwards vertical motion (Bagnold, 1956; Francis, 1973; Sekine & Kikkawa, 1984; Sekine & Kikkawa, 1992). Although the particles in saltation do not become suspended in the flow due to turbulent effects, bed load movement is not only initiated but also maintained by hydrodynamics which work against gravity. The particle step length is the average distance sediment travels from entrainment to rest, which according to Einstein (1950) was always equal to 100 times the particle diameter. While Einstein (1950) furthermore stated that saltation can be neglected in water and that step length is independent of flow conditions, numerous authors have since applied the concept of step length to saltating particles. Some authors have shown that step length in fact does depend on flow conditions. The length travelled by a saltating particle over an erodible was found to increase with increasing friction velocity and vary between 5 and 8 times the particle diameter by Niño & Garcia (1994), between 8 and 12 times by Niño and Garcia (1998), between 2 and 48 times by Lajeunesse et al. (2010), and between 40 and 240 times the particle diameter by Nakagawa & Tsujimoto (1980). When the effects of turbulence on the particle do have a significant effect on its motion the particle can become suspended in the flow (Sekine & Kikkawa, 1992), which means the weight of the particle is supported entirely by the flow (Einstein, 1950). In contrast with bed load, the distance travelled by suspended sediment is much larger. Generally suspended sediment transport is considered to be dominant for a ratio of the friction velocity of the flow to the settling velocity of the particles larger than one.

The spatial lag between local flow and sediment transport arising from the distance sediment particles travel is considered a key process in the transition between dune regimes (Nakagawa & Tsujimoto, 1980). However, often (including in Paarlberg's model) bed load transport along the dune surface is modelled with a transport formula like that of Meyer-Peter & Müller (1948), in which this lag process is not taken into account. Formulae of this type are meant for equilibrium conditions, and are often successfully used in predicting equilibrium dunes. Bed load transport models like the pick-up and deposition model of Nakagawa & Tsujimoto (1980) do model this spatial lag. In this model spatial lag is controlled mainly by the particle step length. Tsujimoto et al., (1990) model this spatial lag with a linear relaxation equation that uses step length as well. The present knowledge of the physical properties of step length is mainly based on lab-experiments under flat bed conditions. How step length behaves under dune conditions is still unknown and has not been investigated experimentally. Shimizu et al. (2009) show that increasing step length eventually may lead to the washing out of dunes (transition to plane bed).

1.4 RESEARCH METHODOLOGY

1.4.1 Research project

This research project has focused on determining whether and how spatial lag processes in the bed load processes can explain the transition to upper stage plane bed and how they affect the evolution of dunes in the lower regime (growth and decay). In addition, it was investigated how these processes can be incorporated in a physically simplified dune evolution model, the model of Paarlberg et al. (2006, 2007, 2009), and whether or not suspended sediment transport processes should be included as well. The project was part of a larger project named 'River Bedform Evolution Modelling for Flood Management', in which two PhD candidates and a post-doc collaborated. The overarching aim of the larger project was to develop knowledge of the physical processes relevant to river dune evolution and apply that knowledge to further develop a dune evolution model that can be used in support of flood management. In other words, the idea was to use or translate knowledge on physical processes in such a way that computational time remains limited but dune morphology is still represented in a satisfactory way.

The other PhD candidate focussed on understanding the dynamic interaction between river dunes and suspended sediment transport and further developing the dune evolution model developed by Paarlberg et al. (2006; 2007; 2009) as well. The post-doc has focused on embedding new knowledge of bedform evolution in hydraulic roughness models that can be used for the modelling of discharge waves in flumes and the field. The topic of hydraulic roughness of river beds with bedforms is therefore not part of the research in this thesis. Besides shared insights, the collaboration has thus far resulted in several joint publications (e.g. Naqshband et al., 2015; Seuren et al., 2014; Warmink et al., 2013).

1.4.2 Research objectives

The research aims of this thesis are i) to better understand the sediment transport processes along dunes and which processes control the transition from a dune regime to an upper-stage plane bed regime, and, ii) based on this understanding, to investigate the possibilities of an idealized dune evolution model (Paarlberg et al., 2006, 2007, 2009) not provided with an advanced turbulence closure, to represent a wide range of dune morphologies including upper-stage plane bed.

1.4.3 Research questions

1. How can the bed load movement along a dune be characterized?
    a. What is the average distance particles travel and what is their velocity?
    b. How does the probability distribution of step length compare with a flat-bed situation?
    c. How do these properties vary along a dune?
    d. How do step lengths along a dune compare with a step length model for a flat bed?
2. How can the modelling of dunes be improved in an idealized dune model?
    a. To which extent is the idealized dune evolution model of Paarlberg et al. (2009), extended with a non-equilibrium sediment transport model that includes spatial lag processes, able to improve the representation of dunes?

   b. What are the prospects of this extended Paarlberg et al. (2009) model to describe the transition of the dune regime to the upper-stage plane bed?
3. How can a step length model be derived that combines bed load and suspended load processes and, implemented in the idealized dune model of Paarlberg et al. (2009), enables the modelling of dune dynamics due to a flood wave?
   a. To what extent can this new model replicate dune dynamics as they occur in flume conditions under variable discharge, including upper-stage plane bed and bedform hysteresis effects?
   b. How does the model behave when it is applied to river situations? And can this type of model in principle also describe upper-stage plane bed in field conditions?

1.4.4 Research approach

To better understand the characteristics of bed load movement along dunes an explorative experiment was done at the University of Braunschweig. In a flume with a mobile sand bed conditions were set to enable the presence of dunes and to be in the bed load regime. Sediment movement at the crest and trough of several equilibrium dunes was recorded with a high speed camera and analysed. This experiment gave an indication of how step length behaves along an equilibrium dune under bed-load conditions, and how this compared with observations of step length along a flat bed and a step length model derived for flat bed.

The effect of using non-equilibrium bed load models within the idealized dune model of Paarlberg et al. (2009) on the representation of various morphologies was studied. For the non-equilibrium bed load models, two different transport model concepts were selected: a model with linear relaxation and a model with separate pick-up and deposition functions. Both incorporate the spatial lag due to the distance sediment travels in the form of a mean particle step length. By implementing both in the model of Paarlberg et al. (2009) it was possible to examine how these transport processes relate to the resulting dune morphology and if these processes enable the idealized dune model to model a transition to upper-stage plane bed in principle.

Lastly, the performance of this idealized model to represent the dune dynamics during flood waves was investigated. Specific attention is given to extend the transport model to total load, i.e. including suspended sediment transport. The performance of the model to represent the transition to upper-stage plane bed is investigated by comparing its results with a more advanced model with regard to a numerical experiment that represents flume conditions. Furthermore, the model is tested with field observations from the Dutch river Waal, to assess its performance under these large time and length scales. Slightly more extreme conditions were used to assess the capabilities of the model with regard to a transition to upper-stage plane bed in the field situation.

1.5 THESIS OUTLINE

The three main research questions will be answered in the following three chapters of the thesis. These chapters can be read separately, and therefore have some overlap with regard to description of model set-up etcetera. These chapters reflect the chronological development of the research; each chapter builds on the previous one, and insights accumulate along the thesis as they did over time.

The first research question is answered in chapter 2, where flume experiments, done to study the behaviour of sediment along a dune, are presented. The dependence of dune characteristics on sediment transport processes is described in chapter 3. The modelling of transitions to the upper-stage plane bed in flumes and rivers is discussed in chapter 4.

The synthesis of the research is in chapter 5. This starts with a discussion of topics related to the research results (section 5.1). Conclusions and recommendations are given in sections 5.2 and 5.3. The original main research questions are repeated and it is shown how they have been answered. Based on the research done here and the broader context thereof identified in section 5.1, recommendations are given for further research and for the use of the model concepts and results presented in this thesis.

2 PARTICLE STEP LENGTH VARIATION ALONG RIVER DUNES*

ABSTRACT

For flood management modelling of lowland rivers it is important to understand the interaction between river flow and bedforms, specifically dunes. In dune evolution models, commonly equilibrium transport formulae like that of Meyer-Peter and Müller (1948) are applied. However, these equilibrium formulae disregard the lag between flow properties and sediment transport which is considered a principal cause of bed instability (Nakagawa & Tsujimoto, 1980). Their pick-up and deposition model was used by Shimizu et al. (2009) to model bed load transport in a dune model. Because the properties of step length under dune conditions are highly uncertain they derived a conceptual model for this important parameter. Sekine & Kikkawa (1992) have made a numerical model of saltation of particles for *flat bed conditions* and compared it to experimental data. They have shown that step length strongly correlates with the ratio of friction velocity to settling velocity.

For this chapter, a new laboratory experiment is undertaken to measure step lengths under *dune conditions*. This explorative experiment is carried out in the bed-load regime, in which for a series of dunes the motion of particles is captured with a high-speed camera. This is done along the length of the dune to get an idea of the spatial variation. The experiment shows that the variation of step length distribution along a dune is small, which is against expectation. It is hypothesized that this is due to the fact that the relation of Sekine & Kikkawa (1992) disregards the specific non-uniform turbulent characteristics as present along dune surfaces.

---

* A part of this chapter has been published as: Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen & S.J.M.H. Hulscher (2012). Particle step length variation along river dunes. In R.M. Munoz (Ed.), River Flow 2012: Proceedings of the International conference on fluvial hydraulics, San Jose, Costa Rica, 5-7- September 2012 (pp. 493-497). London, UK: CRC Press Taylor & Francis Group.

2.1 INTRODUCTION

Hydraulic roughness values play an important role in correctly determining water levels (Casas et al., 2006; Vidal et al., 2007; Morvan et al., 2008), which is critical for flood management purposes. In rivers with bed sediments ranging in size from silt to gravel, river dunes are the dominant bedforms (Kostaschuck 2000; Wilbers and Ten Brinke, 2003; Best, 2005; Jerolmack and Mohrig, 2005; Kleinhans et al., 2007). The hydraulic roughness of the main channel is mainly determined by these dunes, which vary greatly in size and shape during a flood wave. To improve flood modelling, the development of the bed (and thereby dunes), needs to be understood better and modelled in computationally cheap ways.

Recently, models have been developed that directly model many of the hydrodynamic and sediment transport details (e.g. Shimizu et al., 2001; Nelson et al., 2005; Tjerry & Fredsøe, 2005; Giri & Shimizu, 2006; Paarlberg et al., 2007, 2009; Shimizu et al., 2009; Nabi et al., 2010, 2012a, 2012b, 2013a, 2013b). With increasing complexity models become more valuable to study the detailed sediment processes, but can become too computationally intensive for flood management purposes.

Therefore, in this chapter efforts are made to identify which processes are most important, and how these can be implemented or parameterized in an efficient way. One of the important processes associated with dunes is the transition between various regimes, i.e. the transition from flat bed to ripples, ripples to dunes and dunes to upper stage plane bed. There are few models that are able to describe all the transitions from a lower-stage plane bed to an upper-stage plane bed. Especially the transition from dunes to an upper stage plane bed is hard to model. During this and other transitions an important driving factor is that sediment transport and local bed elevation are out of phase (Colombini, 2004), i.e. that the sediment transport and bed shear stress are out of phase (Kennedy, 1963; Nakagawa & Tsujimoto, 1980; Shimizu et al., 2009). Depending on the conditions, bed load alone or bed load and suspended load together may contribute to this transition.

During the process of the transition to an upper stage plane bed, the influence of the phase lag between transport and shear stress is explained as follows. Bed shear stress along a dune reaches a maximum at the crest and decreases on the leeside. If the phase lag is small, i.e. when the bed shear stress reaches its maximum shortly after the crest, the crest erodes but the material that passes the crest is deposited directly on the lee side. This is because the sediment transport rate behind the crest is larger than before the crest, and further decreases along the lee side. This way the dune can migrate while maintaining its size. If the phase lag increases, and the point of maximum transport is moved far enough downstream of the crest, the crest and a part of the lee side erodes and sand is deposited on the lower part of the lee side and the trough of the next dune. Sediment solely reached the lee side before, but now also ends up in the trough of the next dune. This makes the trough fill up while the crest erodes, which means the original dune decays.

The dune evolution model of Shimizu et al. (2009) can describe this transition, though not with an equilibrium bed load transport model. Instead of using an equilibrium bed load transport formula, this model includes the pick-up and deposition formulation of Nakagawa & Tsujimoto (1980) to describe bed load transport. The pick-up is determined from local bed shear stress. The location where the sediment is deposited again is determined using a conceptually derived function. This function uses a particle step length, i.e. the distance a particle moves from entrainment to deposition. This new approach has led to good results. However, the properties of step lengths under dune conditions are highly uncertain (as opposed to a flat bed situation), and Shimizu et al. (2009) have assumed a conceptual relation between the Shields parameter and mean step length. To better understand which parameters and processes are important in determining step lengths of particles transported as bed load along a dune surface an explorative experiment has been undertaken in the bed load regime.

The main research question of this chapter is: how can the bed load movement along a dune be characterized? Therefore this chapter will answer the following research questions: a) what is the average distance particles travel and what is their velocity? b) how does the probability distribution of step length compare with a flat-bed situation? c) how do these properties vary along a dune? d) How do the results compare with a step length model for a flat bed?

The definition of step length, and experimental results from other studies will be discussed in section 2.2. The experimental set-up is handled in section 2.3 and the experimental results are shown in section 2.4. The experimental results are compared with a step length model for flat bed in section 2.5. Finally, the discussions and conclusion are given in sections 2.6 and 2.7.

2.2 STEP LENGTH

Assuming equilibrium between shear stress and transport, the formula devised by Meyer-Peter and Müller (1948) can be directly applied. As Nakagawa & Tsujimoto (1980) argue, bed instability is principally caused by the phase lag between bedform and bed elevation change. They identify two sources of this lag: 1) the spatial distribution of bed shear stress, which can be taken into account by applying the transport formula to the local bed shear stress, and 2) the sediment particle step length, which causes a lag distance between bed shear stress and bed load transport rate. The focus is on the sediment particle step length, which is the distance travelled from entrainment to deposition as defined by Einstein (1950). Einstein (1950) further states that the mean step length Λ can be determined by:

$$\Lambda = \alpha D_{50} \quad (1)$$

where α is the non-dimensional step length, which Einstein assumed to be 100, and D_{50} is the median particle diameter.

Bagnold (1956) has stated that flow power enables sediment to overcome frictional resistance and move along the bed. The amount of flow power available to move sediment can be characterized by parameters such as bed shear stress and friction velocity. Lajeunesse et al. (2010) have investigated particle movement along a mobile and flat bed in relation to the flow power. For one of the series the friction velocity u_* was in the range of 0.01-0.07 m/s and D_{50} was 1.15-5.50 mm, while the range of observed step lengths was from 2 to 48 times the particle diameter. Step length was found to vary between 5 and 8 times the particle diameter by Niño & Garcia (1994), and between 8 and 12 times by Niño and Garcia (1998).

Francis (1973), Fernandez Luque & Van Beek (1976) and Sekine & Kikkawa (1984) have also done experiments to determine the dependence of particle behaviour on various parameters under flat bed conditions. Sekine & Kikkawa (1992) have used this data to make a numerical model of saltation of particles which reproduces these experimental values well. Furthermore, their model shows that the mean step length varies between 10 and about 250 times the particle diameter for values of friction velocity over particle settling velocity u_*/w_s (which is a measure for the relative importance of suspended load) between 0.15 and 0.28. This also matches the range of values for the particle step length of approximately 40 to 240 times the particle diameter Nakagawa & Tsujimoto (1980) have found experimentally for values of u_*/w_s between 0.18 and 0.35. Sekine & Kikkawa (1992) also relate the step length to certain hydrodynamic parameters. Most importantly the step length correlates positively with u_*/w_s, and negatively with the ratio of the critical friction velocity u_{*c} to the particle settling velocity. Sekine & Kikkawa (1992) derived a formula for dimensionless step length α based on their numerical experiments, which states that:

$$\alpha = \frac{\Lambda}{D_{50}} = \alpha_2 \left(\frac{u_*}{w_s}\right)^{3/2} \left(1 - \frac{u_{*c}/w_s}{u_c/w_s}\right)^{3/2} \tag{2}$$

where α_2 equals 3000.

It is likely that observations of step lengths along dunes will differ from existing observations (for flat beds) as the effects of the non-uniformity of flow, (possible) flow separation and turbulence generation after the crest and gravity (upwards dune stoss slope) will probably influence the distribution of the step length. Along a dune the depth averaged velocity increases from the trough towards the crest, due to the increasing bed level and the (slight) decrease of water level at the crest. This means that near bed velocities, the velocity gradient at the bed and friction velocities increase as well. It may therefore be expected that this will lead to greater step lengths at the crest than at the trough.

2.3 EXPERIMENTAL SET-UP

The experiment was conducted at the *Leichtweiß-Institute (LWI)* for Hydraulic Engineering and Water Resources at the TU Braunschweig in Germany over the course of several months. This included time to set up and calibrate the echo sounders that measured bed and water levels, learning to operate the flume and identifying slope and discharge settings that lead to uniform flow as well as devising the experimental set-up of the step length measurements and an efficient workflow.

A recirculating flume with a length of 30 meters was used. It has a width of 2 meters, but the width W was reduced to 1 meter to limit three-dimensional behaviour and reduce the amount of sand needed to cover the bottom. At the end of the flume a settling basin and sediment trap was present. All the sediment and a small part of the water discharge were transported back to the beginning of the flume to ensure a constant supply of sediment from upstream. The remaining discharge flowed over a weir into a basin, to be pumped back up. See Figure 6 for a picture of the laboratory and flume.

Figure 6: picture of the laboratory in Braunschweig. The blue flume in the middle is the flume used in the experiment.

The characteristic grain sizes of the used sand can be found in Table 1. The density ρ_s of the used sand was 2650 kg/m^3. The settling velocity of the used sand is 0.104 m/s according to Soulsby (1997).

Table 1: grain size distribution of the used sand

Nth percentile	Grain size [mm]
10	0.6
50	0.8
90	1.2

For the experiment the goal is to observe the steps particles make when they are transported as bed load along a dune. For this a high-speed camera (MotionScope M3) was used which makes grayscale images at 200 Hz. The camera was installed in a Perspex tube, so that it could be placed in the water, with a frame to ensure that the camera was parallel to the flume bottom. It was placed above several locations along a dune, covering an area of about 15 cm by 15 cm each time. Because the dunes were on average 1.2 m long and 8 cm high, the difference in bed level between the upstream and downstream part of the image is estimated at 1 cm. A schematization of the measurement set-up can be seen below.

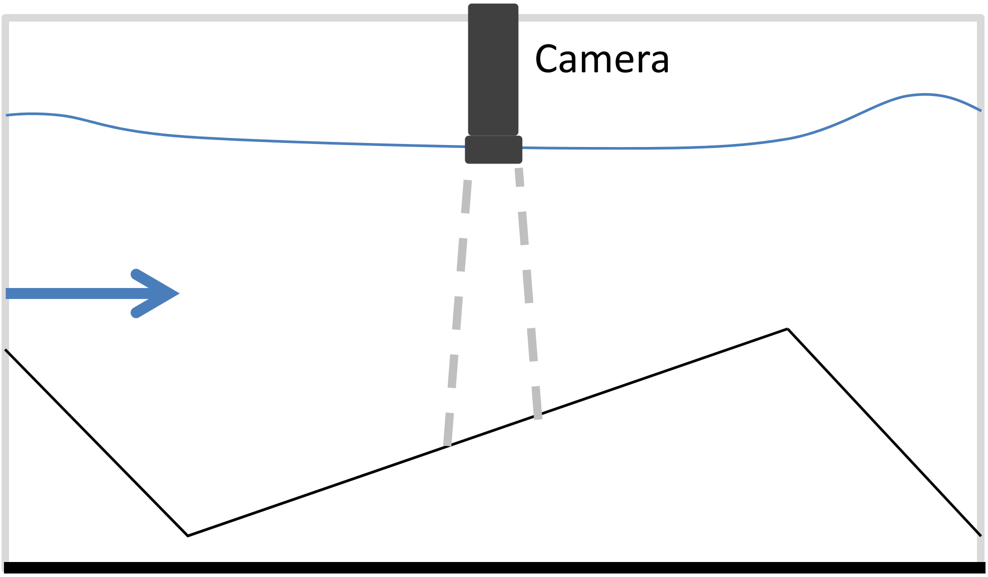

Figure 7: schematization of the experimental set-up

To ensure sharp images the height of the camera was adjusted as it was moved along the dune, so that it would always be approximately 25 cm above the area in the frame. Combined with the slight bed level difference along the frame this led to clearly discernible particles. At each location the camera was first used to take a picture of a reference object, a steel rod with known size. Then the object was removed, and the sediment motion was recorded until the internal storage of the camera was filled, resulting in two seconds of particle motion. The camera was then moved to the next location. The images are 1280 pixels in the mean direction of flow, and 1024 pixels perpendicular to the flow. This means a pixel covers about 0.1 by 0.1 mm^2 and that individual grains with sizes of 0.6-1.2 mm were well resolved in the pictures. For reference an unedited image from the experimental run is shown in Figure 8.

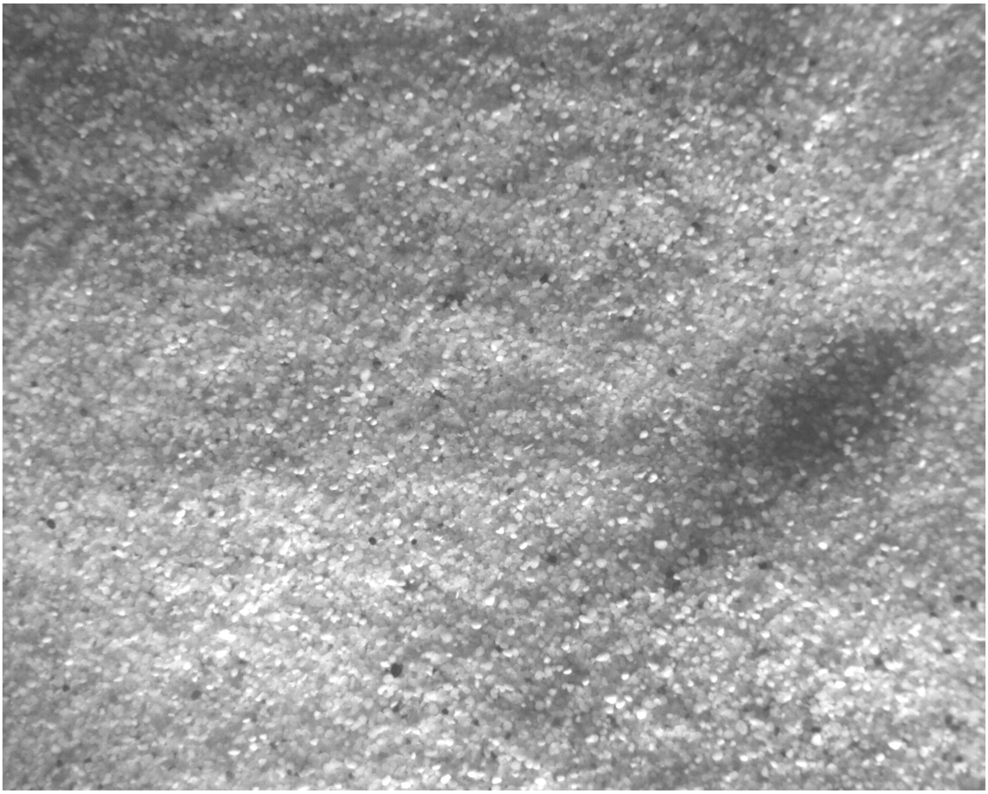

Figure 8: example image from the step length experiment. Flow direction is from right to left.

Particle motion was determined manually by following the steps individual particles took within the image and identifying steps. A step length is defined as the distance a particle travels between two moments of rest. Particle step lengths were generally much smaller than the length of the image frame (15cm). Particles that moved into or out of the frame had to be disregarded because the total step length could not be determined. However, to avoid having to disregard particles movements that ended out of frame as much as possible, the upstream area of the image was focused on when searching for particles that just started moving. This way, it only occurred a few times that a particle's moment of pick-up was observed while the moment of deposition was not.

For each observed step the start and end position of the centre of the particle in the image were noted, as well as the moment of the start and end. This can be easily translated to a step length in meters and duration of movement in seconds respectively. It is estimated that the error in measured step length, due to image focus variations and image distortion and due to the manual way of determining particle movement, is of the order one median grain size.

Since the goal of the experiments is to observe particle behaviour along dunes, conditions were selected that fall in the dune regime. Large amounts of suspended sediment were avoided and the focus was on the bed-load regime. A discharge Q of 0.165 m^3/s was selected, and a water depth h of 28 cm was strived for (making the average flow velocity $\bar{u}_{flow}$ around 0.50 m/s).

Starting from a flat bed, dunes started to grow and eventually the bed developed towards equilibrium. During the first part of this stage bed and water levels were monitored and the slope of the flume as well as the level of the downstream weir were adjusted with two goals. The first goal was to reach the desired water depth of 30 cm and the second to get a uniform section in the streamwise direction of the flume from about x=13 m to x=23 m (with x=0 m being the most upstream boundary). When the mean slope of the water level i was parallel to the mean slope of the bed the flow was considered to be uniform. When the dune heights Δ and lengths λ were in a (dynamic) equilibrium as well, the camera measurements started. The measured hydraulic conditions as well as the measured dune and step length characteristics are presented in the next section.

2.4 PARTICLE MOVEMENT OBSERVATIONS

For the experiment, the settings and the characteristics of the equilibrium dunes are found in Table 2, with r the migration rate of dunes.

Table 2: details of the experiment, reported dune dimensions are equilibrium dimensions.

Q [m^3/s]	**i** [10^{-4} m/m]	**h** [m]	**Δ** [m]	**λ** [m]	**r** [mm/s]
0.165	12	0.28	0.077	1.233	0.473

Based on the above the hydraulic radius $R=hW/(2h+W)$=0.181 m and the friction velocity $u_*=(gRi)^{1/2}$=0.046m/s, which makes the suspension parameter u_*/w_S=0.44 for this experiment. This means that the experiment was in the bed load regime.

In the experiments the dunes were regular in shape and size, without strong lateral variation. For three different dunes the motion of particles was analysed. Along each dune two places of interest are defined: just before the crest and just after the flow reattachment point in the trough. During the crest measurement the camera centre was positioned upstream of the crest by a distance of about 10% of the dune length. During the trough measurement the camera centre was positioned upstream of the crest by a distance of about 70% of the dune length. Per location per dune 30 particle movements were derived from the images.

The results of measured particle step lengths Λ divided by the median grain size D_{50} at the three crests and the three troughs are shown in the histograms of Figure 9 and Figure 10 respectively. It can be seen that although the distribution of step length at the three crests is similar, there is considerable variation. Also, there is a wide spread of measured step length, showing a histogram that is skewed to the right. The same applies to the results at the trough.

The results are summed over the three dunes to better show the difference between step length distribution at the crest and trough in general. The histogram of the measured particle step lengths Λ divided by the median grain size D_{50} at the two locations for the three dunes in total is shown in Figure 11.

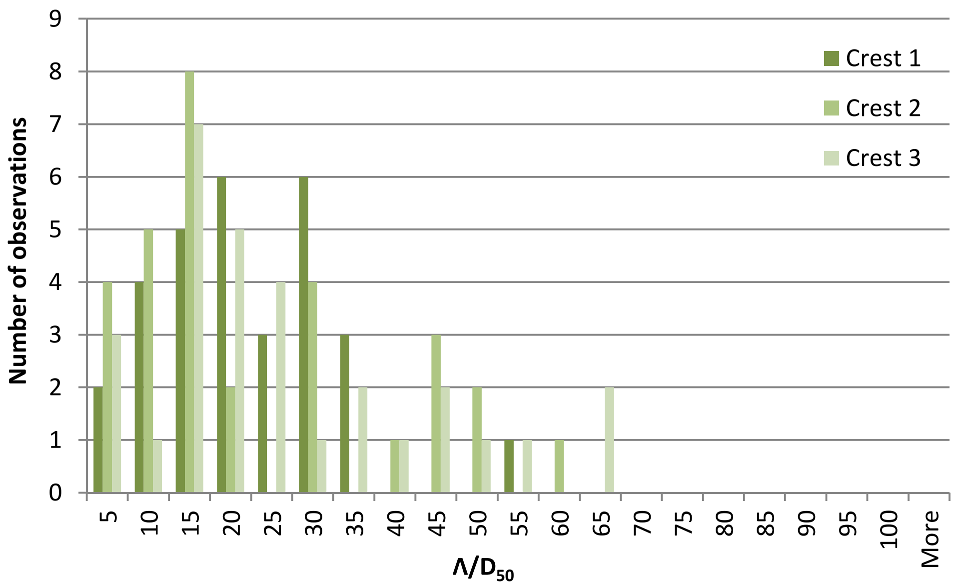

Figure 9: histogram of step length for the crests of the three dunes. Total number of observed particle steps per crest is 30.

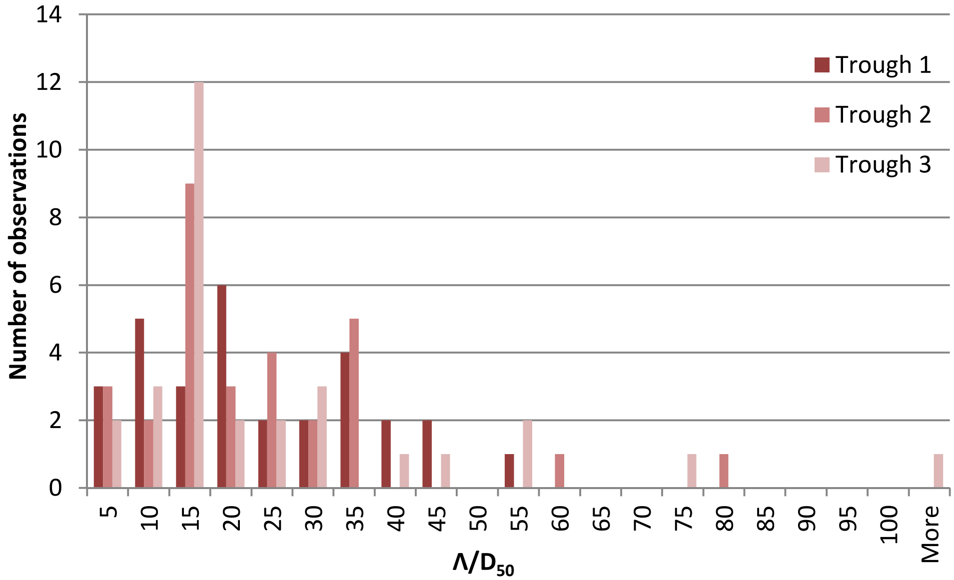

Figure 10: histogram of step length for the troughs of the three dunes. Total number of observed particle steps per trough is 30. The value in the bin 'More' is 114.

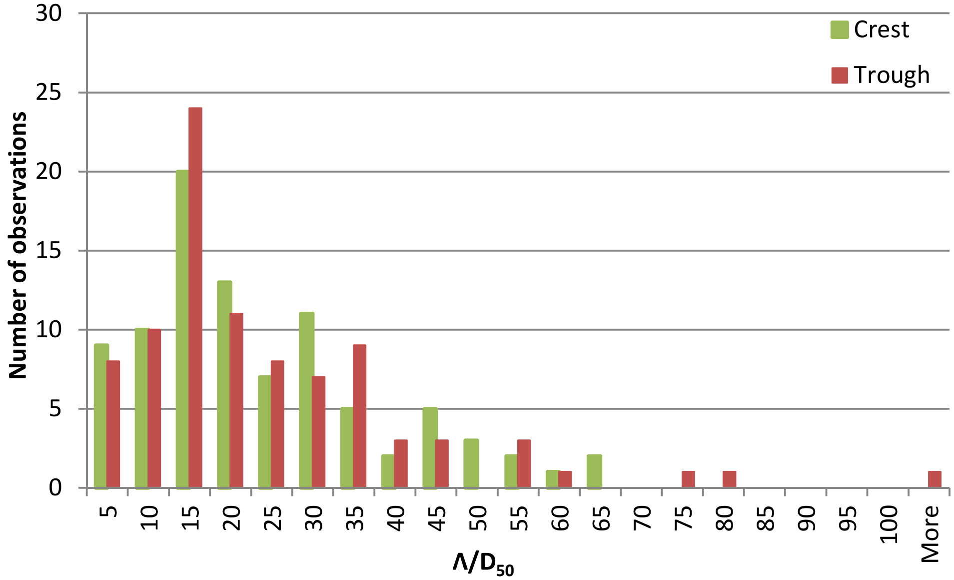

Figure 11: histogram of step length for the crest and trough summed over the three dunes. Total number of observed particle steps is 180; 30 per crest or trough per dune. The value in the bin 'More' is 114.

As can be seen the results differ, but not strongly. The particles at the trough seem to tend to higher step lengths, which is not what was expected. With the number of particle steps per location (90) the distribution seems to be represented well, and it is considered unlikely that with a larger number of observations the measured distributions will change strongly. Nakagawa & Tsujimoto (1980) used an exponential distribution for step length in their pick-up and deposition models. This does not fit with the distribution found in the present research. Nakagawa & Tsujimoto (1980) state this distribution is suggested by their experimental results, but this is not easily seen in their work.

For one series Lajeunesse et al. (2010) also showed the probability distribution of the measured step lengths of particles moving over a flat bed. From that figure it can be derived that the skewness, defined as (mean-mode)/(standard deviation), was 0.60, meaning that the distribution is skewed to the right. For the results of the present study the skewness at the crest is 0.42, which corresponds reasonably well to the skewness of the data of Lajeunesse et al. (2010). The skewness at the trough is 0.37, which means the data is also skewed to the right, but slightly less so than at the crest. Therefore it is concluded that the distribution in the histogram corresponds reasonably well to the distribution in the histogram of step length reported by Lajeunesse et al. (2010). In Table 3 the mean value, the 95% confidence interval of the mean values and the standard deviation of the previously presented results, per location and combined for the crest and trough respectively, can be found.

Table 3: statistical properties of non-dimensional step length Λ/D_{50}

Location		Mean	95% confidence interval	Standard deviation
Crest	1	18.90	14.90 to 22.90	10.72
	2	20.29	14.38 to 26.21	15.85
	3	23.95	17.80 to 30.10	16.47
	Total	21.05	18.00 to 24.10	14.57
Trough	1	20.21	14.02 to 26.41	16.59
	2	23.63	14.94 to 32.32	23.27
	3	21.26	16.44 to 26.09	12.92
	Total	21.70	17.94 to 25.46	17.96

In the through there is some more variation between the individual locations, while the mean values at the crest and trough are roughly the same. This is also the case for the 95% confidence intervals. The standard deviation at the trough is slightly higher than at the crest (83% and 69% of the mean value respectively). For now it is concluded that the measured step lengths at the crest and trough are not significantly different.

Other average results are presented in Table 4. The average step length in streamwise direction (Λ_x), perpendicular to the streamwise direction (Λ_y) and (again) the total (Λ) are given as well as the average particle velocity in streamwise direction (u), perpendicular to the streamwise direction (v) and the total ($\bar{u}$). Results are both given in real dimensions, and non-dimensionalized by D_{50} (for the step lengths) and the mean flow velocity $\bar{u}_{flow}$ (for the particle velocities).

Table 4: mean values of various parameters in dimensional and non-dimensional units

Parameter	Crest	Trough	Parameter	Crest	Trough
Λ [cm]	1.68	1.74	**Λ/D_{50}**	21.05	21.70
Λ_x [cm]	1.56	1.49	**Λ_x/D_{50}**	19.52	18.68
Λ_y [cm]	-0.11	-0.15	**Λ_y/D_{50}**	-1.36	-1.91
$\bar{u}$ [cm/s]	6.20	6.69	**$\bar{u}/\bar{u}_{flow}$**	0.11	0.11
u [cm/s]	5.63	5.78	**$u/\bar{u}_{flow}$**	0.10	0.10
v [cm/s]	-0.64	-0.32	**$v/\bar{u}_{flow}$**	-0.01	-0.01

The particle velocities in the streamwise direction are in the order of 10% of the depth- and dune-averaged streamwise flow velocity. Also for the particle velocitites not much difference is observed between the trough and crest position. The velocities and step lengths of the particles are dominated by streamwise movement. The velocities and step lengths in the direction perpendicular to the streamwise direction are around a factor 10 smaller than in the streamwise direction. That the particle movement over the dune is not solely in the streamwise direction is caused by the local topography of the dune. Due to the chaotic nature of sediment movement and some influence of wall roughness the bed not always slopes only in streamwise direction, but can also slope in other directions. Because flow follows the bed locally, it also moves sediment in directions deviating from the streamwise direction.

Some qualitative properties of the particle movement at the crest and trough were also observed. In general, there was much more particle movement at the crest. This is to be expected, because when dunes migrate in equilibrium condition with a fairly constant dune shape, the sand transport at the crest must be considerably higher than at the trough. Furthermore, it was observed that to a large extent sediment at the trough is transported in bursts, seemingly due to turbulent action resulting from the reattachment of flow shortly after the flow separation zone. Often, a group of particles would start moving simultaneously. At the crest there was also some movement triggered by bursts, but most of the particles were set in motion continuously, likely due to the higher average bed shear stress. Another observation was that at the crest and trough particles can sometimes start moving due to collision with another particle and that their paths are also influenced by collisions.

2.5 STEP LENGTH MODEL VALIDATION

Sekine & Kikkawa (1992) have derived a relation between the observations of particle step lengths for bed load over a flat bed and certain flow and sediment properties (see equation 2). To calculate the value that follows from that equation the *skin friction velocity* is needed, because the experiments used by Sekine & Kikkawa (1992) were done with a flat bed (i.e. there was only grain shear stress). Using the data in Table 2 and the relation between total shear stress and grain shear stress of Engelund & Fredsøe (1982), it follows that the dimensionless grain shear stress θ'=0.080 in the experiment. With the *volumetric* grain shear stress $\tau'=\theta' g(\rho_s/\rho-1)D_{50}$, it follows that $u_*'=(\tau')^{1/2}$=0.032 m/s. This means that the *dune-averaged* suspension parameter due to grain shear stress u_*'/w_s=0.31. The critical Shields parameter of the used sand is 0.031 with the formula of Van Rijn (1984a), which makes the critical friction velocity 0.02 m/s. According to the formula of Sekine & Kikkawa (1992), shown in equation (2), this makes the non-dimensional step length α=193.5: about 9 times higher than the observed *mean* step length. Although the formula of Sekine & Kikkawa (1992) should be applied to the local shear stress, this is still a remarkable difference from the values in Table 3. Both on the crest and in the trough of the dune much lower step lengths were found than predicted with the formula of Sekine & Kikkawa (1992). Of course, that formula was derived for sediment transport over a flat bed so differences are to be expected.

Considering the uncertainty of the 'measured' friction velocity u_* in the present experiment, the sensitivity of the results to the used bed shear stress has been investigated. The bed shear stress has been varied between 50% and 150% of the originally used values, which gives a range of step lengths of 143-257 times the particle diameter. That translates to 7-12 times the observed mean step length of the present dune experiment. The much smaller step lengths of the present dune experiment may partly be due to the effect that sediment mobility is limited on an upwards sloping bed: the particles collide more and move against gravity. Moreover, the flow velocity profiles are strongly distorted by the presence of the dunes.

Furthermore, it should be realized that along a dune, the friction velocity increases towards the crest and therefore increasing step lengths are expected. However, in the Sekine & Kikkawa (1992) formula the friction velocity is a turbulence-averaged value so (turbulent) fluctuations are not taken into account explicitly. Because along a dune the relation between friction velocity and turbulence intensity is different than for the uniform flow over a flat bed, this means that this formula may not fully describe the behaviour of sediment moving along a dune. Although the friction velocity at the trough of a dune (after the flow reattachment point) is lower than at the crest, the turbulent fluctuations are much higher at the trough (Naqshband et al., 2014a). It seems these two differences between flow at the crest and the trough are fairly well balanced, leading to similar step length statistics. It should also be noted that the settling of a particle in the more turbulent flow at the trough (with larger recirculating eddies) will also be different than at the crest. This is not reflected in the settling velocity as used in the formula of Sekine & Kikkawa (1992) which only depends on particle properties and viscosity.

2.6 DISCUSSION

The amount of data analysed in this chapter is limited; more particle movements at more positions and more dunes could still be analysed, as well as more experiments for different sediment, depth and slope combinations could be carried out. It is likely that the histogram of step length observations at the crest and trough is still affected by statistical uncertainty. It should also be noted that although the measurements at the troughs and crests of the three dunes were at different moments in time, they were short (2 s each) and it cannot be excluded that turbulent fluctuations with periods greater than 2 s have been missed. However, with more observations it seems unlikely that the general idea of the results will change drastically. The difference in observed mean step length along the dune, and the predicted step length of the Sekine & Kikkawa (1992) model for mean step length of sediment moving along a flat bed is large. And it is much larger than the statistic uncertainty in the observed step length themselves. This supports the idea that bed load movement along the sloping side of a dune and a flat bed is different.

A qualitative difference between particle movement at the crest and trough was observed. There was much more particle movement at the crest, while particle movement in the trough seemed to be mostly triggered by turbulent bursts. Kleinhans & Van Rijn (2002) have studied the relation between the stochastic nature of bed shear stress and the transport rate of non-uniform sediment near incipient motion. The authors have compared a deterministic method, which predicted transport for each grain size fraction, with a stochastic approach, which extended the former method with a probability distribution for the bed shear stress. With the stochastic method the results were closer to observed values in flume experiments than with the deterministic method. Summed over all fractions, the stochastic method gave 20% larger transport rates than the deterministic method. However, for the largest fractions the stochastic method gave 45-100% larger transport rates. For these fractions, the average bed shear stress was near the critical bed shear stress. This shows that near incipient motion *large fluctuations in bed shear stress* strongly determine transport, while the *average bed shear stress* is less important. It is hypothesized that the stochastic nature of bed shear stress has a similar effect on step length in the trough of a dune (directly after reattachment), but less so at the crest of a dune. The *average* friction velocity at the crest of a dune is much higher than in the trough of a dune, meaning that much more particles will be in motion at the crest. However, extreme *peaks* of the friction velocity in the trough, due to turbulent bursts related to the reattachment of flow after the crest, can lead to sediment motion even when the average friction velocity in the trough is below the critical friction velocity. It is therefore hypothesized that the average step length in the trough is (mainly) determined by the extreme peaks in friction velocity, while the average step length at the crest is determined by a high fairly constant bed shear stress. It is further hypothesized that these two aspects of local flow are of similar importance, making the average step lengths at both locations roughly the same.

It is recommended to further research the process of bed load movement along a dune. This could be in the form of lab experiments as well as numerical experiments. The knowledge gained would be very valuable, as the variation of step length of particles transported as bed load is expected to have marked effects on the dune morphology. For example, it contributes to a transition to upper-stage plane bed from the dune regime (Shimizu et al., 2009).

2.7 CONCLUSION

An explorative experiment has been undertaken to offer an impression of the statistical properties of step lengths of particles transported as bed load in the dune regime (as opposed to the flat bed situation). While the analysis of the data can be expanded to encompass more particle movements, more dunes and more flow and sediment conditions, some interesting characteristics have been found.

From the results presented here it seems that there is little difference between the step lengths found at the crest and trough of a dune, while there is a considerable variation of step length at a single location. The observed mean step length at the crest was ~21 times the grain diameter, while the mean step length at the trough was ~22 times the grain diameter. The standard deviation of step length was 15 times the grain diameter and 18 times the grain diameter respectively. Particle velocity was observed to be 0.06-0.07 m/s, which is in the order of 10% of the depth- and dune-averaged streamwise velocity.

Although the statistics were not fully resolved, the shape of the probability distribution of step length matched well with the distribution as found by Lajeunesse et al. (2010) for particle movement along a flat sediment bed in terms of skewness. At both the crest and trough the measured step length is far below (9 times) the value predicted by the flat bed model of Sekine & Kikkawa (1992).

3 THE MODELLING OF SPATIAL LAG IN BED LOAD TRANSPORT PROCESSES AND ITS EFFECT ON DUNE MORPHOLOGY*

ABSTRACT

In the present chapter, bed load transport models are introduced in the idealized dune model of Paarlberg et al. (2007, 2007, 2009). These allow for the modelling of the spatial lag between the sediment transport rate and bed shear stress along dune surfaces. This lag is an important factor in determining transitions between bedform regimes. Results of the original dune model (using an equilibrium transport formula) are compared with a) a model version that directly models spatial lag with a relaxation equation and b) a model including pick-up and deposition processes.

Both bed load models use mean particle step length as an important parameter, which is varied to assess which value is appropriate for the dune regime. Laboratory experiments of Venditti et al. (2005a, 2005b) are simulated with the model. This shows that the results are best with the pick-up and deposition model version, combined with a step length of 25 times the particle diameter. It is also shown that in principle the model is also able to wash out fully grown dunes, by increasing the step length parameter.

---

* This chapter has been submitted as: Van Duin, O.J.M., S.J.M.H. Hulscher, J.S. Ribberink & C.M. Dohmen-Janssen. The modelling of spatial lag in bed load transport processes and its effect on dune morphology.

3.1 INTRODUCTION

In hydraulic models roughness values play an important role in correctly determining water levels (Casas et al., 2006; Vidal et al., 2007; Morvan et al., 2008), which is important for flood management purposes. In many though not all rivers a large part of the roughness is determined by dunes, which can form on river beds with sediment sizes ranging from silt to gravel (Kostaschuck, 2000; Wilbers and Ten Brinke, 2003; Best, 2005; Jerolmack and Mohrig, 2005; Kleinhans et al., 2007). River dunes increase the hydraulic roughness significantly, because their shape causes form drag. Water level forecasts therefore depend on accurate predictions of the presence and evolution of river dune dimensions, from the lower regime to the upper regime.

In the lower regime the riverbed is flat, and dunes will only appear if the flow power increases. If flow power keeps increasing, the dunes will grow and cause the hydraulic roughness to increase as well. Especially under high water conditions dunes rapidly evolve. At a certain point in the higher regime the flow power will become so high that dunes are washed out completely. The washing out of dunes is linked to various factors, for example a spatial lag between the bedform or flow field and bed load sediment transport (Nakagawa & Tsujimoto, 1980) or an increase in suspended sediment concentration (Smith & McLean, 1977). The sudden disappearance of dunes causes hydraulic roughness to decrease, which causes water levels to decrease as well. Ideally, a dune model can therefore predict the full evolution of a dune from the lower-stage plane bed until the upper-stage plane bed.

Many approaches have been and are used to model dune dimensions, varying from empirical equilibrium dune height predictors (e.g. Yalin, 1964; Allen, 1978; Van Rijn, 1984b) to different forms of stability analyses (e.g. Kennedy, 1963; Engelund, 1970; Fredsøe, 1974; Yamaguchi & Izumi, 2002). Recently, more advanced models have been developed that calculate the turbulent flow field over bedforms, in some cases in combination with morphological computations (e.g. Nelson et al., 2005; Tjerry & Fredsøe, 2005; Shimizu et al., 2009; Nabi et al., 2010, 2012a, 2012b, 2013a, 2013b). These models are valuable to study detailed hydrodynamic processes, but are computationally intensive.

Only a few of these relatively complex models are able to model the transition to an upper-stage plane bed in flume conditions. The Shimizu et al. (2009) model may have been the first model, which takes into account both turbulent flow over the bedform and morphological development, that was able to predict this transition. The authors have shown that their model predicts this transition in various numerical scenarios. Furthermore, the model is able to represent other important physical processes like hysteresis effects with regard to discharge and dune height. Shimizu et al. (2009) have stated that the prediction of the transition to upper-stage plane bed is enabled by the way they model the mean particle step length. This variable is the distance travelled from dislodgement to rest according to Einstein (1950). To predict step length Shimizu et al. (2009) have used a conceptual model based on the flat-bed bed load experiments of Nakagawa & Tsujimoto (1980) and the work of Engelund (1966). Additionally, their dune evolution model uses the pick-up and deposition model of Nakagawa & Tsujimoto (1980) to calculate bed load transport.

The Nakagawa & Tsujimoto (1980) pick-up and deposition model inherently allows a phase-lag effect between bed elevation and bed elevation change. As Nakagawa & Tsujimoto (1980) have argued, this lag is the principal cause of bed instability and thereby regime transitions. They have identified two important sources of this lag. The first is due to the spatial distribution of bed shear stress, which can be taken into account by applying the transport formula to the local bed shear stress. The second is the sediment particle step length. This creates a phase-lag effect in non-uniform flow which they have incorporated in their bed load model by calculating the pick-up of sediment first and then determining the deposition of sediment away from the pick-up point with a distribution function that relies on the mean step length. This spatial lag is not taken into account in the often used bed load formulation of Meyer-Peter and Müller (1948), which is meant for equilibrium conditions. The flow in the dune evolution model of Shimizu et al. (2009) is modelled with non-hydrostatic two-dimensional (2DV) flow equations, a free surface and a nonlinear k-ε turbulence closure. In the context of flood early-warning systems such a detailed hydrodynamic model is a drawback as it leads to too large computation times, especially when applied on the large spatial domain of a river segment.

Besides the pick-up and deposition model of Nakagawa & Tsujimoto (1980), there are other ways to model the phase lag effect caused by the probability distribution of sediment deposition. For example, Tsujimoto et al. (1990) have derived a linear relaxation equation that also accounts for this phase lag effect. This equation is based on the definition of sediment deposition and equilibrium bed load transport of Einstein (1950), and the relaxation equation describing the response of bedform geometry to changes in flow presented by Allen (1974) and Nakagawa & Tsujimoto (1980). Furthermore it should be noted that suspended sediment transport can play a role in transitions to the upper-stage plane bed as well through similar processes with regard to spatial lag. However, in the present study the focus is on the phase lag in bed load processes. It is expected that phase-lag of bed load alone may have a significant effect regarding bedform regimes and transitions (as shown by Shimizu et al., 2009).

The idea of the present study is to study the effect of spatial lag on dune dimensions, and explore the potential of an existing idealized dune evolution model (Paarlberg et al., 2006, 2007, 2009) to represent a transition to upper-stage plane bed. This computationally cheap dune evolution model works well in the dune regime, without needing to incorporate a very advanced turbulence model. The aforementioned bed load models that allow for the naturally occurring phenomenon of spatial lag due to the travel distance of sediment, will be implemented. This means that more physical processes are taken into account than with a bed load formula like that of Meyer-Peter and Müller (1948), while it is expected that computational time still remains limited. The focus will be on sand beds and flume conditions.

In the model of Paarlberg et al. (2009) the flow separation zone is parameterized instead of using full hydrodynamic equations. Furthermore, the model employs a constant eddy viscosity as a very basic turbulence closure. The model is able to predict the evolution of dunes from small initial disturbances up to equilibrium dimensions with limited computational time and good accuracy (Paarlberg et al., 2009). In addition, this model has been coupled with an existing large-scale (depth-averaged) hydraulic model to form a 'dynamic roughness model' which works efficiently on the river scale (Paarlberg et al., 2010). The coupled model clearly shows the expected hysteresis effects in dune roughness and water levels during flood waves, and different behaviour of sharp-peaked versus broad-peaked flood waves within the dune regime (Paarlberg et al., 2010).

Paarlberg et al. (2009) assumed that along a dune stoss side the shear stress and sediment transport are directly coupled as they are in steady uniform conditions. With this assumption a transport formula like that of Meyer-Peter and Müller (1948) can be used. However, with this model set-up it is impossible to predict a transition to upper-stage plane bed. This is also caused by the way sediment transport in the flow separation zone is handled. When the lee side slope exceeds 10° in the model of Paarlberg et al. (2009), flow separation is triggered and the shape of the flow separation zone is determined with an experimentally derived parameterization. Within the flow separation zone the flow velocity, and thereby bed shear stress, is assumed to be zero. All sediment that reaches the crest of the dune is deposited at the lee side, which grows towards the angle of repose (30°). This means that once flow separation is triggered in the model it will always remain active. This also means that dunes cannot wash out and reach upper-stage plane bed conditions because the lee side of the dune will remain fixed at 30°.

An additional drawback of the model is that it cannot model a field of dunes properly, because dune length and height are overestimated when a fixed large domain length is used. This is due to the lack of processes that break up larger dunes (Warmink et al., 2014). Therefore the model is limited to predicting the dimensions of a single dune, and the domain length equals the wave length of the fastest growing bedform as determined with a stability analysis. However, as stated before, the model performs well in the dune regime, and requires limited computational effort. Therefore, despite the aforementioned drawbacks, this model is chosen for this research.

This chapter will answer the following research questions: a) to which extent are the linear relaxation equation (Tsujimoto et al., 1990) and the pick-up and deposition sediment transport formulation (Nakagawa & Tsujimoto, 1980) in the Paarlberg et al. (2009) model able to reproduce and/or improve the results of the MPM formulation for describing dunes? b) what are the prospects for the linear relaxation equation (Tsujimoto et al., 1990) and the pick-up and deposition sediment transport formulation (Nakagawa & Tsujimoto, 1980) to describe the transition of the dune regime to the upper-stage plane bed in the model of Paarlberg et al. (2009)?

The organisation of the chapter is as follows. In section 3.2 the set-up of the model and the different sub models will be discussed. Section 3.3 shows the results of the model runs with the different transport model alternatives, and in sections 3.4 and 3.5 the discussion and conclusion are presented.

3.2 DUNE MODEL

3.2.1 General set-up

The basis of the present model is the dune evolution model developed by Paarlberg et al. (2009). Paarlberg et al. (2009) modified the process-based morphodynamic sand wave model of Németh et al. (2006), which is based on the numerical model of Hulscher (1996), to enable simulation of finite amplitude river dune evolution in unidirectional flow.

The original model consists of a flow module, a sediment transport module and a bed evolution module which operate in a decoupled way. This means that, based on the bed levels at the start of a calculation step, first the flow is calculated. Then bed shear stress is derived from the flow, and used to determine sediment transport along the domain. The gradient of sediment transport determines bed evolution, and so finally new bed levels for the next calculation step are calculated. See Figure 12 for a schematic representation of these steps in the calculation. The elements added by Paarlberg et al. (2009) to represent flow separation are in grey and explained in 3.2.7.

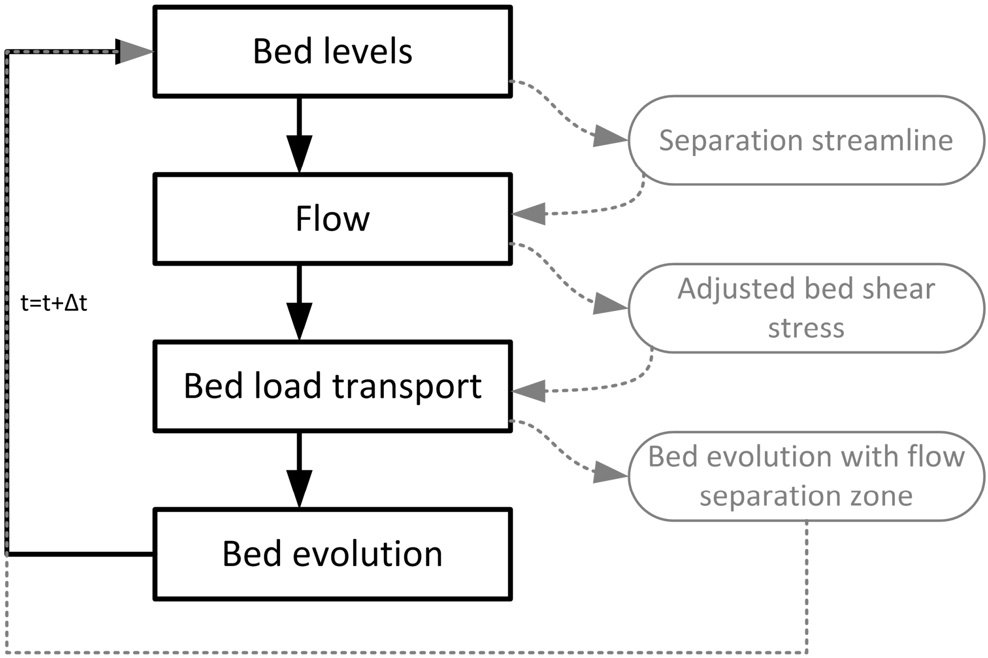

Figure 12. Model process without flow separation (black lines), and with flow separation (black lines and grey lines). t=t+Δt signifies the moment when the calculation is advanced by one computational step Δt. Figure adapted from Paarlberg et al. (2009).

The model simulates a single dune, so the domain length is always equal to one dune length. The model uses periodic boundary conditions, which implies that the sediment transport and flow at the downstream boundary is used as input at the upstream boundary of the model. The dune length is selected by a numerical stability analysis, which is included in the model. This model calculates the growth rate of a series of small bed disturbances with a range of different wavelengths. The length of the fastest growing disturbance is chosen as the dune length. If the water depth changes more than 5% compared to the value with which the dune length was determined, the linear stability analysis is done again to determine a new dune length. Paarlberg et al. (2009) have shown that by using this method most predicted dune lengths are less than 25% larger or smaller than the observed dune lengths. Colombini & Stocchino (2012) have also shown that linear stability analyses can predict the wave length of two-dimensional dunes well.

3.2.2 *Flow model*

In the 2DV flow model *x* is the streamwise coordinate and *z* is the coordinate perpendicular to *x*. The x-axis follows the average channel slope *i*, which is an input parameter for the model. A schematization of a dune moving along a downwards sloping bed is shown in Figure 13. The coordinate system of the computational domain is superimposed on the dune to show that it is rotated according to channel slope *i*. It should be noted that *i* is generally much smaller than implied in Figure 13: in the order of 10^{-3} for flumes and 10^{-4} for lowland rivers.

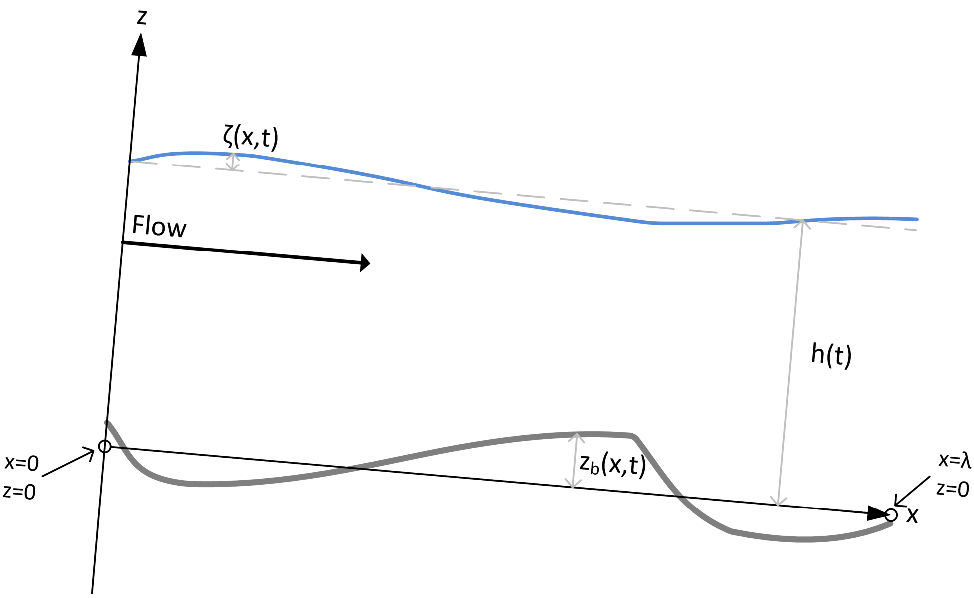

Figure 13. Schematization of a dune moving along a downward sloping bed, with the computational domain superimposed.

In Figure 13 λ denotes the dune length, *h* is the domain-averaged water depth and z_b is the bed level relative to the *x*-axis. The water surface elevation is defined as the deviation from the average water elevation and is denoted by ζ.

3.2.2.1 *Governing equations*

The flow in the model of Paarlberg et al. (2009) is described by the steady two-dimensional shallow water equations in a vertical plane (2-DV), assuming hydrostatic pressure conditions. For small squared Froude numbers (Fr^2<<1) and small vertical flow accelerations the momentum equation in vertical direction reduces to the hydrostatic pressure condition, and the time variations in the horizontal momentum equation can be dropped. The governing model equations that result from the analysis done by Paarlberg et al. (2009) are shown in equations (3) and (4).

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -g\frac{\partial \zeta}{\partial x} + A_v\frac{\partial^2 u}{\partial z^2} + gi \qquad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad (4)$$

The velocities in the x and z directions are u and w, respectively. The parameter g is the acceleration due to gravity, and A_v denotes the eddy viscosity. The flow in the domain is forced by the term gi, which signifies the effect of the water level gradient along the domain due to the channel slope.

3.2.2.2 *Boundary conditions*

The boundary conditions are defined at the water surface ($z=h+\zeta$) and at the bed ($z=z_b$). The boundary conditions at the water surface are that there can be no flow through the surface (equation 5) and no shear stress at the surface (equation 6).

$$u\frac{\partial \zeta}{\partial x}\bigg|_{z=h+\zeta} = w \qquad (5)$$

$$\frac{\partial u}{\partial z}\bigg|_{z=h+\zeta} = 0 \qquad (6)$$

The kinematic boundary condition at the bed (equation 7) yields that there is no flow through the bed.

$$u\frac{\partial z_b}{\partial x}\bigg|_{z=z_b} = w \qquad (7)$$

As a basic turbulence closure, a time- and depth-independent eddy viscosity is assumed which leads to a parabolic velocity profile (see Engelund, 1970 and Hulscher, 1996). In order to represent the bed shear stress correctly for a constant eddy viscosity, the partial slip condition at the bed presented in equation (8) is necessary.

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

In equation (8) τ_b (m^2/s^2) represents the volumetric bed shear stress, u_b (m/s) is the flow velocity at the bed, and the resistance parameter S (m/s) controls the resistance at the bed. Engelund (1970) used a parameter similar to S to relate friction velocity and thereby bed shear stress to the flow velocity at the bed. Paarlberg et al. (2009)

have determined that $A_v=1/6*\beta_1\kappa u_*h$ and $S=\beta_2 u_*$, where β_1 and β_2 are calibration parameters, the Von Kármán constant κ=0.407 and u_* is the friction velocity. The calibration results of Paarlberg et al. (2009) are used, who have found that $\beta_1=\beta_2=0.5$.

3.2.3 *Solving the flow equations*

To solve the flow equations the average water depth is needed as input. However, to be able to model flume situations the discharge is used as input. This means that the average water depth has to be determined iteratively. The model starts with an initial value for h and solves the flow equations described in 3.2.2.1 and further. The discharge that results from the flow field is compared to the discharge given as input, and h is adjusted if they are not equal. This process is repeated until they do match. For more details about the model equations and numerical solution procedure, reference is made to Paarlberg et al. (2009) and Van den Berg et al. (2012).

3.2.4 *Bed load sediment transport model*

Three different bed load models are used: 1) the Meyer-Peter and Müller (1948) formulation as used in Paarlberg et al. (2009), 2) a Meyer-Peter and Müller (1948) formulation with a spatial lag via a relaxation equation, and 3) the Nakagawa & Tsujimoto (1980) pick-up and deposition model.

3.2.4.1 *Meyer-Peter and Müller sediment transport model*

In the original dune evolution model a formula of the type of Meyer-Peter and Müller (1948), including gravitational bed slope effects, is used. Equation (9) denotes this formula in dimensional form (as volumetric bed load transport per unit width, m²/s):

$$q_{b;e}(x) = \begin{cases} \beta[\tau_b(x) - \tau_c(x)]^n \left(1 + \eta \frac{\partial z_b}{\partial x}\right), & \tau_b > \tau_c \\ 0 & , \tau_b \leq \tau_c \end{cases} \tag{9}$$

where τ_c(x) is the local critical (volumetric) bed shear stress (m²/s²), n=3/2 and $\eta=\tan(\varphi)^{-1}$ with the angle of repose φ=30° for sand. It should be noted that when flow separation occurs the above equation is only used outside of the flow separation zone. The sediment that reaches the flow separation point at the crest of the dune is deposited along the lee side, see 3.2.7. The proportionality constant β (s²/m) describes how efficiently the sand particles are transported by the bed shear stress (Van Rijn, 1993) and its value can be estimated with

$$\beta = m/(\Delta g) \tag{10}$$

where $\Delta=\rho_s/\rho-1$ and the empirical coefficient m=4 is based on analysis done by Wong and Parker (2006). The grain density of sand ρ_s is set to 2650 kg/m^3, and the density of water ρ is set to 1000 kg/m^3. The local, critical bed shear stress $\tau_c(x)$, corrected for bed slope effects, is given by the following equation:

$$\tau_c(x) = \tau_{c0}\frac{1+\eta\frac{\partial z_b}{\partial x}}{\sqrt{1+\left(\frac{\partial z_b}{\partial x}\right)^2}} \tag{11}$$

with τ_{c0} the critical bed shear stress for flat bed, defined by equation (12).

$$\tau_{c0} = \theta_{c0} g \Delta D_{50} \tag{12}$$

In this equation θ_{c0} is the critical Shields parameter and D_{50} is the median grain size.

3.2.4.2 Meyer-Peter and Müller sediment transport model extended with linear relaxation

Tsujimoto et al. (1990) have shown that sediment does not directly respond to changing flow conditions along the bed (i.e. using equilibrium transport introduces errors in that situation): the sediment transport only reaches its equilibrium value after a certain adaptation length. Nakagawa & Tsujimoto (1980) have proposed a pick-up and deposition model to capture this relaxation process, which is presented in the next section. As an alternative Tsujimoto et al. (1990) have derived a simple relation to model relaxation in sediment transport, namely:

$$\frac{dq_b}{dx} = \frac{q_{b;e}-q_b}{\Lambda} \tag{13}$$

where $q_{b;e}$ is the equilibrium sediment transport (following Meyer-Peter and Müller, 1948) and Λ (m) is the mean step length. Einstein (1950) states that the mean step length is the average distance travelled by sediment particles (from where they were entrained to where they were deposited) under certain flow conditions and can be determined by:

$$\Lambda = \alpha D_{50} \tag{14}$$

where α is a non-dimensional step length parameter which is often assumed to be 100 as originally defined by Einstein (1950). This parameter is further discussed in section 3.2.5. Tsujimoto et al. (1990) have shown that equation (13) follows from a more general linear approximation of the change of sediment transport over distance (or time) as the result of a difference between its local value and its equilibrium value. This depends on a spatial (or temporal) scale of relaxation, which in this case is the mean step length.

It should be noted that equation (13) needs a boundary condition at x=0 for q_b. Only a periodic boundary condition is defined which states that values at the start of the domain (x=0) are equal to the values at the end of the domain (x=λ), which is not enough information as it does not directly define q_b(x=0). To come to a solution, the value at x=0 is estimated, and the subsequent values are determined using equation (13) and a backwards Euler scheme. The value at the end of the domain should be the same as the value at x=0, if this is not the case an improved estimate is made. This process is repeated until the periodic boundary condition is met, or until the difference between the value at x=0 and x= λ is smaller than 0.1%. Different 'first guesses' at x=0 were tested (e.g. q_b=0, q_b= $q_{b;e}$), but this did not have an effect on the final result. The model in its current version uses q_b(x=0)= $q_{b;e}$(x=0)/2.

3.2.4.3 Pick-up and deposition model

The pick-up and deposition model of Nakagawa & Tsujimoto (1980) uses the following formulae to determine bed load transport. Pick-up of sediment (probability of a particle being picked up in s^{-1}) is determined by

$$p_s(x) = F_0\sqrt{\frac{\Delta g}{D_{50}}}\,\theta(x)\left[1-\frac{\theta_c}{\theta(x)}\right]^3 \tag{15}$$

where F_0=0.03, θ is the Shields parameter, and θ_c is the critical Shields parameter. The determination of deposition is done by applying the following formula:

$$p_d(x) = \int_0^{\infty} p_x(x-s)f(s)ds \tag{16}$$

where the distribution *f(s)* determines the fraction of sediment that is deposited a distance *s* away from the pick-up point *(x-s)*. This means that in order to determine the deposition at a certain location *x* the pick-up of sediment at the *upstream* locations needs to be known. The model first determines the pick-up along the domain, and then for each cell distributes the picked-up sediment among the cells downstream from it according to the distribution function. The pick-up at each cell in turn is simply the sum of the fractions of picked-up sediment it receives from upstream. The distribution function is defined as follows:

$$f(s) = \frac{1}{\Lambda}\exp\left(\frac{-s}{\Lambda}\right) \tag{17}$$

The integral of this function is F(s)=-exp(-s/Λ). This means that the fraction of sediment picked up at a certain location that is deposited between that location and 5 times the step length in downstream direction, equals exp(0)-exp(-5)=99.3%. Because of this, equation (16) is applied from s=0 through s=5*Λ instead of applying it from s=0 through s=∞. The remainder of the sediment (0.7%) is deposited at the cell where s=5*Λ. Finally the transport gradient along the domain is determined as follows:

$$\frac{\partial q_b}{\partial x} = D_{50}[p_s(x) - p_d(x)] \quad (18)$$

3.2.5 Step length

Francis (1973), Fernandez Luque & Van Beek (1976) and Sekine & Kikkawa (1984) have done lab experiments with moving sand along a plane bed to determine the dependency of among others bed load transport and particle velocity on various parameters. The latter authors have used this data to validate a numerical model of saltation of particles (Sekine & Kikkawa, 1992). Their predictions for the thickness of the saltating bed load layer furthermore closely match the data of Sekine & Kikkawa (1984); the particles remain within a few grain diameters from the bed, as expected for bed load transport.

They have furthermore compared the step length values that follow from their model with the step length values derived from experiments by among others Nakagawa & Tusjimoto (1980). The experiments of the latter authors showed a range of approximately 40 to 240 times the particle diameter. The suspension parameter u_*/w_s ranged from about 0.18 to 0.35, which is clearly in the bed load regime. Sekine & Kikkawa (1992) have shown through numerical model experiments that the mean step length can vary between near 10 and about 250 times the particle diameter and is mostly related to friction velocity u_* (directly proportional) and settling velocity w_s (inversely). The suspension parameter u_*/w_s ranged from about 0.15 to 0.28. They found that all computed step length values are no more than two times larger or smaller than the observed values.

Based on the preceding information, in the following the step length will be varied between 25 and 300 times the particle diameter, which is consistent with bed load motion as observed in experiments. This way it can be assessed how sensitive the results are with respect to this parameter. Step length will be held constant along the dune, in line with the findings in Van Duin et al. (2012) and chapter 2.

3.2.6 Bed evolution

The bed evolution is modelled using the Exner equation given by equation (19), where the sediment transport rate is calculated with one of the three aforementioned bed load models and ε_p=0.4 is the bed porosity.

$$\left(1-\varepsilon_p\right)\frac{\partial z_b}{\partial t}=-\frac{\partial q_b}{\partial x} \tag{19}$$

The equilibrium transport model is only applied outside the flow separation zone. See section 3.2.7 for the avalanching procedure that is used inside the flow separation zone.

In case the linear relaxation model or the pick-up and deposition model is used, equation (19) is applied inside as well as outside of the flow separation zone. When at a certain location the angle of the bed exceeds the angle of repose at the end of a calculation step, sediment is moved downwards until the angle of repose is no longer exceeded anywhere. This means that In contrast to the original method as presented by Paarlberg et al. (2009), the avalanching procedure described in section 3.2.7 is *never* applied. In this way picked-up sediment is allowed to deposit in the (non-existent) separation zone.

3.2.7 Flow separation

The hydraulic model of Paarlberg et al. (2009) does not lead to flow separation by itself. This limited the ability of bedforms to grow, and their shapes remained less skewed and with a gentle lee side instead of evolving to dunes with strongly skewed forms and steep lee sides as typically seen in the flume. To be able to simulate dunes with the proper dimensions and shapes Paarlberg et al. (2009) therefore used a parameterization of flow separation. Flow separation is forced in the model when the leeside slope exceeds 10°, after which the slope always grows towards 30°. The flow velocity and bed shear stress *within* the flow separation zone is assumed to be zero. This means that the transport rate calculated with equation (9) will be zero in the flow separation zone as well, although sand can still enter the flow separation zone as it avalanches from the crest. See Figure 12 for a schematic representation of the following more detailed explanation of the mentioned steps in the calculation.

The flow separation streamline behind the dune is determined with a third-order polynomial based on experimental data of turbulent flow over two-dimensional subaqueous bedforms gathered by Paarlberg et al. (2007). With this relation the separation streamline is calculated using only the bedform height as input. As shown by Paarlberg et al. (2007), with this method the length of the flow separation zone varies between 4 and 6 times the bedform height, which corresponds well with literature. Following the method of Kroy et al. (2002) for aeolian sand dunes, the flow is then computed with the flow separation streamline acting as the bed level in the flow separation zone The bed shear stress downstream of the flow separation zone is slightly adjusted to account for the presence of the flow separation zone (see Paarlberg et al., 2009). With the used parameterization of flow separation the influence of flow separation on the flow along a dune is taken into account, without needing a more advanced hydraulic and turbulence model.

However, a procedure to handle the discontinuity in sediment transport at the crest in a physically reasonable way is needed. To overcome this, the bed load transport that reaches the crest of the dune at the flow separation point is deposited on the leeside of the slope in such a way that the lee side grows towards the angle of repose, which approximates real life avalanching. Effectively this means that in the flow separation zone the crest moves forward but the rest of the bed remains undisturbed because the shear stress is zero there. Because of this method of handling sediment transport in the flow separation zone the lee side slope always remains 30° and flow separation is permanent. Outside the flow separation zone the bed is of course normally active as the change of bed level there follows from the transport gradient.

It should be noted that the parameterization of flow separation described in this section is only used with the original bed load transport formulation described in 3.2.4.1, and not with the two new formulations described in 3.2.4.2 and 3.2.4.3. With those transport concepts sediment has to be able to settle naturally in the area behind the crest, as the filling of the trough is one of the processes leading to the washing out of a dune. Although this means that flow velocity and bed shear stress are no longer zero in the flow separation zone, both are generally low. This means that there is no or only little pick-up of sediment in that zone. Also, the dunes become strongly skewed with a steep lee side without further intervention.

3.3 RESULTS

The reference case used for this study is flow A of an experiment done by Venditti et al. (2005a, 2005b). This flow will be used to assess which value of α best fits for the bed load regime. The new model will then be compared with the results from flow B, C, D and E of Venditti et al. (2005a, 2005b). The experiment of Venditti et al. (2005a, 2005b) was done in a recirculating flume of 15.2 m long, 1 m wide and 0.30 m deep. The suspension parameter u_*/w_s was between 0.3 and 0.4, so the experiment was in the bed load regime. The initial parameters of the various flows of Venditti et al.

(2005a, 2005b) are presented in Table 5. In this table h_i is initial water depth and q is discharge per unit width, which was constant during the experimental run.

Table 5: Initial parameters of the experiments of Venditti et al. (2005a, 2005b)

	Flow A	Flow B	Flow C	Flow D	Flow E
h_i [m]	0.152	0.152	0.153	0.153	0.153
i [10^{-4} m/m]	12	11	7	5.5	5.5
q [m^2/s]	0.077	0.0723	0.0696	0.0611	0.0546
D_{50} [mm]	0.5	0.5	0.5	0.5	0.5

Starting from a flat bed, the bedforms developed towards their equilibrium dimensions in 1.5 hours for flows A, B and C. The bedforms for flow D and E each grew from a single artificially made bed defect in the flume as opposed to the bedforms of flow A, B and C which developed over the entire bed without interference (Venditti et al., 2005a). Bedform height, length and migration rate were determined from measurements with echo sounders, and water depth with ultrasonic water level probes (Venditti et al., 2005a). Because bed load measurements were too infrequent, Venditti et al. (2005b) calculated the volumetric dry sediment transport rate of the bedforms per unit width $Q_{s;v}$ with equation (20).

$$Q_{s;v} = \beta_b(1 - \varepsilon_p)R_b\Delta_b \tag{20}$$

In this equation Δ_b is the bedform height, R_b is the migration rate, and $\beta_b=A/(\Delta_b*\lambda)$ is a bedform shape factor which depends on frontal bedform area A and the dune height and length. Venditti et al. (2005b) reported that the values of β_b of their dunes (0.54-0.60) were similar to earlier experiments. Multiplying $Q_{s;v}$ with ρ_s gives the dry sediment transport rate of the bedforms in m/s^2. The resulting equilibrium values can be found in Table 6.

Table 6: Experimental results of Venditti et al. (2005a, 2005b). The equilibrium dune has a length λ_e, height Δ_e, migration rate R_e, and sediment transport rate $Q_{s;e}$. The equilibrium water depth is h_e.

	Flow A	Flow B	Flow C	Flow D	Flow E
Δ_e [m]	0.048	0.042	0.036	0.022	0.020
λ_e [m]	1.17	0.86	0.95	0.38	0.30
h_e [m]	0.17	0.17	0.17	0.17	0.17
R_e [mm/s]	0.65	0.37	0.33	0.17	0.10
$Q_{s;e}$ [kg/h]	102.4	47.9	36.7	17.1	11.3

Venditti et al. (2005b) reported a value of $Q_{s;e}$=102.4 kg/h for flow A, which is the mean of the estimates of sediment transport rate over a period of time in the equilibrium stage of the experiment. Using the equilibrium dune characteristics of flow A as presented in Table 2, instead of using the full time-series as Venditti et al. (2005b) did, and directly applying equation (20), the equilibrium sediment transport rate $Q_{s;e}$=100.0 kg/h which is consistent with the reported value. The same method will be used to determine sediment transport rate from the model results.

The model starts with a flat bed and uses a θ_{c0} of 0.05. Discharge, slope and grain diameter remain constant during the model run. The model was run using the three options for the sediment transport formulation described before. In Table 7 the equilibrium dune dimensions, water depth, bedform migration rate and sediment transport rate of the bedforms are presented for flow A and the corresponding model runs.

The results from the model runs in Table 7 are discussed in the following sections 0-3.3.4. The results of the best-fitting model version for flow B, C, D and E are presented in section 3.3.5. The potential of the model for prediction of a transition to the upper-stage plane bed is shown in section 3.3.6.

Table 7: Experimental results of flow A of Venditti et al. (2005a, 2005b) and model results. The equilibrium dune has a length λ_e, height Δ_e, migration rate R_e, and sediment transport rate $Q_{s;e}$. The equilibrium water depth is h_e.

Experiment		MPM	Linear relaxation α				Pick-up and deposition α							
			25	*50*	*75*	*100*	*25*	*50*	*75*	*100*	*150*	*200*	*250*	*300*
Δ_e [m]	0.048	0.064	0.029	0.023	0	0	0.042	0.039	0.037	0.033	0.019	0	0	0
λ_e [m]	1.172	1.33	1.11	1.1	1.07	1.07	1.18	1.17	1.15	1.14	1.09	1.07	1.07	1.07
h_e [m]	0.17	0.19	0.16	0.16	0.15	0.15	0.17	0.17	0.16	0.16	0.16	0.15	0.15	0.15
R_e [mm/s]	0.65	0.59	1.2	1.3	-	-	0.29	0.58	0.88	1.19	1.94	-	-	-
$Q_{s;e}$ [kg/h]	102.4	162.5	179.5	155.6	-	-	58.1	111.8	161.2	201.2	188.4	-	-	-

3.3.1 Flow A with the original bed load model

Using the original bed load model, Meyer-Peter and Müller (1948), an equilibrium dune height of 0.064 m, dune length of 1.33 m and water depth of 0.19 m are found. The dune length is predicted reasonably well with an overestimation of about 13% (the experimental result was 1.172 m), but the dune height is overestimated by about 33%. The migration rate is close to the experimental result, while the transport rate is overestimated by 62%. The resulting water depth is around 12% higher than the experimental result of 0.17 m. In Figure 14 the evolution of the dune shape is shown.

The model actually predicts the dimensions of a single dune, but in Figure 14 (and Figure 15 and Figure 17) a train of four identical dunes is shown instead to make the results more clear. It can be seen that first low-angle dunes appear which then evolve to high-angle dunes (triggering flow separation) which then becomes dunes with a lee side of 30° (due to the avalanching from the crest, see 3.2.6).

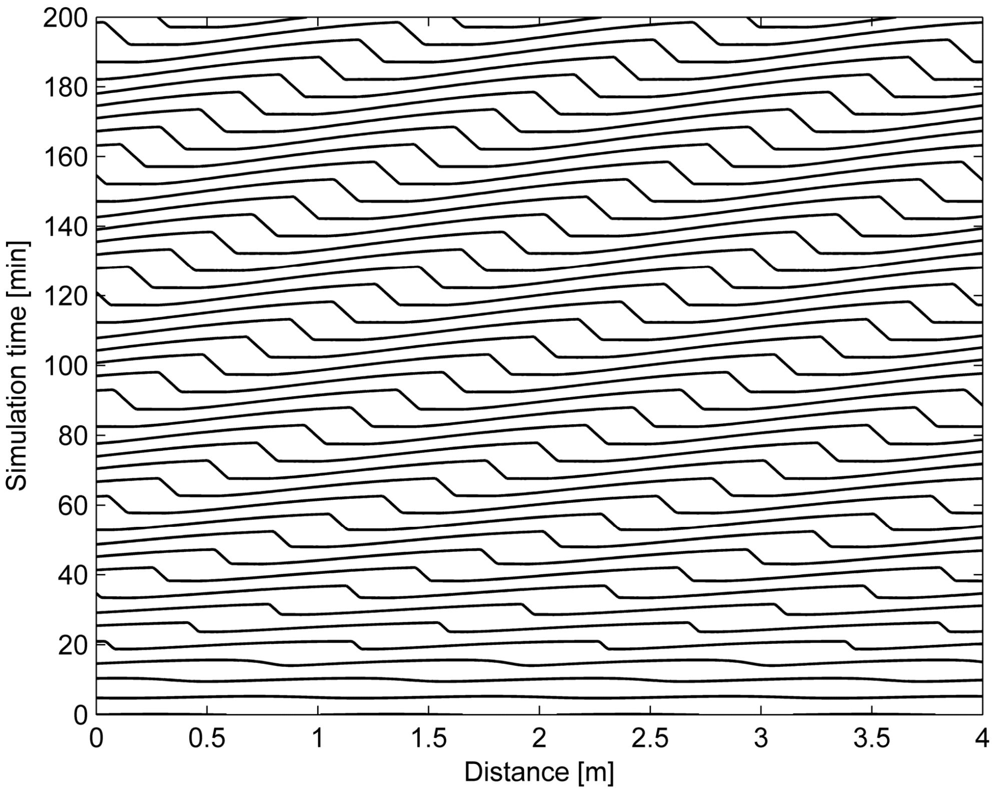

Figure 14. Evolution of dune shape over time of the model run with the original bed load formulation (flow left to right)

3.3.2 Flow A with linear relaxation

Extending the original bed load model with spatial lag, it is observed that applying spatial lag in this way leads to a strong suppression of the dune height and a limited suppression of the dune length. The height is reduced partly because with this bed load model flow separation with steep lee sides (and the resulting forced avalanching from the crest) is not used. With flow separation all sand that reaches the crest would have remained in the flow separation zone, spreading out over the lee side and contributing solely to the height of the dune. However, now the lee side of the dune is still active; sediment is transported away from there towards the stoss side of the 'next' dune. This means that sediment arriving at the lee side does not contribute as strongly to the height of the dune as it would in a situation with flow separation.

While dune height is more than 50% smaller than before, the water depth is only about 16% smaller. Paarlberg et al. (2009) have shown the dune length that follows from the numerical stability analysis is nearly linearly related to the water depth. This is also reflected in the results here, as the decrease of water depth with about 16% corresponds to the decrease of dune length of about 16%.

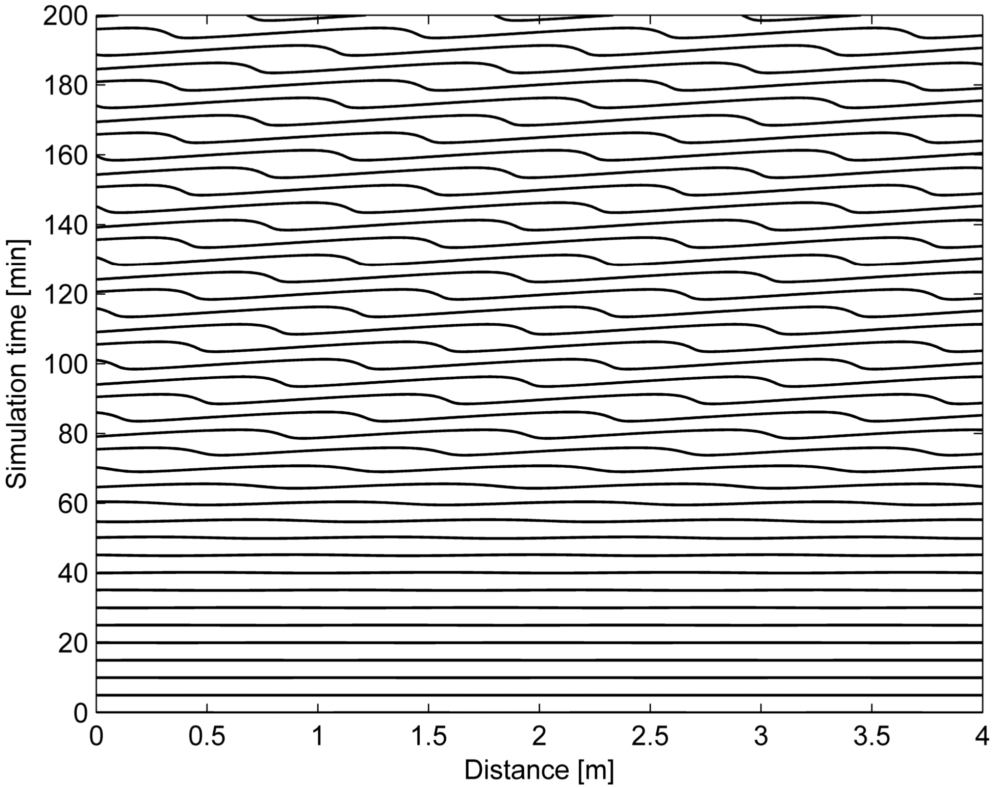

Figure 15. Evolution of dune shape over time of the model run with the linear relaxation bed load formulation, α=25 (flow left to right)

Because water depth and dune length were overestimated with the original model, they are actually closer to the experimental results with the linear relaxation model; an underestimation of about 5% and 6% respectively. The resulting less steep and smoother dunes of limited height are shown in Figure 15, presenting the bed morphology with a non-dimensional step length parameter α of 25. It can be seen that dune growth is slower than with the original model (see Figure 14).

The computational results for flow A are normalized by dividing the modelled parameter values by the measured value of that parameter. This is presented in Figure 16, where the normalized values are plotted against the dimensionless step length α. This clearly shows that dune height decreases with step length, but step length does not have a great effect on water depth and dune length.

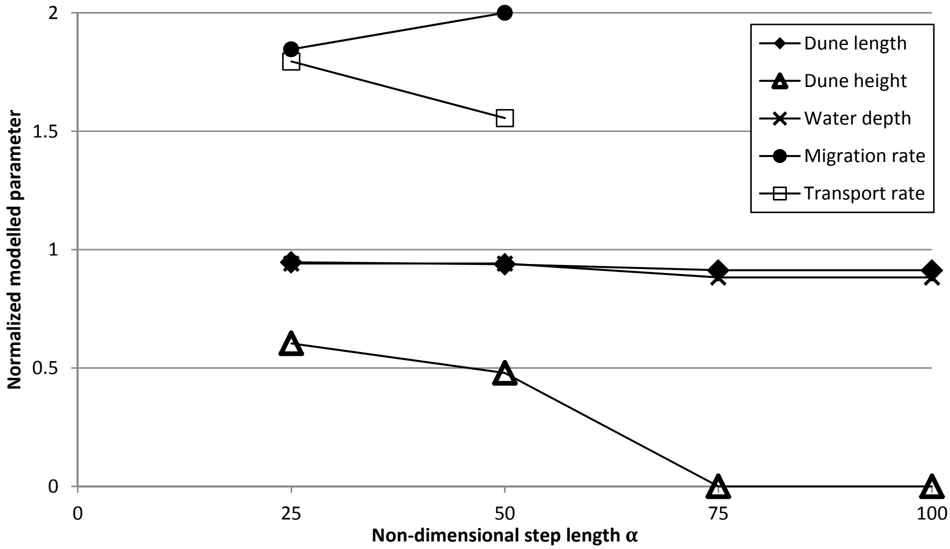

Figure 16. Evolution of normalized modelled parameters with changing step length in the linear relaxation model (flow A). It should be noted that for values of α>50 dune height is zero so there is no meaningful migration rate and transport rate (which is derived from migration rate).

The migration rate of dunes, is overestimated by 85% and 100% with α=25 and α=50 respectively. Regarding the sediment transport rate, this is partly compensated by the underestimation of the dune dimensions. The sediment transport is overestimated by 63% and 79% respectively. Because the overall performance is best with *α=25*, this value is chosen as the best-fit value for this model version.

With a stronger lag (non-dimensional step length of 75 and greater) the 'smearing' effect of the linear relaxation model is so strong that no more dune growth occurs at all. Because the dune height is small to non-existent in that case, there is less hydraulic roughness so the water depth is smaller than in a regime with dunes.

3.3.3 Flow A with pick-up and deposition

Using the pick-up and deposition model of Nakagawa & Tsujimoto (1980), the water depth and dune length are very similar to the experimental and model results with linear relaxation – these are predicted very well. In general, the dune height is underestimated compared to the experimental results for all values of α. This underestimation is smaller than with the linear relaxation model. Using α=25 the bed load model performs the best (dune length is only 13% smaller, dune height and water depth are almost exactly predicted as measured), and better than with the original model. See Figure 17 for the resulting dune evolution using $\alpha=25$. It can be seen that although the dunes are smoother than with the original model, they still are about as steep.

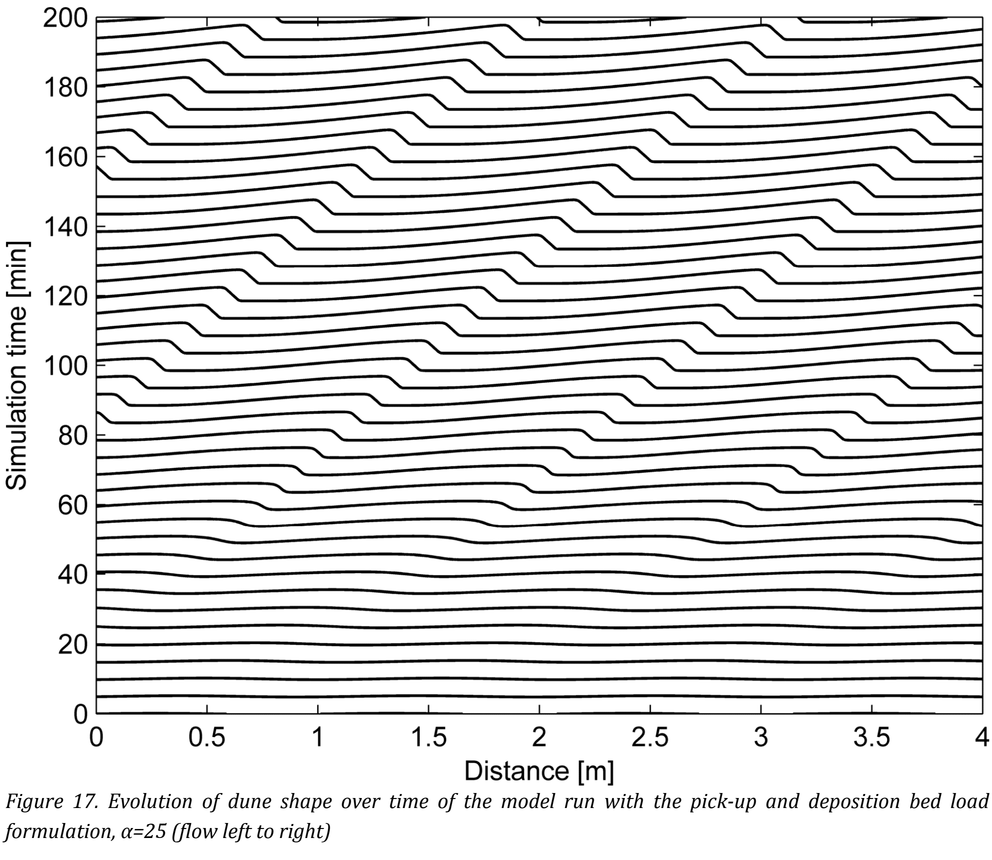

Figure 17. Evolution of dune shape over time of the model run with the pick-up and deposition bed load formulation, α=25 (flow left to right)

The results for flow A are again normalized by dividing the modelled parameter values by the observed value of that parameter. This is presented in Figure 18, where the normalized values are plotted against the dimensionless step length α. This again clearly shows that dune height decreases with step length, but step length does not have a great effect on water depth and dune length. Migration rate and transport rate seem to increase with step length.

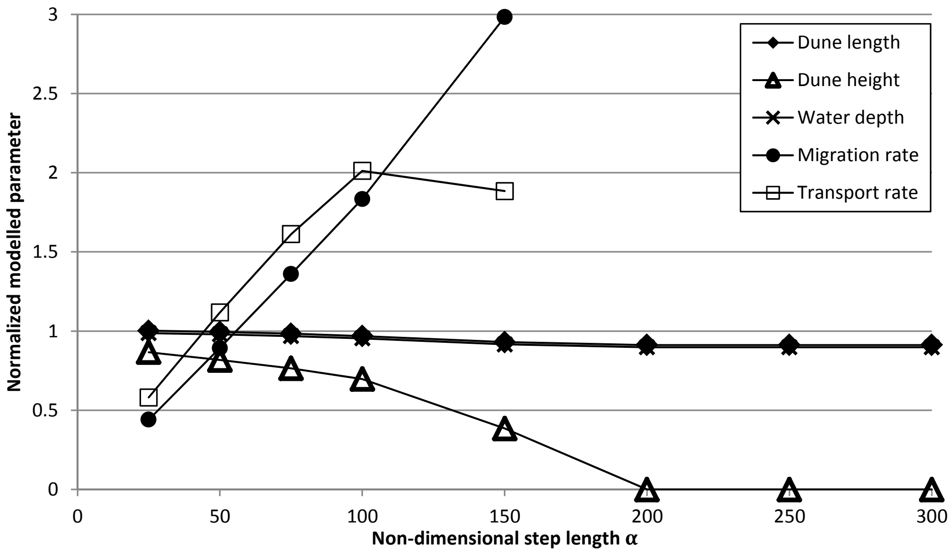

Figure 18. Evolution of normalized modelled parameters with changing step length in the pick-up and deposition model (flow A). It should be noted that for values of α>150 dune height is zero so there is no meaningful migration rate and transport rate (which is derived from migration rate).

For α=25, the migration rate and sediment transport rate are underestimated by 56% and 42% respectively. For values of α of 50, 75 and 100 the result is further from the experimental results regarding dune dimensions. Per increase in step length the dune height decreases, with an underestimation of the experimental dune height with 30% for α=100. For the values of α higher than 100, dunes are strongly suppressed due to the smearing effect, which leads to an underestimation of the dune height with 61% for α=150. Starting at an α-value of 200 dunes do not grow anymore at all, i.e. the initial bed disturbance is completely washed away for the values above 200. The migration rate and sediment transport rate of the dunes increase until α=100, after which they decrease. The migration rate and sediment transport rate are predicted best with α=50, with an underestimation of 10% and an overestimation of 12% respectively.

3.3.4 Dune shapes

The height along each dune is normalized with the crest height of that dune, and the distance along the dune is normalized with the dune length. The resulting equilibrium dune shapes of the three different model versions can be seen in Figure 19. The normalized dune shapes of the three model versions are similar, but have some significant differences. The dune of the linear relaxation variant is quite smooth and not as strongly skewed towards the crest as the other two.

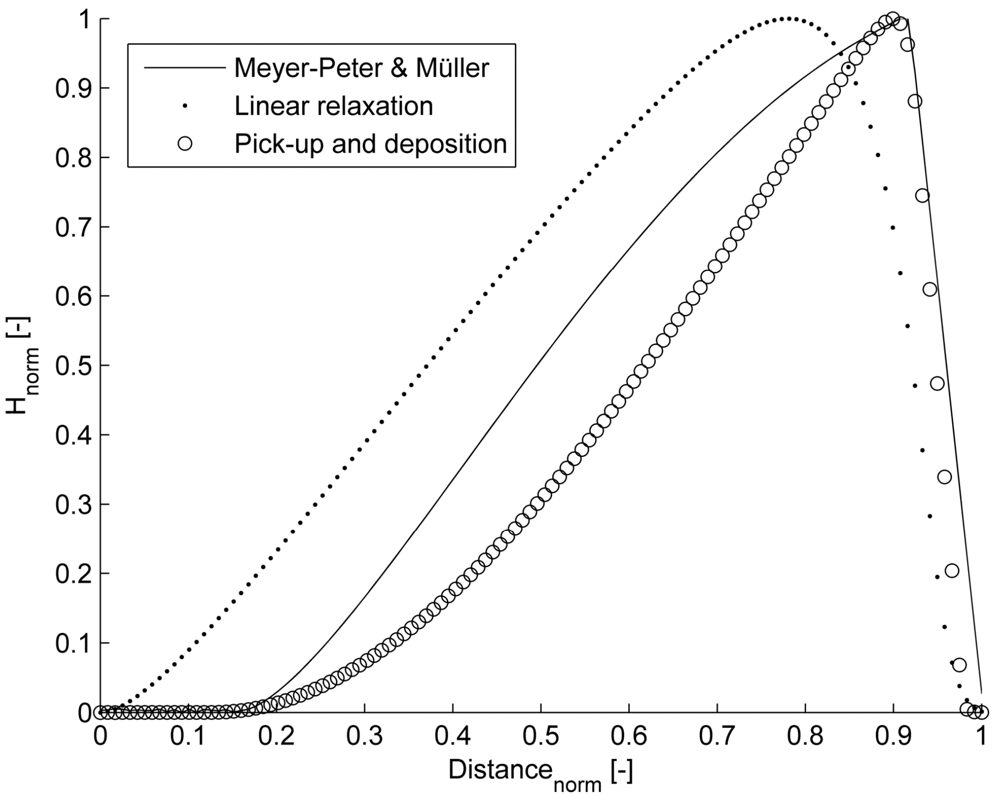

Figure 19. Equilibrium dune shapes of the three model versions, with α=25 for linear relaxation and α=25 for the version with pick-up and deposition (flow left to right). H_{norm} is the normalized height, $Distance_{norm}$ is the normalized distance along the dune.

The original model lets the lee side grow towards the angle of repose (30°) with an avalanching module that forces the lee side to migrate as one front, which causes a very sharp lee side. The pick-up and deposition version does not use this module, but the lee side angle still grows towards the angle of repose. This is because although bed shear stress is non-zero in the trough of the dune, it is still very small. Virtually no pick-up occurs in the trough while deposition does occur, but decreases with distance from the crest. In the end this leads to a distribution of sediment in the separation zone similar to the original model. In this case the lee side angle is almost 27°. Because the lee side develops 'naturally' it is somewhat smoother than the forced lee side of the original model. The results with the linear relaxation model show a gently sloping dune with a leeside angle of about 16°. As can be expected, the dune shape here is more evenly smeared out than with the other variants.

3.3.5 Results with best-fitting model settings

The dune evolution model predicted the dune dimensions of flow A best with the pick-up and deposition bed-load formulation and α=25, compared to the other two bed-load formulations and different values of α. With regard to the migration rate and transport rate the pick-up and deposition bed-load formulation with α=25 did not give the best fit, as the results with α=50 were better. Because correctly predicting dune dimensions and especially dune height is more important in context of predicting hydraulic roughness, the choice is made to use α=25 to model the other flows of Table 5 as well. These results are presented in Table 8, alongside the experimental results from Table 6.

Table 8: Experimental results of Venditti et al. (2005a, 2005b) and model results using the pick-up and deposition model with α=25 for flow A, B, C, D and E. The equilibrium dune has a length λ_e, height Δ_e, migration rate R_e, and sediment transport rate $Q_{s;e}$. The equilibrium water depth is h_e.

	Experiment					**Model**				
	A	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
Δ_e [m]	0.048	0.042	0.036	0.022	0.020	0.042	0.039	0.036	0.022	0.023
λ_e [m]	1.17	0.86	0.95	0.38	0.30	1.18	1.15	1.26	1.10	1.13
h_e [m]	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.18	0.16	0.16
R_e [mm/s]	0.65	0.37	0.33	0.17	0.10	0.29	0.26	0.14	0.08	0.09
$Q_{s;e}$ [kg/h]	102.4	47.9	36.7	17.1	11.3	58.1	49.9	23.3	9.4	9.9

The results from Table 8 are again normalized by dividing the modelled and experimental values of each parameter by the maximum observed value of that parameter. The normalized experimental results are plotted against the normalized modelled results in Figure 20.

Dune height resulting from the model generally agrees well with the experimental results. All model results are within 0.5-17% of the experimental results. Dune length is represented less well, especially for flow D and E where there are very large errors. It seems that the new model cannot reproduce the length of these artificially made defects (Venditti et al., 2005a) well, which is to be expected as the model of the present study is meant for naturally occurring dunes. For flow A, B and C the dune lengths are overestimated by 0%, 34% and 33% respectively. Water depth is represented well, all model results are within 10% of the experimental results. Migration rates are all underestimated, between 12% and 58%. This is part of the reason that the sediment transport rate is underestimated between 12% and 45%, except for flow B where the sediment transport rate is overestimated by 4%.

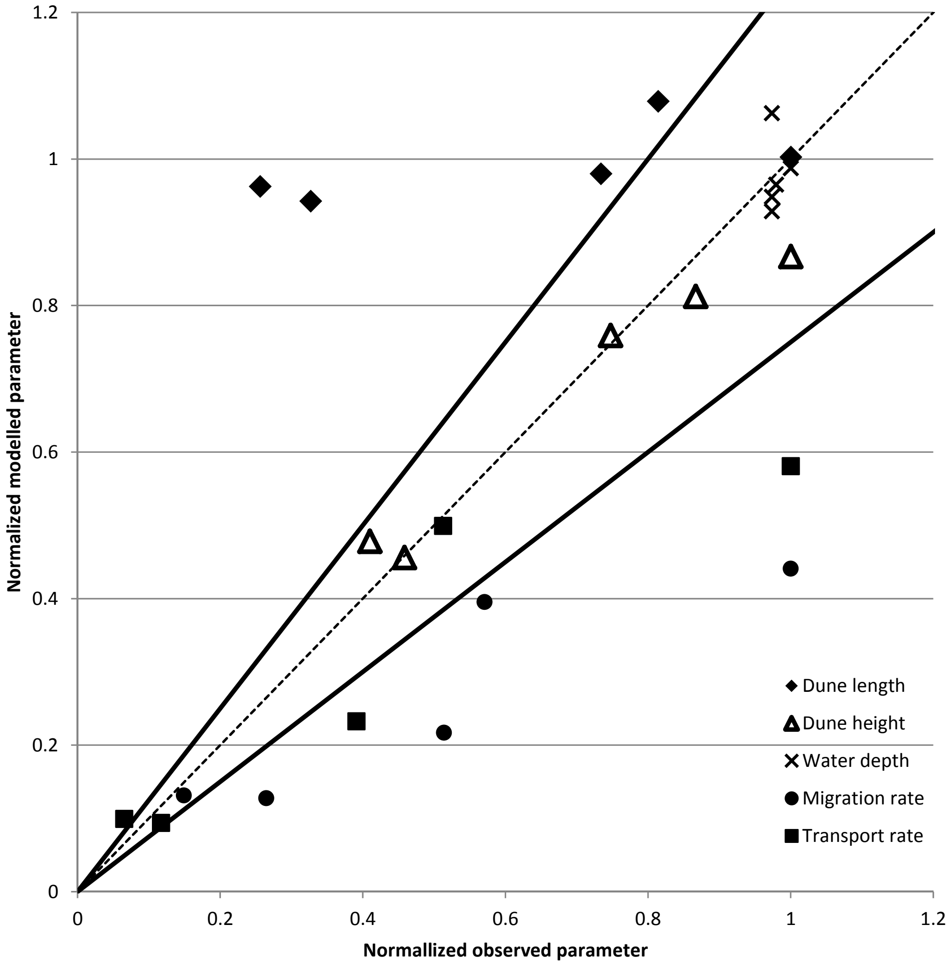

Figure 20. Comparison of normalized modelled and observed parameters. The dashed line represents a perfect match between modelled and observed, while the area between the black lines represent modelled values within 25% of the observed value.

3.3.6 Potential for prediction of upper-stage plane bed

To investigate the potential of the new pick-up and deposition model for the prediction of an upper-stage plane bed, the model is now run with step-wise increasing α, without starting from a flat bed for each α as before. This mimics the increase of step length with increasing flow strength as found by Sekine & Kikkawa (1992) and also assumed by Shimizu et al. (2009). The reference case is again Flow A of Venditti et al. (2005a, 2005b). The pick-up and deposition version of the model is used, because it performs best in the dune regime (see Table 7) though now α is no longer constant. According to the previous results as found in Table 8 certain results are expected from this model run. To begin with α=100, for which dunes are expected. After that α is increased to 150, and the dunes are expected to become smaller and have less steep lee sides. In the final step α is increased to 250, for which the dunes should disappear completely. While this is not a realistic way to determine step length, it enables identifying the effect bed load lag has on fully grown dunes. The results of this model run are presented in Figure 21.

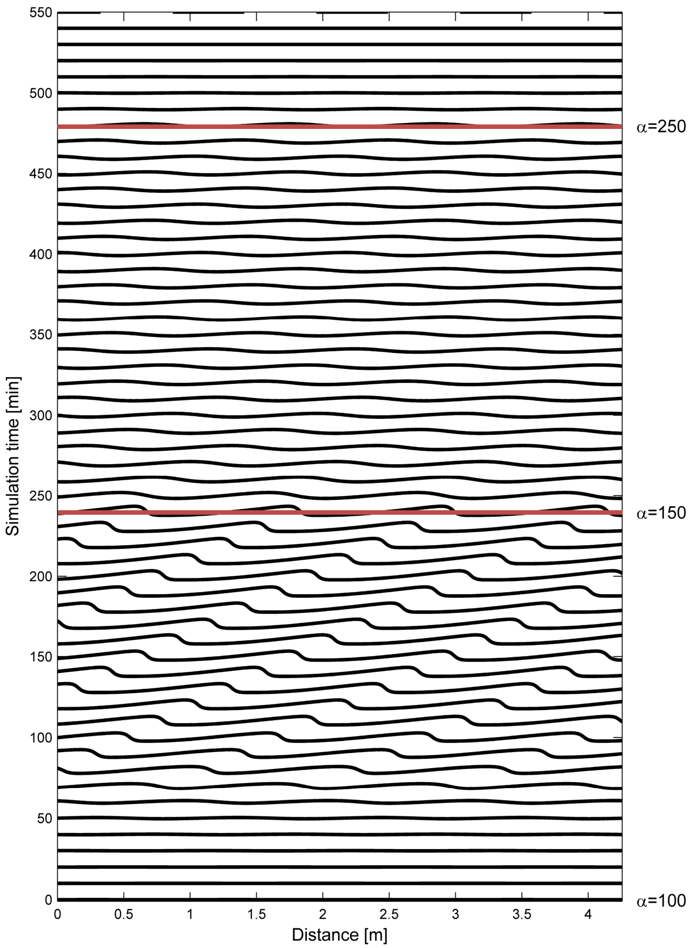

Figure 21. Dune evolution with pick-up and deposition; starting with α=100, then α=150 (first red line) and then α=250 (second red line).

The results in Figure 21 show how the transition to upper-stage plane bed can occur. First dunes arise, then they become low-angle dunes before finally washing out. The results indicate that the model has the potential to simulate the washing out of existing dunes, and not just the small initial disturbances of before.

3.4 DISCUSSION

Both the model with linear relaxation and with pick-up and deposition have the potential to simulate a transition to upper-stage plane bed. With both new bed load formulations the model is able to completely wash out the small initial disturbance with certain constant step lengths. It was furthermore shown that pick-up and deposition processes are able to wash out fully grown dunes, by increasing the step length.

However, to model a transition in a more realistic way, it may be necessary to vary the step length over time and/or space automatically. For example, this can be done with the conceptual model of Shimizu et al. (2009) or the step length model for bed load of Sekine & Kikkawa (1992). The Sekine & Kikkawa (1992) model depends on friction velocity u_*, settling velocity w_s and the critical friction velocity u_{*c}. Therefore it depends inherently on sediment diameter as well. The model is based on numerical and physical experiments regarding bed load movement over a plane bed. The step length model of Sekine & Kikkawa (1992) is presented in equation (21), where α_2 equals 3000.

$$\alpha = \frac{\Lambda}{D_{50}} = \alpha_2 \left(\frac{u_*}{w_S}\right)^{3/2} \left(1 - \frac{u_{*C}/w_S}{u_C/w_S}\right)^{3/2} \tag{21}$$

Shimizu et al. (2009) use the minimum and maximum value of non-dimensional step length α measured by Nakagawa & Tsujimoto (1980) to derive a relation between α and dimensionless grain shear stress θ'. The values of θ' that determine the transitions between the various regimes are derived from the work of Engelund (1966). For values of θ' between zero and 0.5 (the dune regime), α is constant at the minimum value of 50. For values of θ' above 0.8 (the upper stage plane bed regime), α is constant at the maximum value of 250. For values of θ' from 0.5 and 0.8 (the transitional regime), α is linearly interpolated between 50 and 250 based on θ'. There is no further dependency on sediment parameters. Both methods, i.e. Shimizu et al. (2009) and Sekine & Kikkawa (1992), model the behaviour of step length with regard to flow parameters in significantly different ways, however, the models are consistent in selecting increasing step length under increasingly high flow conditions in the form of increasing friction velocity and grain shear stress.

High values of α will lead to the washing out of dunes within the model of Paarlberg et al. (2009), with the two newly implemented bed load models. The question is whether α should be varied only due to the changing flow regime, or along the dune as well because of local variation in shear stress. From experimental results, Van Duin et al. (2012) have found that mean step lengths in the trough of a dune may be very similar to mean step lengths at the crest of a dune, which suggests that variation along the dune is very limited. This is probably because, although the turbulence-averaged bed-shear stress in the trough is lower, the extreme turbulent events (e.g. due to flow reattachment) are much stronger. The mean step lengths therefore become more or less the same along the dune, which implies that it is probably adequate to vary step length due to the changing flow regime but keeping it constant along the dune. The effect of a variable α is most pronounced under changing discharge, so the effect of using different possible models for step length is most important in that context and requires further study.

The modelled step lengths as used in this study fall in the bed load range; they are based on experiments which only considered bed load transport (Nakagawa & Tsujimoto, 1980). However, it should be noted that suspended transport plays a role in the transition to upper-stage plane bed as well, as it also causes a lag between shear stress and the transport rate. Suspended sediment can make larger steps than those found for bed load. Based on the success of the new model with regard to incorporating the effects of spatial lag in bed load processes, it is suggested to further investigate the use of a similar model concept for suspended transport.

3.5 CONCLUSION

The dune evolution model of Paarlberg et al. (2009) was chosen for this study because it fits the criteria for application within a flood management modelling framework: it is computationally cheap and works well within the dune regime. With this model three bed load models were tested: i) a formulation like that of Meyer-Peter and Müller (1948) as in the original dune evolution model, ii) a formulation like that of Meyer-Peter and Müller (1948) with a simple linear relaxation based on the step length (as proposed by Tsujimoto et al., 1990), and iii) the Nakagawa & Tsujimoto (1980) pick-up and deposition model.

The first research question was how the two new model versions compare to the original. It was shown that the resulting dune morphology (dune height, length and general shape) significantly depends on the bed load transport formulation used. The dune shapes with all bed load models have the typical shape of dunes, namely a smoothed triangle, skewed towards the crest. They differ with respect to the original in terms of reduced lee side angle and increased smoothness (especially for the linear relaxation variant). The version with the pick-up and deposition model with α=25 gives the best agreement with a series of measured dune dimensions in the bed-load regime (Venditti et al., 2005a, 2005b).The second research question was what the prospects of modelling a transition to upper-stage plane bed are with the two new bed load models. Both new models show their potential to simulate the washing out process of small initial bed disturbances. The model version with the pick-up and deposition model was chosen to show that it is capable to wash out fully grown dunes as well by increasing the step length.

Further research and model development is needed to simulate the transition to upper-stage plane bed during flood waves. It is likely that the time-dependency of the step length parameter α should be included in the model, as well as the influence of suspended transport lag processes.

4 MODELLING REGIME CHANGES OF DUNES TO UPPER-STAGE PLANE BED IN FLUMES AND IN RIVERS*

ABSTRACT

In the previous chapter spatial lag effects of bed load have been incorporated in the dune evolution model of Paarlberg et al. (2009) by replacing the equilibrium bed load formulation with separate models for the sediment pick-up and deposition processes. This approach enabled the modelling of the transition from dunes to the upper-stage plane bed. It was shown that by increasing the step length (the average distance travelled by sediment particles) the lag between shear stress and bed load transport rate increases and the dunes eventually become smoother and lower, until finally the dunes wash out.

In this chapter a new version of the model for the mean step length is derived, which is dependent on the mean bed shear stress. This model lets the step length increase with increasing flow strength, in line with previous experimental results. To account for suspension and the large scale turbulent structures in rivers, the step length also is made dependent on water depth.

This model approach is tested successfully with a synthetic data set where plane bed conditions are indeed reached in the model, similar to the results of a more advanced model. It is shown that with increasing discharge the flow strength increases, which leads to higher step length and which leads to the washing out of dunes. Although the present model still overestimates the dune height for river cases, the potential of the model concept for river dune dynamics including the transition to upper-stage plane bed is shown. The model results indicate that, if a transition to upper-stage plane bed occurs in a realistic river scenario, a reduction of the water depth of approximately 0.5 m can occur.

---

* This chapter will be submitted as: Van Duin, O.J.M., S.J.M.H. Hulscher, J.S. Ribberink. Modelling regime changes of dunes to upper-stage plane bed in flumes and in rivers

4.1 INTRODUCTION

Hydraulic roughness values play an important role in correctly predicting water levels in rivers (Casas et al., 2006; Vidal et al., 2007; Morvan et al., 2008), which is critical for flood management purposes. River dunes increase the hydraulic roughness significantly, because their shape causes form drag. Because of their significant impact on hydraulic roughness, water level forecasts during a high river water discharge depend on accurate predictions of the evolution of river dune dimensions. One aspect of this is the correct prediction of a transition to upper-stage plane bed conditions. The aim of this chapter is to develop a relatively simple and physics-based dune evolution model that is able to capture proper dune dimensions and dynamic behaviour under transitional conditions. In effect, the goal is to model dune behaviour under varying discharge from the lower stage plane bed to the upper stage plane bed. This model should work under flume and field conditions, and should predict transitions at the appropriate moments.

In the past, many approaches have been used to model dune dimensions, varying from empirical equilibrium dune height predictors (e.g. Yalin, 1964; Allen, 1978; Van Rijn, 1984b) to different forms of stability analyses (e.g. Kennedy, 1963; Engelund, 1970; Fredsøe, 1974; Yamaguchi & Izumi, 2002). Recently, more advanced models have been developed that calculate the turbulent flow field over bedforms, in some cases in combination with morphological computations (e.g. Nelson et al., 2005; Tjerry & Fredsøe, 2005; Shimizu et al., 2009; Nabi et al., 2010, 2012a, 2012b, 2013a, 2013b). These models are valuable to study detailed hydrodynamic processes, but are computationally intensive which makes them unsuitable for the prediction of bedform evolution and roughness over long river reaches.

To be able to efficiently predict dune dimensions over the time-scale of a flood wave Paarlberg et al. (2009) have developed a model in which the flow and sediment transport at the flow separation zone is parameterized instead of using full hydrodynamic equations. This model is able to predict the evolution of dunes from small initial disturbances up to equilibrium dimensions with limited computational time and good accuracy. In addition, this model has been coupled with an existing large-scale depth-averaged hydraulic model to form a ‘dynamic roughness model’ (Paarlberg et al., 2010). Results are promising, as the coupled model clearly shows the expected hysteresis effects in dune roughness and water levels and different behaviour of sharp-peaked versus broad-peaked flood waves within the dune regime (Paarlberg et al., 2010).

As Nakagawa & Tsujimoto (1980) have argued, a lag distance between flow properties (and thereby bed shear stress) and sediment transport is the principal cause of bed instability and thereby regime transitions. One of the contributing factors is the step length of sediment particles, which is the distance travelled from dislodgement to rest according to Einstein (1950). This creates a phase-lag effect which is not taken into account in the equilibrium transport formula like that of Meyer-Peter and Müller (1948). This formula was used in the original model of Paarlberg et al. (2009), which made it impossible to model a transition to upper-stage plane bed. The pick-up and deposition model, as proposed by Nakagawa & Tsujimoto (1980), inherently allows a phase-lag effect over distance. The deposition of sediment away from the pick-up point is determined by using a probability distribution function that relies on the mean step length. This pick-up and deposition model has already been used in the dune evolution model of Shimizu et al. (2009), with good results regarding prediction of dunes and upper-stage plane bed.

Therefore, the Paarlberg et al. (2009) model was extended to enable predictions of a transition to upper-stage plane bed. Van Duin et al. (submitted, see chapter 3) has shown that replacing the transport formula of Meyer-Peter and Müller (1948) with the pick-up and deposition model of Nakagawa & Tsujimoto (1980) leads to improved predictions of dune dimensions in the dune regime. Furthermore, this model is in principle able to simulate the washing out of dunes as well, signifying the potential of this approach for the prediction of a transition to upper-stage plane bed. Manually selecting high values of the step length leads to the washing out of dunes within this model. However, the automatic selection of a physics-based step length is still an issue which will be discussed in this chapter.

Due to the fact that the previously extended model does not incorporate suspended sediment, it may even be needed to allow for step length values that are higher than those typically found for bed load. Under influence of turbulent action at the bottom of a flume or channel sediment may be entrained in the water column. Depending on the flow and turbulence structure there, sediment may be transported over a large distance in suspension. If this suspended transport occurs along dunes, the average distance travelled by sediment becomes far larger than for bed load alone. This has implications for the spatial lag between flow and sediment transport, and thereby for the dune morphology as well.

Naqshband et al. (2014b) have shown that with an increasing suspension parameter dunes first become larger and then become smaller. This can be seen in Figure 22 (from Naqshband et al., 2014b), where for a large set of experiments the non-dimensional dune heights are plotted against the suspension number for high Froude numbers (generally flumes) and low Froude numbers (generally rivers). These results indicate that high suspension numbers are required for the dunes to wash out, and that alongside the influence of bed load lags also suspension lags should be included in determining dune dimensions.

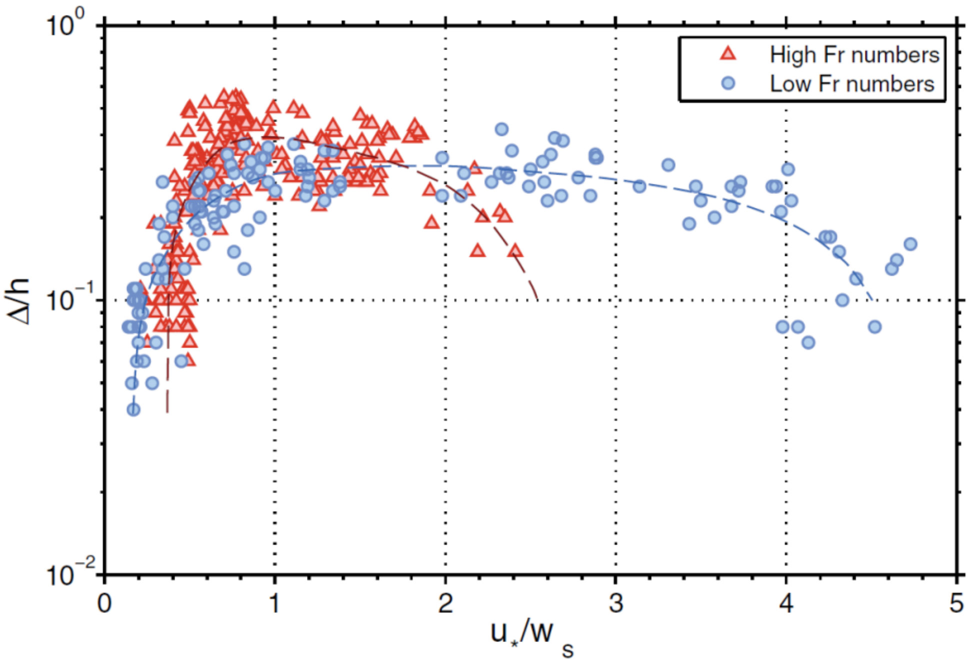

Figure 22: Relation between dimensionless dune height (Δ/h) between the suspension number (u_*/w_s). u_* is friction velocity (m/s), w_s is settling velocity (m/s), Δ is dune height (m) and h is water depth (m). Low Froude numbers are between 0.05 and 0.32 and high Froude numbers are between 0.32 and 0.84. From Naqshband et al. (2014b).

One of the mechanisms contributing to this dependence of dune morphology on suspended sediment has been studied by Naqshband et al. (2014a). The authors have shown that significant portions of suspended load 'escape' the dune by not avalanching on the lee side of the dune but going over the flow separation zone and depositing further away (also shown by Kostaschuk et al., 2010). The authors find that while bed load and suspended load are comparable in magnitude, the gradient of bed load is larger than that of suspended load. This implies that the general shape of these equilibrium dunes is mostly determined by bed load, and to a lesser extent by suspended load which deposits more evenly along the dune. However, for strongly increasing flow strength turbulence becomes stronger and suspended load can become more and more dominant. Then the situation could arise that so much sediment is spread out evenly, that dunes start decaying and maybe even disappear entirely. See also Engelund and Fredsøe (1974), Fredsøe and Engelund (1975), Smith and McLean (1977), and Bridge & Best (1988). In the present work this effect will be taken into account implicitly in the idealized dune evolution model (originally developed by Paarlberg et al., 2006, 2007, 2009).

The main research question is: how can a step length model be derived that combines bed load and suspended load processes and enables the modelling of dune dynamics due to a flood wave in an idealized dune model? Therefore this chapter will answer the following two research questions: a) To what extent can this new model replicate dune dynamics as they occur in flume conditions under variable discharge, including upper-stage plane bed and bedform hysteresis effects? b) Can this type of model in principle describe dune dynamics, including upper-stage plane bed and hysteresis effect, in field conditions?

The organisation of the chapter is as follows. In section 4.2 the set-up of the model is discussed, while step length models from literature and a new step length model is discussed in sections 4.3 and 4.4 respectively. Section 4.5 shows the model results for flume conditions, while section 4.6 shows the model results for river conditions. In sections 4.7 and 4.8 the discussion and conclusion are presented.

4.2 DUNE MODEL

4.2.1 General set-up

The basis of the present model is the dune evolution model developed by Paarlberg et al. (2009). Paarlberg et al. (2009) extended the process-based morphodynamic sand wave model of Németh et al. (2006), which is based on the numerical model of Hulscher (1996), with a parameterization of flow separation, to enable simulation of finite amplitude river dune evolution.

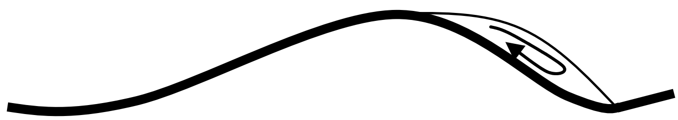

Figure 23: Schematization of a dune (flow left to right)

The model consists of a flow module, a sediment transport module and a bed evolution module which operate in a decoupled way. The model simulates a single dune which is assumed to be in an infinite train of identical dunes. Therefore periodic boundary conditions are used. Because varying discharge means the linear stability analysis as used by Paarlberg et al. (2009) has to be done often during a model run, this approach is computationally expensive. Paarlberg et al. (2009) have shown the dune length that follows from the numerical stability analysis is nearly linearly related to the water depth. Therefore, for computational efficiency, the dune length in the current model is modelled as 7.3 times the water depth. This follows from the empirical relations for dune height and length of Van Rijn (1984b) as presented by Julien & Klaassen (1995).

4.2.2 Flow model

In general the flow is forced by the difference in water level along the domain. While the water depth at the start and end of domain are the same due to the periodic boundary conditions, the water level differs because the domain is sloped. The average bed level is taken as zero and has a slope (this average bed slope is an input parameter for the model). By solving the flow equations with a certain average water depth a discharge is found. The average water depth is adjusted until this discharge matches the discharge given as input.

4.2.3 Governing equations

The flow in the model of Paarlberg et al. (2009) is described by the steady two-dimensional shallow water equations in a vertical plane (2-DV), assuming hydrostatic pressure conditions. For small Froude numbers and small vertical flow acceleration the momentum equation in vertical direction reduces to the hydrostatic pressure condition, and that the time variations in the horizontal momentum equation can be dropped. The governing model equations that result are shown in equations (22) and (23).

$$u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -g\frac{\partial \zeta}{\partial x} + A_v\frac{\partial^2 u}{\partial z^2} + gi \quad (22)$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (23)$$

The velocities in the x and z directions are u and w, respectively. The water surface elevation is denoted by ζ, i is the average channel slope, g is the acceleration due to gravity, and A_v denotes the constant vertical eddy viscosity. Note that a steady flow model is used to compute unsteady flow of a flood wave. This is a reasonable approach, because the length scale of a dune is small so the remaining terms are large compared to the time derivatives. The computational domain is shown in Figure 24.

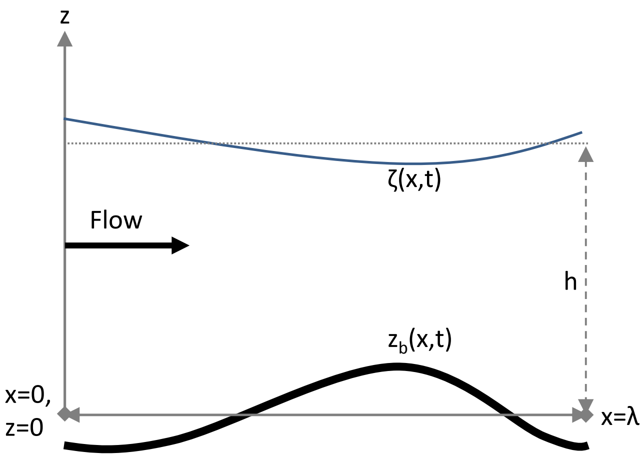

Figure 24: The computational domain

In Figure 24 the symbol λ denotes the dune length (in m), h is the domain-averaged water depth (in m) and z_b is the bed level relative to the x-axis (in m). The flow is forced in the domain because the x-axis is actually at a slope i with regard to the real horizontal plane, creating a water level difference along the domain.

4.2.3.1 Boundary conditions

The boundary conditions are defined at the water surface (z=h+ζ) and at the bed (z=z_b). The boundary conditions at the water surface, equation (24) represents no flow through the surface and equation (25) means no shear stress at the surface. The kinematic boundary condition at the bed, equation (26) yields that there is no flow through the bed.

$$u\left.\frac{\partial \zeta}{\partial x}\right|_{z=h+\zeta} = w \tag{24}$$

$$\left.\frac{\partial u}{\partial z}\right|_{z=h+\zeta} = 0 \tag{25}$$

$$u\left.\frac{\partial z_b}{\partial x}\right|_{z=z_b} = w \tag{26}$$

In order to close the turbulence model, a time- and depth-independent eddy viscosity is assumed. In order to represent the bed shear stress correctly for a constant eddy viscosity, a partial slip condition at the bed, equation (27) is necessary.

$$\tau_b = A_v \frac{\partial u}{\partial z}\Big|_{z=z_b} = Su_b \qquad (27)$$

In equation (27) τ_b (m^2/s^2) represents the volumetric bed shear stress, u_b (m/s) is the flow velocity along the bed, and the resistance parameter S (m/s) controls the resistance at the bed. For more details about the model equations and numerical solution procedure, reference is made to Paarlberg et al. (2009) and Van den Berg et al. (2012). See also chapter 3.

4.2.4 Bed load sediment transport model

The pick-up and deposition model of Nakagawa & Tsujimoto (1980) uses the following formulae to determine bed load transport. Pick-up of sediment (probability of a particle being picked up in s^{-1}) is determined by:

$$p_s(x) = F_0\sqrt{\frac{\Delta g}{D_{50}}}\,\theta(x)\left[1 - \frac{\theta_c}{\theta(x)}\right]^3 \qquad (28)$$

where F_0=0.03, θ is the Shields parameter, θ_c is the critical Shields parameter.

The local, critical volumetric bed shear stress $\tau_c(x)$, corrected for bed slope effects, is given by the following equation.

$$\tau_c(x) = \tau_{c0}\frac{1+\eta\frac{\partial z_b}{\partial x}}{\sqrt{1+\left(\frac{\partial z_b}{\partial x}\right)^2}} \qquad (29)$$

with τ_{c0} the critical volumetric bed shear stress for flat bed, defined by equation (30). In this equation θ_{c0} is the critical Shields parameter for flat bed and D_{50} is the median grain size.

$$\tau_{c0} = \theta_{c0} g \Delta D_{50} \qquad (30)$$

Deposition at a location is determined by adding all the sediment that arrives at that specific location. So, in order to determine the deposition at a certain location x the distribution of picked up sediment from all upstream locations is needed. The determination of deposition is done by applying the following formula:

$$p_d(x) = \int_0^\infty p_x(x-s) f(s) ds \qquad (31)$$

where the distribution f(s) determines the fraction of sediment that is deposited a distance s away from the pick-up point (x-s). The distribution function is defined as follows:

$$f(s) = \frac{1}{\Lambda}\exp\left(\frac{-s}{\Lambda}\right) \tag{32}$$

By using this function, 99.3% of the sediment that has been picked up at certain location is deposited between that location and 5 times the step length in downstream direction. The remaining 0.7% is deposited at $x=5\Lambda$. Finally the transport gradient is determined as follows:

$$\frac{\partial q_b}{\partial x} = D_{50}[p_s(x) - p_d(x)] \tag{33}$$

To summarize, the entire sediment transport calculation process is as follows. First the dimensionless bed shear stress is determined from flow characteristics. Then the pick-up of sediment along the dunes follows from bed shear stress. With an exponential decay function the deposition of sediment away from each pick-up point is determined. The difference between sediment deposition and pick-up determines the net transport gradient along the dune.

4.2.5 Step length

To calculate how the sediment is distributed moving away from each pick-up point, the mean step length of the sediment particles has to be calculated. Step length is defined by Einstein (1950) as

$$\Lambda = \alpha D_{50} \tag{34}$$

where α is a non-dimensional step length parameter. Francis (1973), Fernandez Luque & Van Beek (1976) and Sekine & Kikkawa (1984) have done experiments to determine the dependency of among others bed load transport, particle velocity and step length on various parameters with moving sand along a plane bed. This data shows a range of approximately 40 to 240 times the particle diameter, for values of u^*/w_s from about 0.18 to 0.35. From this data different step length models are derived by various authors. In paragraph 4.3 and paragraph 4.4 two methods are discussed, and a third method (based on the results with the first two and other considerations) is presented. Step length is assumed constant along the dune, so it can vary only over time depending on dune-averaged flow parameters.

4.2.6 Bed evolution

The bed evolution is modelled using the Exner equation (38), where the sediment transport gradient is calculated with equation (33) and ε_p=0.4 is the bed porosity.

$$\left(1-\varepsilon_p\right)\frac{\partial z_b}{\partial t}=-\frac{\partial q_b}{\partial x} \qquad (35)$$

After each time step for the bed evolution the model checks the angle of the bed between every pair of neighbouring calculation points. If necessary, the model avalanches the 'excess' sand so that the angle of the bed does not exceed the angle of repose (30°) anywhere.

4.3 STEP LENGTH MODELS FROM LITERATURE

4.3.1 Sekine & Kikkawa (1992) step length model

Sekine & Kikkawa (1992) have used the data sets mentioned in paragraph 4.2.5 to verify a numerical model of saltation of particles. They have found that all computed step length values are no more than two times larger or smaller than the observed values. Their predictions for the thickness of the saltating bed load layer closely match the data of Sekine & Kikkawa (1984); the particles remain within a few grain diameters from the bed. They further show that in their calculations the mean step length varies between about 10 and about 250 times the particle diameter. It is directly proportional to friction velocity u_* ($u_* = (\tau/\rho)^{1/2}$) and inversely proportional with settling velocity w_s. The suspension parameter u_*/w_s ranges from about 0.15 to 0.28 in this set of calculations, so bed-load conditions were present ($u_*/w_s<1$). The relation between these parameters and the non-dimensional step length α is

$$\alpha=\frac{\Lambda}{D_{50}}=\alpha_2\left(\frac{u_*}{w_s}\right)^{3/2}\left(1-\frac{u_{*c}/w_s}{u_c/w_s}\right)^{3/2} \qquad (36)$$

where α_2=3.0*10^3 and u_{*c} is the critical friction velocity ($u_{*c}=\tau_c^{1/2}$; note that this is *volumetric* bed shear stress, which has a unit of m^2/s^2).

4.3.2 Shimizu et al. (2009) step length model

Shimizu et al. (2009) have used a minimum (α_{min}=50) and maximum (α_{max}=250) value of non-dimensional step length α in a conceptually derived relation between α and dimensionless grain shear stress θ'. For values of θ' between zero and 0.5 (the dune regime), α was assumed to be constant at the minimum value (α_{min}). For values of θ' above 0.8 (the upper stage plane bed regime), α was assumed to be at the maximum value (α_{max}). In the transitional regime (θ' from 0.5 to 0.8), α was linearly interpolated.

Besides the Shields parameter, there is no further dependency on sediment parameters.

4.3.3 Comparison of step length models

Both the conceptual model of Shimizu et al. (2009) and the more physics-based model of Sekine & Kikkawa (1992) are tested in the dune model described in 4.2. For this test calculation scenario A4 of Shimizu et al. (2009) was used, which corresponds to a flood wave in a flume setting. For the model runs sediment with a D_{50} of 0.28 mm, a slope i of $2*10^{-3}$, and a hydrograph as presented below are used.

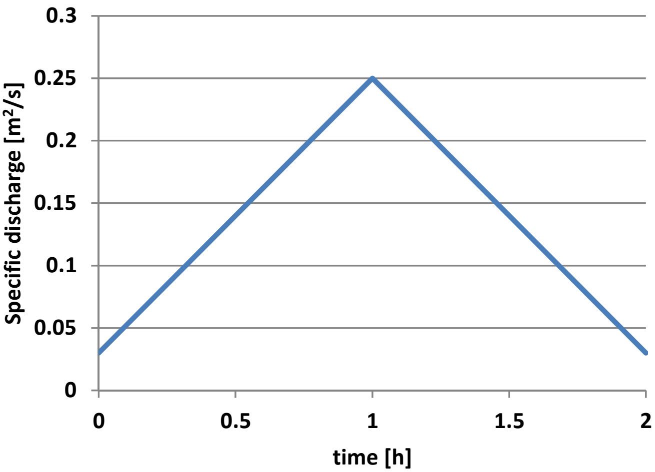

Figure 25: Hydrograph of scenario A4 from Shimizu et al. (2009).

This artificial scenario has not been measured, but corresponds to flume conditions with regard to water depth and dune height. The goal of the present calculations is to investigate if transition to the upper-stage plane bed occurs roughly in the same way as the dune evolution model of Shimizu et al. (2009) predicts, as well as the general qualitative behaviour of their model. This advanced dune evolution model is provided with a k-ε turbulence closure model and a separate advection-diffusion model for suspension. Scenario A4 of Shimizu et al. (2009) started from a flat bed, and showed dunes growing to about 4 cm. A transition to upper-stage plane bed occurred at about 0.6 hours, and a re-emergence of dunes occurred at about 1.7 hours. Both step length models in the current model are tested with this scenario. The resulting development of the dune trough and crest positions (in the vertical) and water depth over time are shown in Figure 26.

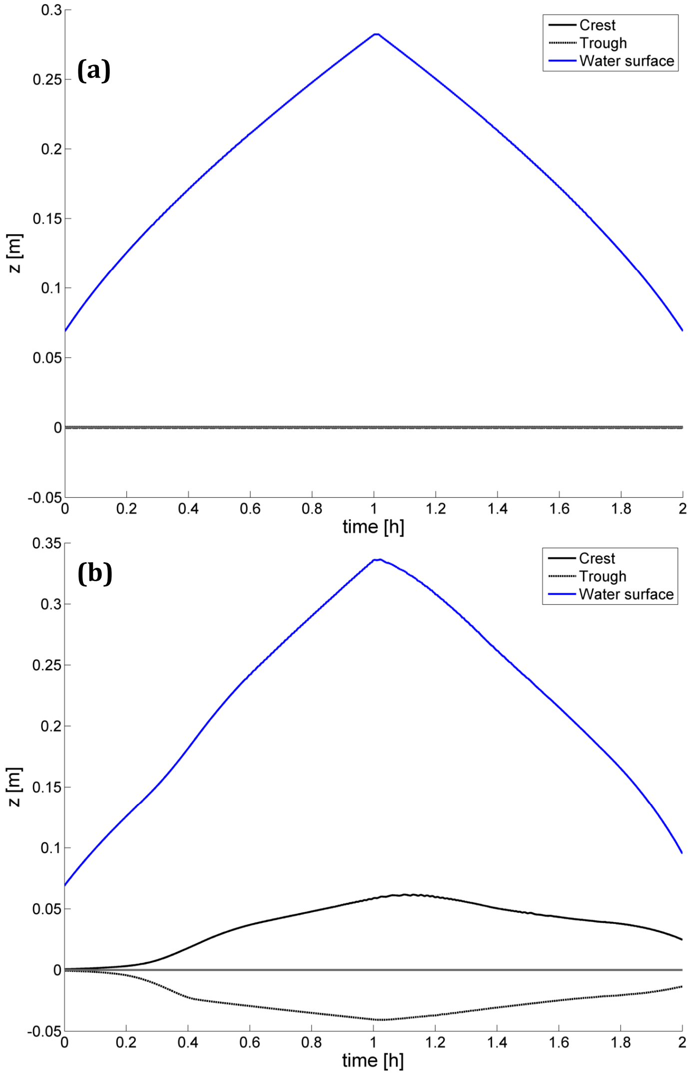

Figure 26: Dune crest and trough position (black lines) and water depth (blue line) over time with the step length model of a) Sekine & Kikkawa (1992) and b) Shimizu et al. (2009).

Using the Shimizu et al. (2009) step length model leads to bedform growth, though no upper stage plane bed occurs. Apparently, this step length model does not lead to strong enough lag in the present study; the dunes do not wash out at all but keep growing at the moment in time where the k-ε dune evolution model of Shimizu et al. (2009) predicted a transition to upper-stage plane bed (0.6 hours). Besides growing for too long, the dunes also become too high (10 cm). With the Sekine & Kikkawa (1992) step length model, no dunes are able to grow at all, which is completely different from the results of the k-ε dune evolution model of Shimizu et al. (2009).

4.4 NEW STEP LENGTH MODEL

Because using the Shimizu et al. (2009) step length model leads to results closest to the results of the Shimizu et al. (2009) dune evolution model, it has been tuned further. To compensate for not modelling suspended transport explicitly and since $u^*/w_s>1$ for most of the scenario (it varied between 0.9 and 1.8), the parameter α needs to become much higher with the new step length model to implicitly take into account the effects of suspended transport. Suspended sediment load differs from bed load in the sense that it is mixed over the water depth by the turbulent vortices. Due to the vertical mixing and settling process of suspended sediment, the suspended sediment load does not respond to variations in bed-shear stress (and thereby sediment pick-up) immediately, but with a spatial (and/or time) lag. The turbulent mixing capacity ε_s is related to turbulent eddy viscosity ν_t, which for wall boundary layer flows is related to the friction velocity u_* and the water depth h as follows (see e.g. Van Rijn, 1993).

$$\varepsilon_s \sim \nu_t \sim u_* h \qquad (37)$$

The suspension mixing height above the bed is controlled by the turbulent mixing capacity ε_s and the settling by gravity (settling velocity w_s) and scales with $\varepsilon_s/w_s= u_*h/w_s$ (Rouse, 1937). This vertical suspension mixing height directly relates to the spatial or time lag suspended sediment experiences. Galappatti & Vreugdenhil (1985) show that the spatial lag of suspended sediment transport load can be approximated as a relaxation length:

$$\Lambda_{s;l} = \frac{u_*}{w_s} exp\left(-a\frac{w_s}{u_*}\right)\frac{C}{\sqrt{g}}h \qquad (38)$$

In this formula C is the Chézy coefficient and a represents the influence of sediment diffusion. Also, Claudin et al. (2011) derived a similar relation for relaxation length of suspended sediment.

So, where the step length of bed load mostly depends on friction velocity, these formulae show that the step length of suspended sediment scales with friction velocity and the water depth. As a first step it is therefore assumed in the present study that the step length of particles α should scale with the water depth h in order to simulate the influence of suspended sediment. The new model for non-dimensional step length α is defined by the following equation, which depends on both non-dimensional grain shear stress and water depth.

$$\alpha(\theta', h) = \alpha_g(\theta')\frac{h}{h_{ref}} \tag{39}$$

Here h_{ref} is a reference water depth equal to the water depth at the start of the transitional regime of the case used to tune the step length model, scenario A4 of Shimizu et al. (2009), of which the results can been seen in 4.5. The value of the non-dimensional grain shear stress-dependent step length α_g follows from a modified version of the Shimizu et al. (2009) step length model, as can be seen in Figure 27. To reiterate, with this modification the step length no longer depends on only bed shear stress or friction velocity as with bed load, but also on the water depth as with suspended transport. It represents processes inherent in the turbulent mixing of suspended material. Namely that larger water depth leads to larger turbulent vortices, which in turn leads to sediment higher in the water column and a larger settling distance.

Furthermore, in the new step length model the dimensionless step length keeps increasing for θ' values above 0.8 (with the same slope as between θ'=0.5 and θ'=0.8) because formulae for the step length or relaxation length of suspended sediment are generally not capped at a certain value (see e.g. Galappatti & Vreugdenhil, 1985; Claudin et al., 2011). Different values of α_{min} at θ'=0.5 and α_{max} at θ'=0.8 have been tested, and using α_{min}=50 and α_{max}=350 works best within the new dune evolution model compared to the dune evolution results of Shimizu et al. (2009). The water depth at the start of the transitional regime was 0.1166 m which will be used as the reference water depth h_{ref}. In Figure 27 the currently used model for α_g is compared with the Shimizu et al. (2009) step length model for α_S. It should be noted that this figure is without the additional influence of the water depth as defined in equation (39). Combining that equation with the figure above and all other previous considerations leads to the following new equation for α:

$$\alpha(\theta', h) = \begin{cases} \alpha_{min}\frac{h}{h_{ref}}, \ \theta' \leq 0.5 \\ \left[\alpha_{min} + (\theta' - 0.5)\frac{\alpha_{max}-\alpha_{min}}{0.8-0.5}\right]\frac{h}{h_{ref}}, \ \theta' > 0.5 \end{cases} \tag{40}$$

where α_{min}=50, α_{max}=350 and h_{ref}=0.1166 m.

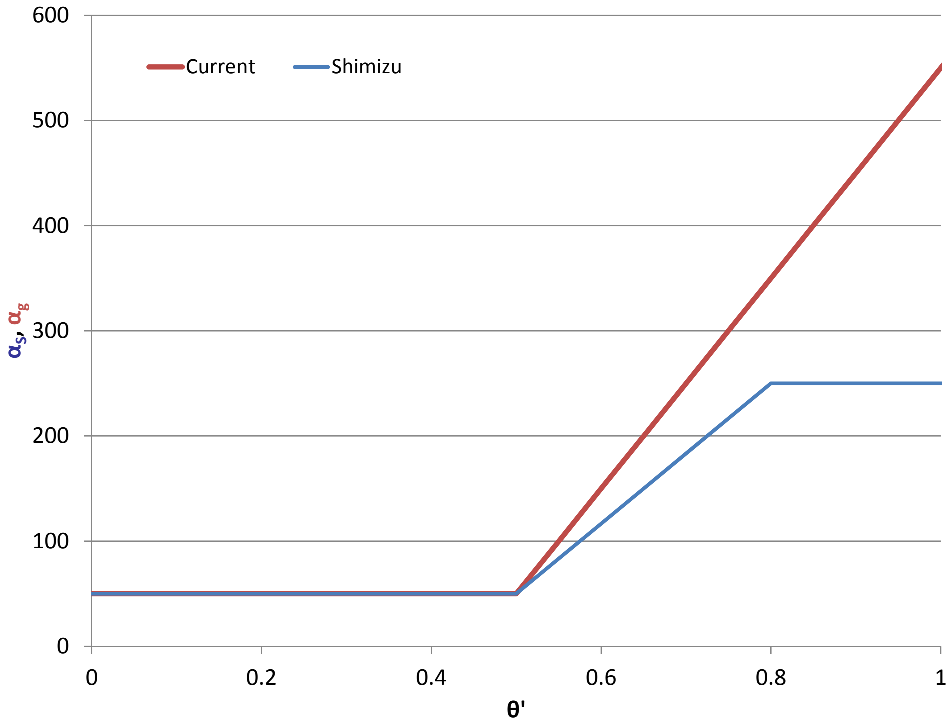

Figure 27: The non-dimensional step length of the non-dimensional step length model of Shimizu et al. (2009) using α_S for bed load, and the currently used step length model using α_g which represents the grain shear stress-dependent part of non-dimensional step length in the new model.

By multiplying the result with the median grain diameter the dimensional step length is found (as defined by equation (34)). By using this method the value of α can become higher than the maximum observed value of α (250) found in the bed load experiments of Nakagawa & Tsujimoto (1980). This makes it plausible that suspended load is modelled implicitly by the new step length model, as intended.

4.5 RESULTS WITH FLUME CONDITIONS

To show that the model is able to model a transition to upper-stage plane bed for flume conditions, computational scenario A4 as presented by Shimizu et al. (2009) is used (see section 4.3.3). With this scenario Shimizu et al. (2009) show that their model is able to predict transitions to the upper-stage plane bed. Also the model clearly shows hysteresis effects; the relation between discharge and water depths is significantly different for the rising limb of the hydrograph as it is for the falling limb. The parameters of the scenario are equivalent to a flume scenario. With the model runs presented here the suspension parameter u^*/w_s varied between 0.9 and 1.8

during the scenario, so with this sediment and this flow regime the suspension regime is present for most of the time. Using scenario A4 from Shimizu et al. (2009) the following development of the dune field over time is found.

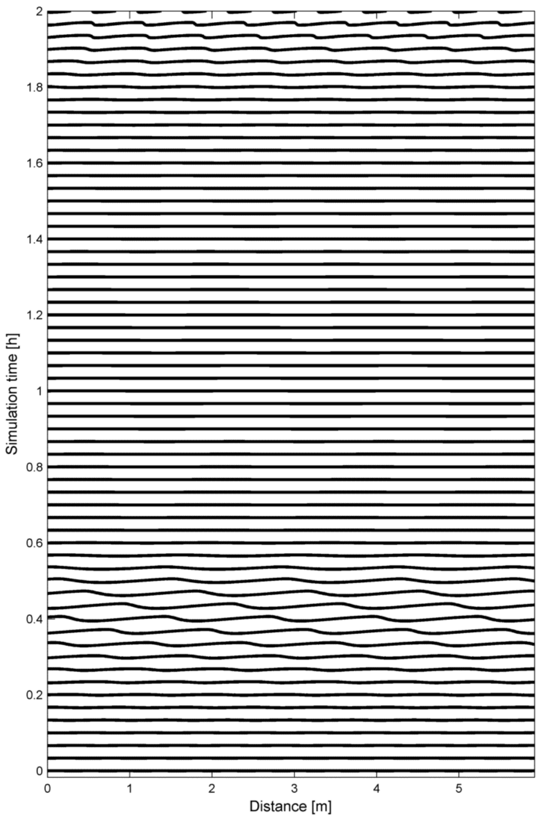

Figure 28: Dune field over time.

Here the washing out and regrowth of the dunes can be clearly observed. From the same results the development of the dune trough and crest positions (in the vertical) and water depth over time are shown in Figure 29. As can be seen in the beginning of the run dunes start developing along with increasing discharge. At a certain high discharge the shear stress and the step length become so high that the dunes are washed out. Due to the decrease in form drag and thereby *total shear stress* the water level stabilizes temporarily, despite still rising discharge. The bed remains washed out until the discharge and step length become so low that dunes start developing again.

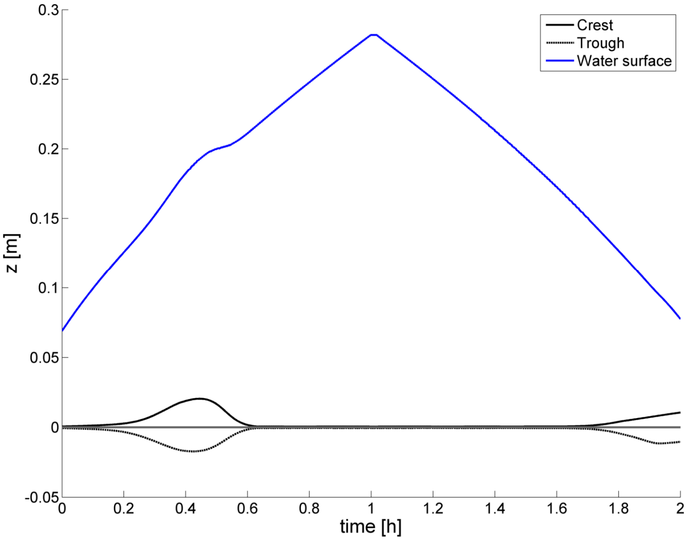

Figure 29: Dune crest and trough position (black lines) and water depth (blue line) over time.

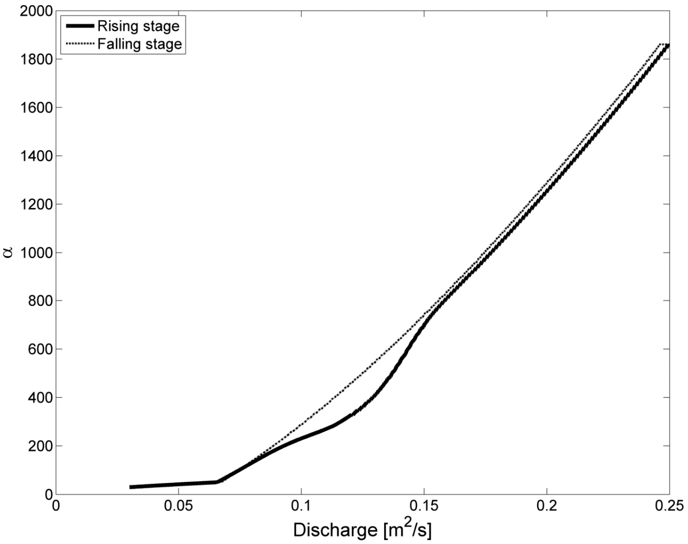

Figure 30: Specific discharge versus non-dimensional step length α separated for the rising and falling stages of the hydrograph.

Shimizu et al. (2009) found roughly the same moments of washing out (0.6 h) and re-emergence of dunes (1.7 h). Furthermore, the dune evolution model of Shimizu et al. (2009) predicted a dune with a maximum height of about 4 cm, which corresponds rather well with the present model result (3.75 cm). The relation between the step length parameter α and the specific discharge for the rising and falling stages of the hydrograph can be seen in Figure 30.

Here already a hysteresis effect is observed, caused by the transition to upper stage plane bed and then later returning to the dune regime. With the same discharge dunes can be present in the rising stage and not in the falling stage. Because of the presence of dunes, a part of the flow power is lost due to form drag. This means the shear stress acting on the sand grains (effective bed shear stress) is relatively lower, and a lower step length is selected then when there are no dunes present. The effect of hysteresis on water depth can be seen in Figure 17.

In the rising part of the hydrograph dunes are able to develop firstly at medium discharges, while in the falling part the dunes start developing at the end of the flood wave at lower discharges. This has a clear effect on the resulting water depths at the same discharge. For example, at a specific discharge of 0.12 m^2/s the water depth in the rising part is clearly higher than in the falling part. In the rising limb the dunes have had a longer time to grow than in the falling limb, and are therefore higher. Because the dunes are higher, the water depth is higher despite the discharge being the same. Shimizu et al. (2009) have clearly shown this hysteresis effect as well, though for their model it's more pronounced. They have also reported in the order of 25% lower water depths than reported here.

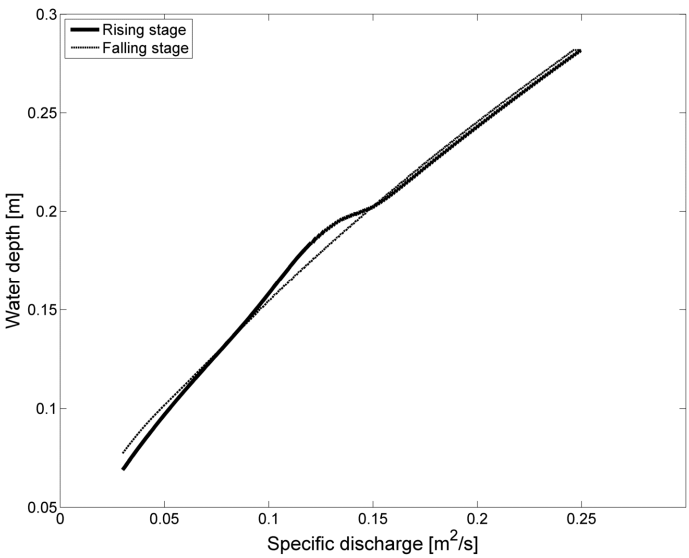

Figure 31: Specific discharge versus water depth separated for the rising and falling stages of the hydrograph.

4.6 RESULTS WITH RIVER CONDITIONS

In order to test how the model behaves under river conditions, the model is run with similar conditions to the Dutch river Waal during the flood of 1998. At the peak of this flood wave the total discharge was 6250 m^3/s in the river Waal, and just under 9500 m^3/s at Lobith (Julien et al., 2002). The dune evolution model is applied to only the main channel; floodplains are not taken into account. It is assumed that 60% of the peak discharge went through the main channel. The main channel is assumed to be 300 m wide, which corresponds well to the width of the main channel along the river Waal in the SOBEK model made by Deltares and used by Paarlberg (2012) and Paarlberg & Schielen (2012). This would make the specific discharge 12.5 m^2/s, which is rounded to 13 m^2/s for the current study. To simulate these conditions a D_{50} of 1.2 mm (in the range presented by Giri et al., 2008), a slope i of $1*10^{-4}$ (Sieben, 2004), and a hydrograph as presented in Figure 32 are used as input for the model. This hydrograph leads to water depths between 8.5 and 11.1 m, which correspond well to the water depths in the Waal for the flood of 1998 as reported by Julien et al. (2002).

Compared to the flood wave of 1998, as shown by Julien et al. (2002), the duration of the rising limb is the same, while the duration of the falling limb is shortened somewhat. The entire duration of the flood wave presented here is exactly 12 days. The calculation time is very reasonable, with a time step of 2 minutes the model goes through 12 days modelled time in under 55 minutes real time. To let the model adjust to the hydrodynamic conditions, the flood wave is modelled twice. The bed configuration of the first flood wave is used as input for the second flood wave. The results of the second run are reported in section 4.6.1.

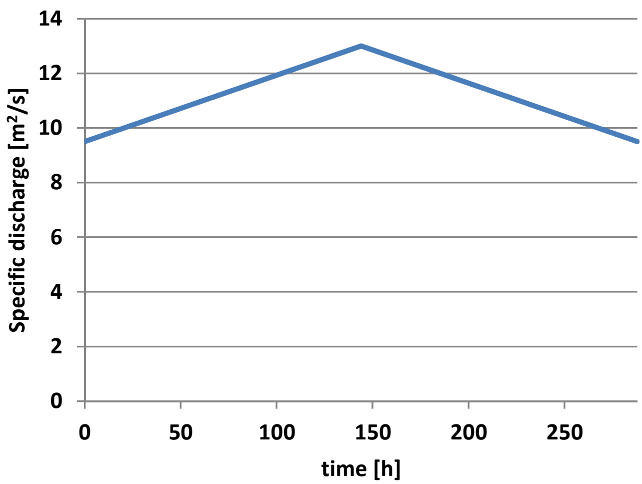

Figure 32: Hydrograph of the river scenario

To test if a transition to the upper-stage plane bed can be modelled for river conditions, the model is run also with a 5% higher discharge than for the scenario above. This leads to water depths between 9 and 11.4 m which is about 5% higher than the water depths in Waal for the flood of 1998 as reported by Julien et al. (2002). The duration of the flood wave is the same as in the other scenario, and the calculation time is just under 35 minutes. This is less than before, because in this scenario dunes are washed out during a part of the run which lets the model solve the flow equations more efficiently. Again, to let the model adjust to the hydrodynamic conditions, the flood wave is modelled twice. The results of the second run are reported in section 4.6.2.

4.6.1 Results for the river scenario

The development of the dune field, starting from an already developed dune field, can be observed in Figure 33.

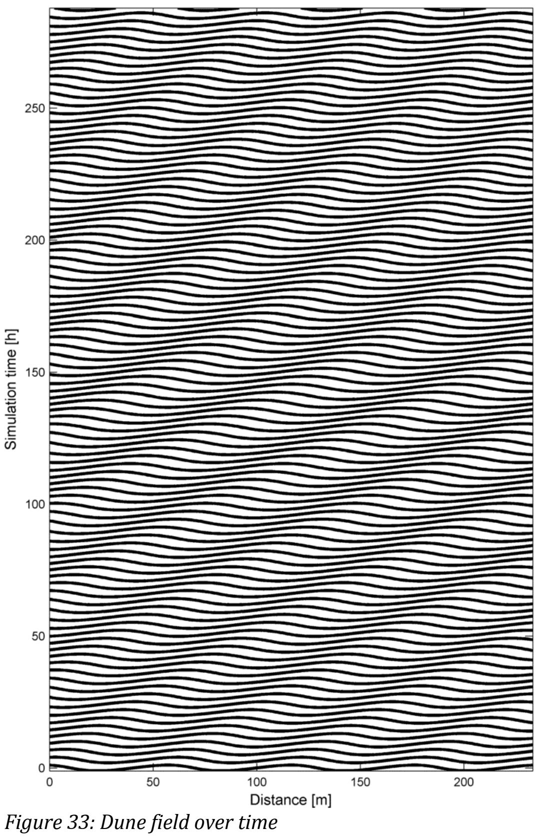

Figure 33: Dune field over time

The dunes grow and shrink during the flood wave, though in general the dune height variation is low. From the same results the development of the dune trough and crest positions (in the vertical) and water depth over time are shown in Figure 34. As can be seen in the beginning of the run dunes start developing slowly along with increasing discharge. This continues past the moment of peak discharge until about 155 hours, after which the dune height decreases. Due to the increase in discharge the water level still increases and decreases, with seemingly little influence of the dune height.

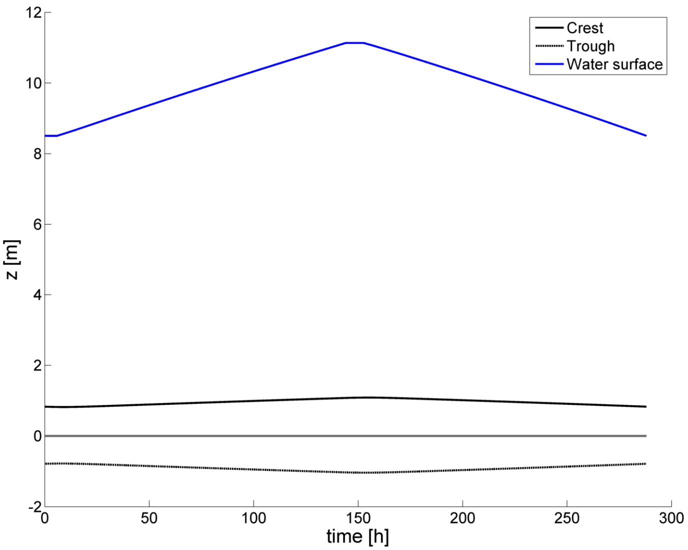

Figure 34: Dune crest and trough position (black lines) and water depth (blue line) over time.

During the flood wave of 1998 dune heights in the Waal varied between 0.2 and 0.6 m on the centreline (Julien et al., 2002), while the model predicts values between 1.6 and 2.1 m. This shows that further calibration needs to be done, as dunes grow too large in the model. Increasing the step length likely has a dampening effect on the dune height, but it also causes the dunes to wash out sooner. Therefore, care should be taken in adjusting the model settings. In Figure 35 the response of dune height to changing discharge can be seen.

The hysteresis loop observed here is in the same direction as for the flood wave of 1998 as reported by Julien et al. (2002), with dune heights in the falling limb being higher than in the rising limb. And also here the dune height keeps growing for a period of time after the discharge is already decreasing. The relation between the non-dimensional shear stress and the dune height can be seen in the following figure. The dunes do not wash out though they do decrease in height about 5 hours after the maximum discharge has been reached.

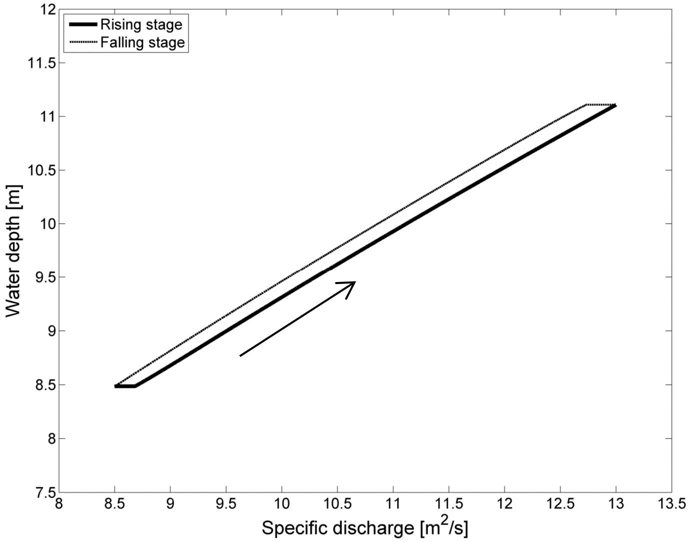

Figure 35: Discharge versus dune height for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

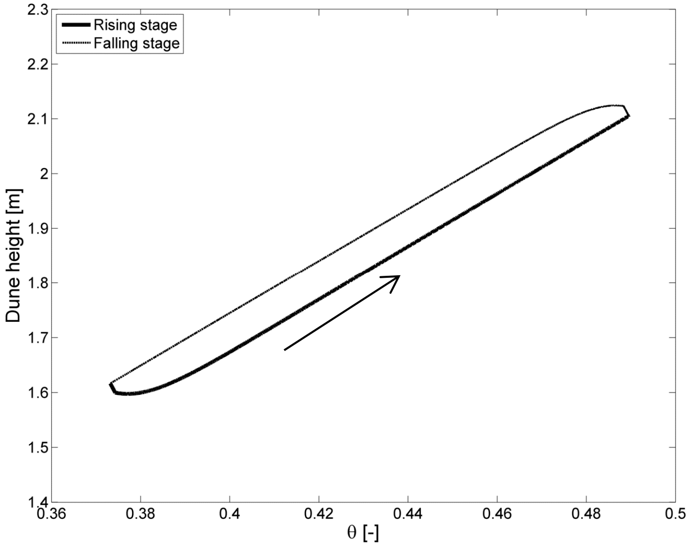

Figure 36: Non-dimensional shear stress θ versus dune height for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

The relation between α and the specific discharge for the rising and falling stages of the hydrograph can be seen in Figure 37. Here again a hysteresis effect is observed, caused by the lag between dune development and discharge. It should be noted that now much higher step lengths are reached than for the flume scenario, up until α=4750 which is a dimensional step length of about 6 m. This is about 2.6 times higher than that of the flume scenario.

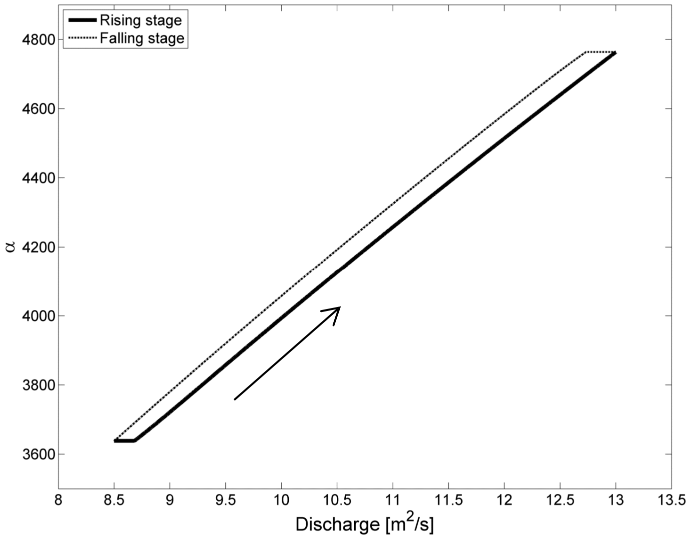

Figure 37: Specific discharge versus non-dimensional step length α separated for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

The effect of hysteresis on water depth can be seen in Figure 38.

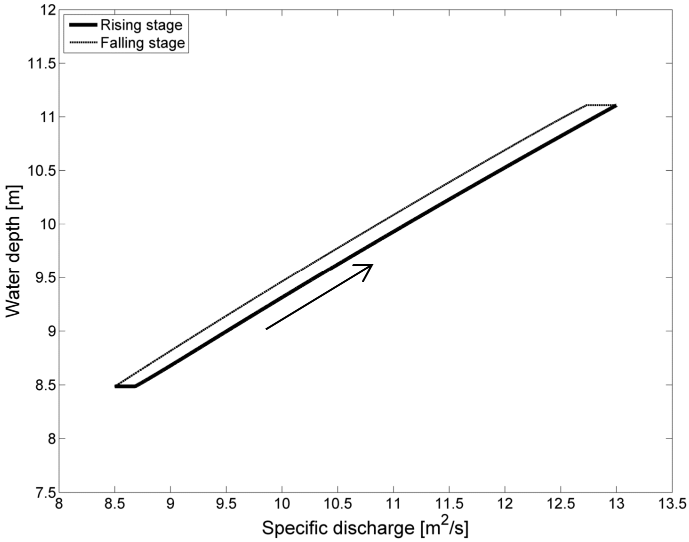

Figure 38: Specific discharge versus water depth separated for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

In the rising part of the hydrograph dunes increase in height, while in the falling part the dune height first remains constant before decreasing later on. Because of the delay in dune height development compared to discharge, the water depth in the falling limb of the hydrograph is larger than in the rising limb, which agrees again in a qualitative sense with what is reported by Julien et al. (2002) for the flood wave of 1998.

4.6.2 Results for the more extreme river scenario

With the artificial more extreme scenario, which includes an increase of the discharge of 5%, a transition to upper-stage plane bed is predicted. It should be realized that this transition was not observed in the river Waal in 1998 (Julien et al., 2002), nor in the Dutch Rhine Branches in 1995 when the discharge at Lobith was 25% higher than it was in 1998 (e.g. Wilbers & Ten Brinke, 2003). The computed development of the dune field, starting from an already developed dune field, can be observed in Figure 39.

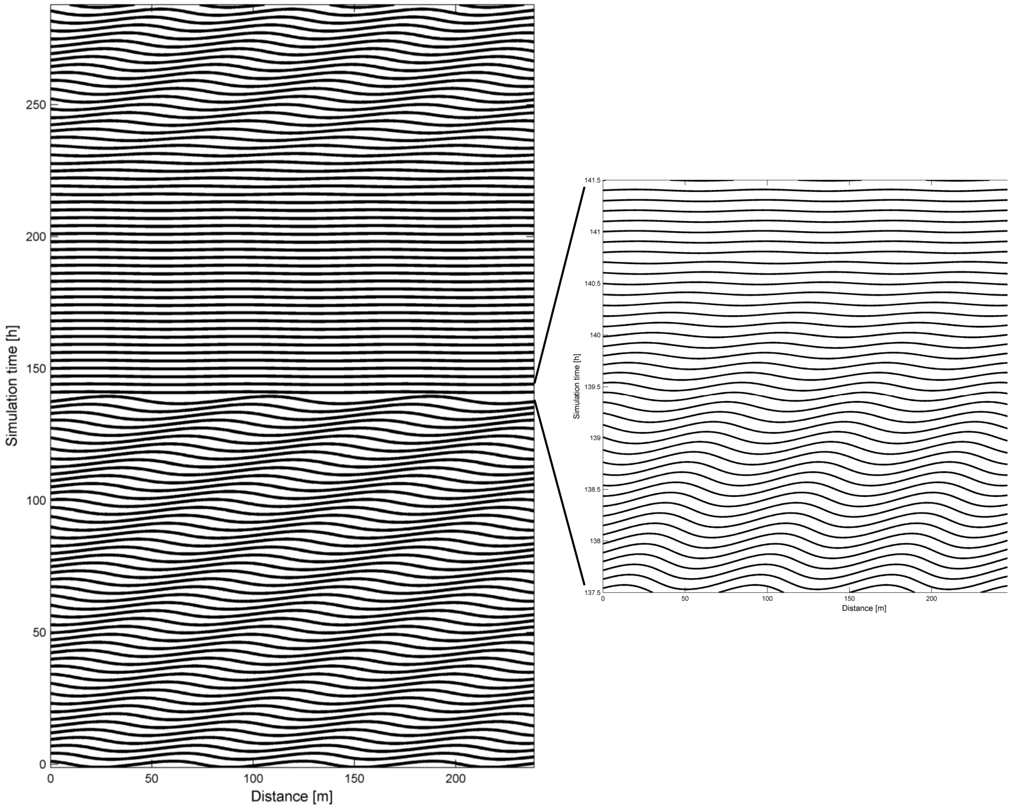

Figure 39: Dune field over time. The right part zooms in on the dune field in the period where the transition occurs.

Here the growth and washing out of the dunes can be observed on the left, and the washing out itself can be observed more clearly on the right. From the same results the development of the dune trough and crest positions (in the vertical) and water depth over time are shown below (Figure 40). As can be seen in the beginning of the run dunes start developing along with increasing discharge. At around 137 hours from the start of the model run the dunes start washing out, and they're completely gone at about 141 hours, 5 hours before the maximum discharge occurs. Due to the decrease in form drag and thereby *total shear stress* the water level goes down, despite still rising discharge. The bed remains washed out until the discharge is low enough for dunes to start developing again.

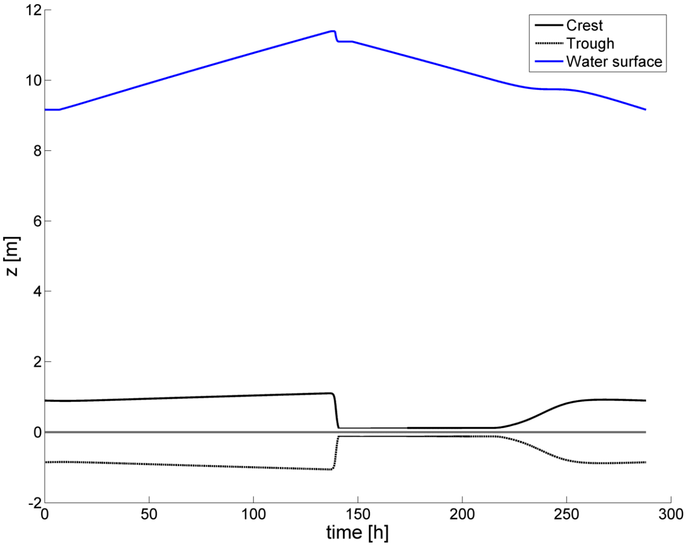

Figure 40: Dune crest and trough position (black lines) and water depth (blue line) over time.

For the flood of 1998 dune heights in the Waal varied between 0.2 and 0.6 m on the centreline, while the model results indicate values between 0.2 and 2.2 m. In Figure 41 the response of dune height to changing discharge can be seen.

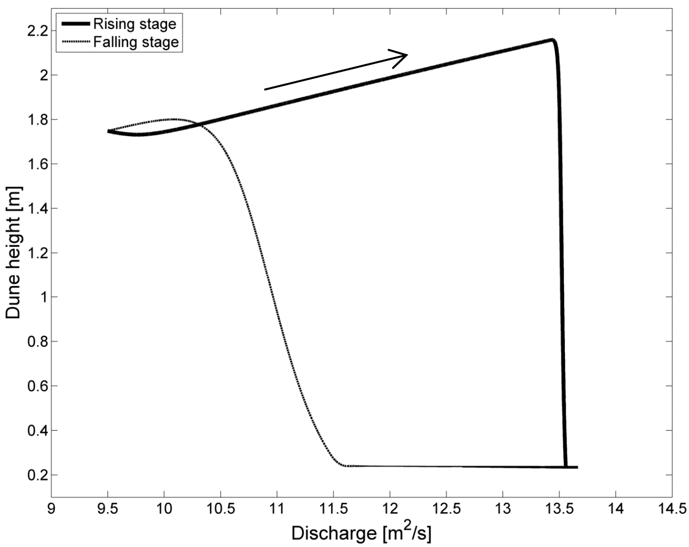

Figure 41: Discharge versus dune height for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

The hysteresis loop observed here is in the opposite direction of the measured flood wave of 1998 as reported by Julien et al. (2002). Due to the washing out of dunes during the flood wave, dunes are generally lower in the falling limb than in the rising limb.

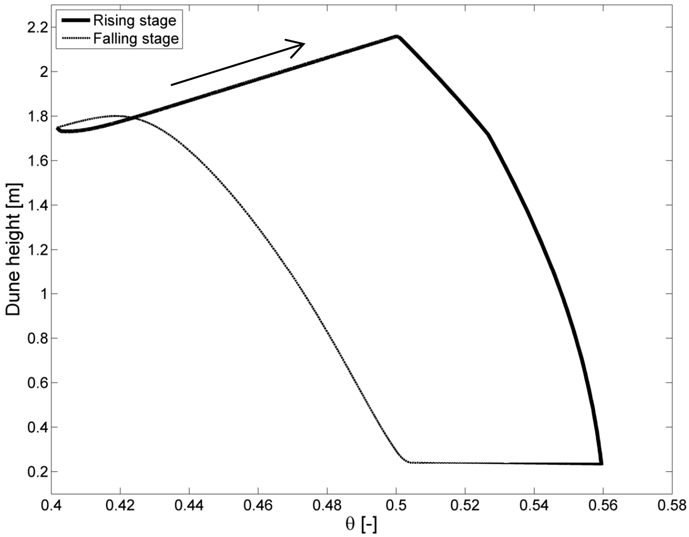

Figure 42: Non-dimensional shear stress θ versus dune height for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

The relation between dune height and non-dimensional shear stress can be seen in Figure 42. The dunes start really washing at around θ=0.5, and are completely gone at around θ=0.56. The relation between α and the specific discharge for the rising and falling stages of the hydrograph can be seen in Figure 43.

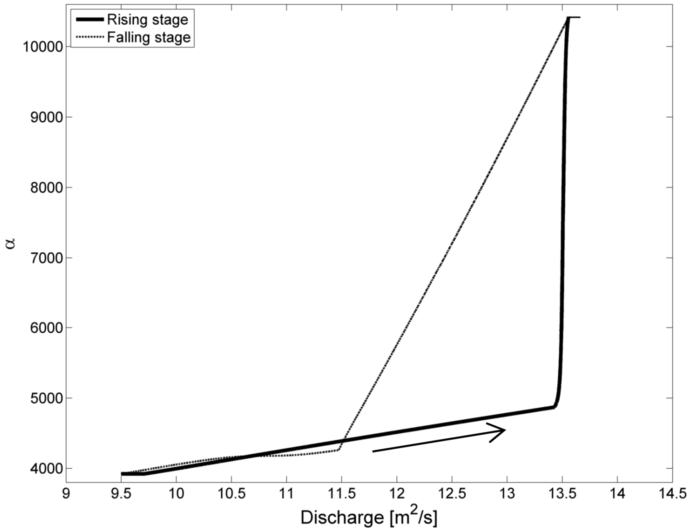

Figure 43: Specific discharge versus non-dimensional step length α separated for the rising and falling stages of the hydrograph. The arrow signifies the direction of development over time.

Here again a hysteresis effect is observed, caused by the transition to upper stage plane bed and back to the dune regime. It should also be noted that now much higher step lengths are reached, up until α=10800 which is a dimensional step length of about 13 m. This is about 10 times the value of the flume scenario. For the river scenario of section 4.6.1 the maximum step length was only 2.6 times higher than the flume scenario. This difference between the river scenarios mostly relates to the washing out of dunes which only occurs for the more extreme river scenario. When the dune is washed out water depth drops somewhat, but due to the lack of bedforms the flow can exert more force on the particles which increases step length because that is partly based on grain shear stress. The effect of hysteresis on water depth can be seen in Figure 44.

In the rising part of the hydrograph dunes are able to develop firstly at lower discharges, while in the falling part the dunes start developing at higher discharges. This has a clear effect on the resulting water depths at the same discharge. The hysteresis loop is reversed compared to the results in section 4.6.1. Of great importance for the river situation is the significant drop in water levels when dunes are washed out. Within 4 hours the water levels become about 0.25 m lower, while the discharge is still growing; if it assumed dunes keep growing instead, and extrapolate from the point where the water depth is still rising the difference in water levels is approximately 0.5 m. Though this effect will be mitigated in real life by the presence of floodplains, it is still a significant effect. This example shows that knowing when the transition to upper-stage plane bed occurs is very important, because it may have a large impact on the water levels and thereby on the dike heights needed to prevent flooding.

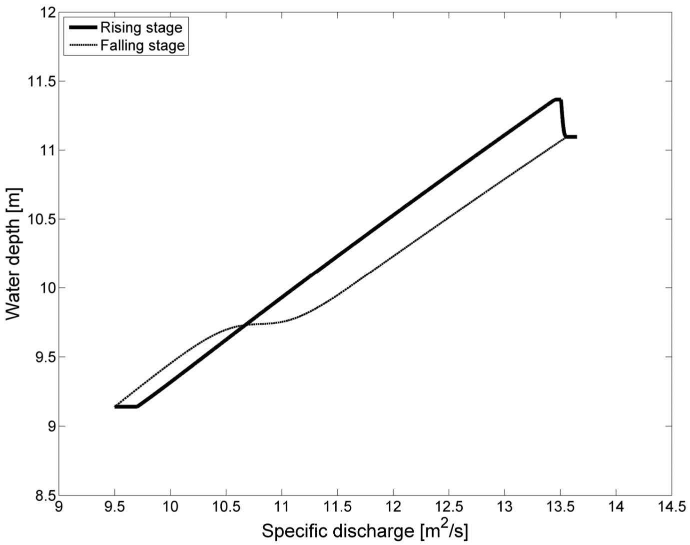

Figure 44: Specific discharge versus water depth separated for the rising and falling stages of the hydrograph.

4.7 DISCUSSION

In the present study, under flume conditions, differences have been observed in outcome between the new model and the k-ε model of Shimizu et al. (2009), i.e. step lengths have to become significantly larger to reach the transition to an upper-stage plane bed and there are differences of 25% in water depths. Of course, the models differ in significant ways. Firstly Shimizu et al. (2009) have used a non-hydrostatic flow model with a non-linear k-ε model for turbulence closure whereas in the idealized dune evolution model a hydrostatic flow model with a constant eddy viscosity has been used. Secondly, their transport module also used a separate suspended sediment model while in this research suspended sediment has been only modelled implicitly. Pinpointing the exact reason of the differences is hard because the A4 flume case under review is a 'synthetic' case; there are no actually measured values as a reference to determine which model is closer to the truth. The Shimizu et al. (2009) dune model is more physically complex, which suggest that its results should be better. However, it's still promising that the new relatively simple model presented in this research is able to represent similar bedform behaviour during a flood wave as the more complex model in a qualitative sense.

During the research for this chapter it was found that the timing of a transition to upper-stage plane bed is sensitive to the value of α. As an example the results of the first 45 minutes for scenario A4 of Shimizu et al. (2006) with α_{max}=300 as well as α_{max} =350 are shown in Figure 45. Here it can be seen that the bed is washed out at about 37 minutes with α_{max}=300 instead of 35 minutes as with α_{max}=350, and that the maximum dune height is 3.75 cm and 2.8 cm respectively. This shows that the results are sensitive to the settings of the step length model, though there is no extreme effect on general model behaviour.

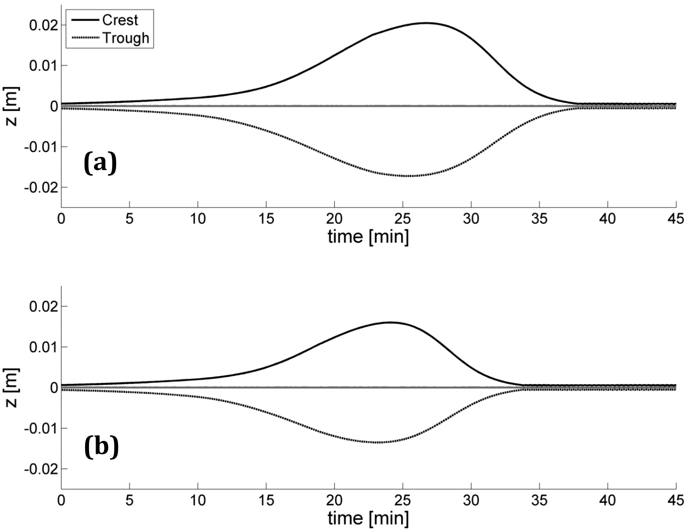

Figure 45: Dune crest and trough position for the first 45 minutes of scenario A4 of Shimizu et al. (2009) with a) α_{max}=300 and b) α_{max}=350.

To ensure that the model still represents the dune regime well, the model was run again for the experimental conditions of Venditti et al. (2005a, 2005b) tested in section 3.3.5. Compared to the previous results the dune height is now generally slightly lower, though still represented well. Dune length is very similar to before, represented well except for the artificial defects of bedforms D and E. Migration rate and thereby transport rate are much higher than before, and are now generally overestimated instead of underestimated. This is in line with the results presented in 3.3.3, where the migration rate and thereby transport rate increased strongly with step length. Overall the results are slightly worse than with the model version optimized for the dune regime, though dune dimensions are still represented well by the new model.

The question arises whether the step length should be varied only due to the changing flow regime as is done now, or also along the dune as well (because of local variation in shear stress). Explorative experiments of Van Duin et al. (2012) suggest that the latter is not necessary, but this warrants further research.

Although the model results show hysteresis effects with regard to discharge and water depth caused by the development of dunes, it should be realized that the present model does not describe the hysteresis effects due to the phase lead of discharge with respect to water depth, which may be relevant for field situations. This phase lead arises from the phenomenon that the pressure gradient of the front of the flood wave is higher than in the tail of the flood wave as described by Jones (1915) and later studied by various authors (e.g. Henderson, 1966; Fread, 1982; Dottori et al., 2009).

It could be interesting to use a separate suspended transport model similar to the bed load models used in this study, with the lower step lengths used for bed load and the higher step lengths used for suspended load. With such a method, it is important to know what the appropriate step lengths are for each of the transport modes. This could be done by either implementing more physics based predictors of the step length for bed load and suspended load, or by calibrating the step length models using dune data sets from the field like that of Sieben (2004) as a benchmark.

In general, a well calibrated version of the dune evolution model could then be applied within a model of a river system (replacing a part of the hydraulic roughness model), to better determine if and under which conditions a transition to upper-stage plane bed may occur. For the Dutch rivers washing out of dunes with a high discharge has never occurred in the field, and it is unknown what will happen with the extreme (design) discharges that may occur in the future. In current practice roughness values are calibrated by matching observed and modelled water levels (Wasantha Lal, 1995; Van den Brink et al., 2006). This means that there is significant uncertainty in roughness for extreme discharges that have not been observed yet. Using a dynamic roughness model which includes the dune dynamics may lead to physically more correct results. The river Waal case in this study for the 1998 flood has shown that a relatively small increase in river discharge can lead to the occurrence of upper-stage plane beds together with a considerable drop in water depth in a relatively short time. This shows that the occurrence of upper-stage plane bed can be an unexpected and rapid occurrence.

4.8 CONCLUSION

In this study the dune evolution model of Paarlberg et al. (2009) was extended with an alternative sediment transport model using sediment pick-up, deposition and step length models instead of the usual equilibrium transport formula. The model was devised in such a way that similar dune behaviour is obtained as with the more complex k-ε model of Shimizu et al. (2009) for a flood wave corresponding to flume conditions.

Step lengths have been allowed to become larger than with the step length model of Shimizu et al. (2009). Also, higher step lengths than the maximum observed in the experiments of Nakagawa & Tsujimoto (1980) have been used such that effects of suspended load are implicitly taken into account. It was shown that in this way the model is able to predict a transition to upper-stage plane bed and clearly shows hysteresis effects due to the lag between bedform dimensions and discharge. While the simulated associated moments in time and the maximum dune height are close to the results of Shimizu et al. (2009), the exact results in terms of water depth still showed differences of about 25%.

A scenario corresponding to the 1998 flood in the river Waal was modelled as well. While the qualitative behaviour of the dunes was represented well, the dune height was overestimated. This signifies the need for further model improvement/calibration. For the river scenario the step length is significantly higher than the values used for the flume conditions. It was shown that the model is still very computationally efficient. By slightly increasing the discharge of the original river scenario, a transition to upper-stage plane bed was also modelled. Although in 1995 for much higher discharges no transition to upper-stage plane bed has occurred and dunes kept growing as seen in the measurements reported by Wilbers & Ten Brinke (2003), this does show the sensitivity of the dune dynamics in this transitional regime and also indicates the need for a well-validated dune evolution model for extreme discharges.

It should be noted that, when a transition to upper-stage plane bed indeed occurs during design conditions, this would greatly reduce the design water depth because the hydraulic roughness of the main channel would be significantly lower. For the model results presented here, the difference in water levels is approximately 0.5 m. Although in reality this effect would be dampened due to the presence of floodplains, this is still considered as a significant effect.

5 SYNTHESIS

This chapter is meant as a reflection on the broader context of the research in this thesis and the research itself. Therefore, in section 5.1 a number of topics will be addressed that are relevant to the research in this thesis but have not been discussed extensively. These topics give some insight into how the newly developed model can be improved, as well as how the model itself or concepts in it may be of use in other contexts. The research questions defined in the research methodology (section 1.4) are answered in the conclusions, section 5.2. The most immediate improvements that follow from this reflection are given as recommendations for further research in 5.3.

5.1 DISCUSSION

5.1.1 The role of suspended load combined with bed load

Within the research group associated with this thesis, also a version of the dune evolution model with separate suspended load and bed load models has been developed. This is an explicit way to represent the effects of suspension, as opposed to the implicit way used in this thesis. As shown in Nasqhband et al. (2015), this model can predict a transition to upper-stage plane bed by using a *non-equilibrium* suspended load model (a modified version of the pick-up and deposition model used in this thesis) along with an *equilibrium* bed-load model (of the type of Meyer-Peter & Müller, 1948). In other words, in this model the bed load model used is not able to represent the spatial lag processes. It was indeed shown by Nasqhband et al. (2015) that the model with just the equilibrium bed load model could not predict such a transition (see Figure 46).

Looking at just the results of Nasqhband et al. (2015) would suggest that only suspended load plays a role in the transition to plane bed, while the results presented in this thesis suggest that bed load can at least contribute to this transition in some cases (see section 3.3.6). This contradiction is solved by acknowledging the physical reality that both transport modes play a role in this process. The question then remains in which situation which process is dominant. It may be that in the flume a transition to upper-stage plane bed under certain conditions can occur mostly due to the phase lag in bed load processes because the step length in that case is relatively large compared to the dune length. In the river case dune length is clearly much larger than realistic step lengths of bed load. In that case it may well be that a transition to upper-stage plane bed is only possible when there is suspended load, because of the far larger distances it typically travels.

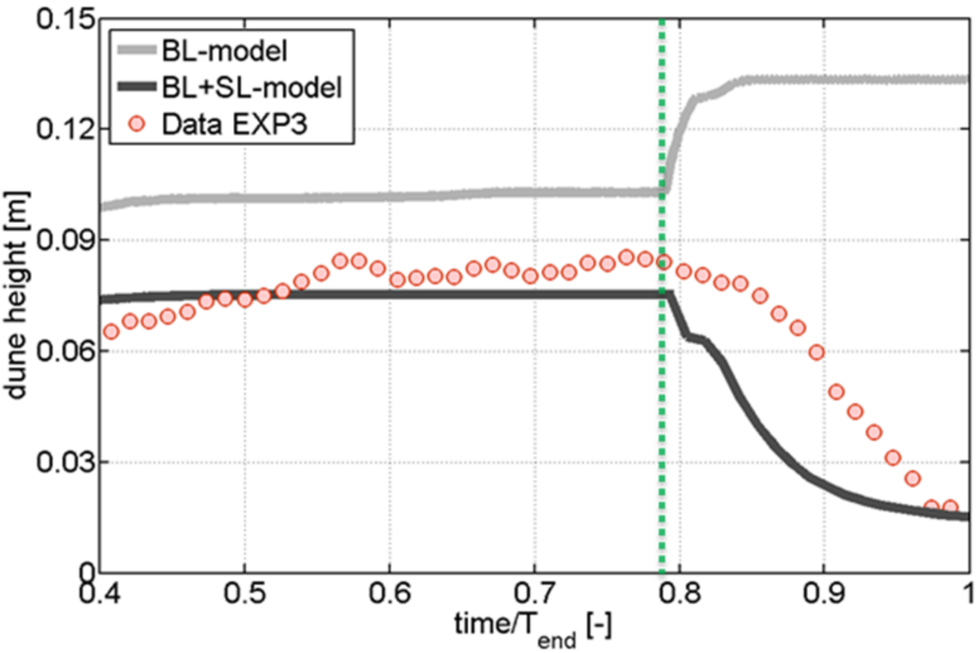

Figure 46: resulting dune height from a model with just bed load (grey line) and with bed load and suspended load (black line) compared to experimental results (red dots). The green vertical line signifies a sudden strong increase of discharge. From Naqshband et al. (2015).

5.1.2 Hydraulic roughness in flood modelling

In the context of flood modelling the hydraulic roughness of the main channel is often used as a calibration parameter, with either a single value or a discharge-dependent value. Because of the development of bedforms which lag behind the discharge, this approach does not allow to properly model hysteresis effects.

As an alternative way to incorporate this phenomenon, Warmink (2013) models dune evolution by using the equilibrium predictor of Yalin (1964) for dune height and length and the empirical relations proposed by Coleman et al. (2005) to incorporate time-lag effects. With this method a part of the lag effects in dune development was captured, and the prediction of dune dimensions under a flood wave were improved compared to using the equilibrium predictors alone (Warmink, 2013). In a flood model, the hydraulic roughness could then be predicted by coupling the approach of Warmink (2013) with a roughness predictor which uses dune dimensions. This still requires further study.

A previous version of the idealized dune model (Paarlberg et al., 2009) has been incorporated within a SOBEK model that predicts flow in a river (Paarlberg et al., 2010; Paarlberg, 2012; Paarlberg & Schielen, 2012). During simulation of a flood wave, the hydraulic roughness of the main channel is determined by translating dune dimensions to a roughness value. The dune dimensions are predicted by the dune evolution model, which uses the water depth from the SOBEK model. This enables the modelling of hysteresis effects due to lag in bedform development with respect to the discharge, and makes the model as a whole more physically correct. The new dune evolution model developed in this thesis is being tested within the context of the broader research project. Preliminary results can be found in Warmink et al. (2015).

5.1.3 The influence of the lateral variation of dunes, superimposed bedforms and other forms of irregularity on roughness

In flumes, enough control can be exerted to force dunes to be very nearly 2D. The width of the flume can be limited, the flow strength can be kept low or very coarse sediment can be used, so that in the end dunes only have a slight crest curvature and are regular. However, when the experimental conditions allow for more free development, dunes may become much more complex. Venditti et al. (2005c) have shown this in their flume experiments, as presented here in Figure 47.

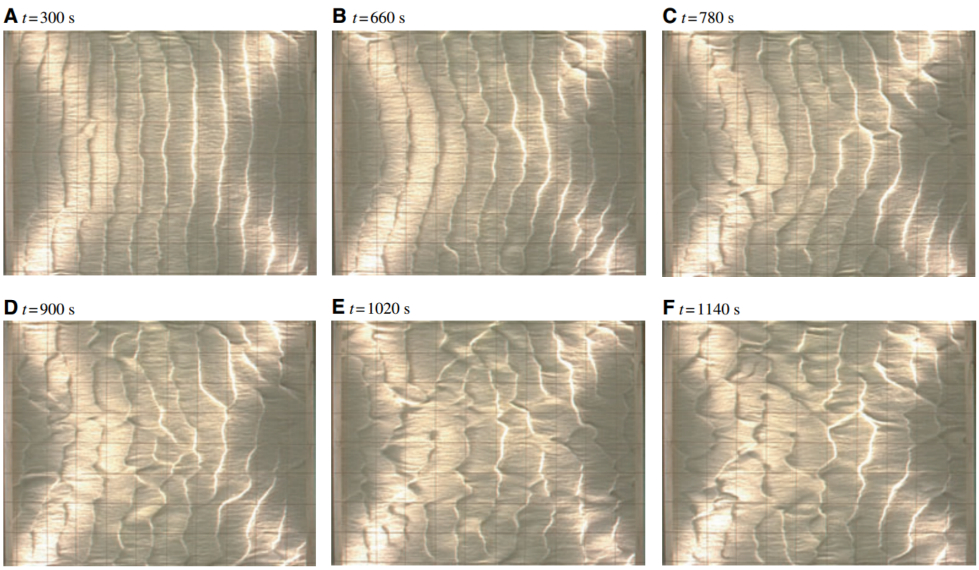

Figure 47: transition from 2D to 3D dunes, flow is from left to right (from Venditti et al., 2005c)

While 2D models can often still predict the length and height of these dunes well, there is another complicating factor. The flow and turbulence characteristics and bed shear stresses over fixed dunes are significantly different for varying crestline curvature of 3D dunes (Venditti, 2003, 2007) and fixed dunes with alternating crest line maxima at the center and sides (Maddux et al., 2003a and 2003b). This has implications for how dunes grow and develop, but also for the total form drag they actually have. The presence of superimposed bedforms as observed by Venditti et al. (2005b) in the flume also has implications for form drag as they are additional roughness elements. As Lefebvre et al. (2011) have shown for bedforms in a tidal channel, secondary bedforms have significant influence on the velocity profiles. The splitting of dunes as reported and modelled by Warmink et al. (2014) is an additional complicating factor. This phenomenon contributes to the variability of the dunes themselves, as well as the variability of average dune characteristics over time.

Dunes show irregularity in rivers as well. As studies by Allen (1978), Ten Brinke et al. (1999), Wilbers and ten Brinke (2003), Wilbers (2004), Parsons et al. (2005) and Nittrouer et al. (2011) have shown, dune fields in rivers are highly complex; the bedforms themselves can be irregular, and also forms of different wavelength and heights can be observed simultaneously. This shows that the translation to a roughness value on the basis of just a length and height may be too straightforward for field situations. These effects should therefore be considered when using a dune evolution model to predict (a part of) hydraulic roughness.

5.2 CONCLUSIONS

The research presented here was aimed at improving the understanding of the bed load processes involved in the evolution of dunes, and specifically those sediment transport processes that lead to a transition to upper-stage plane bed. The overarching goal of this research was to better understand these processes to enable the improvement of a simple idealized dune evolution model that is capable of predicting a wide range of morphologies with limited computational effort which can be employed within operational flood models.

During this research 1) important properties of bed load movement along dunes were identified, 2) the modelling of fully-developed dunes with a dune evolution model was improved by using a modified bed-load description and 3) transitions to upper-stage plane bed were simulated with the new dune evolution model using an adjusted sediment transport model concept. The original research questions as stated in chapter 1 (Introduction) will be answered in the following.

1. How can the bed load movement along a dune be characterized?

Early in the research an important aspect of bed load movement was identified: step length, the average distance sediment particles travel. While this is a relatively small scale process, it has implications for higher order processes like the initiation of dunes and the transition to upper-stage plane bed. This is because step length controls the spatial lag between bed shear stress and sediment flux, and the variation of spatial lag is one of the processes that control the growth and decay of dunes. Under higher bed shear stress higher step length is expected, as reported for experiments in flat bed situations.

Since the existing knowledge about step length is based on flat-bed situation only, an explorative flume experiment was done to investigate the behaviour of step length along dune surfaces. A high speed camera was used to record sediment movement along a dune, which was then manually processed to find steps of individual particles in the crest and trough of three dunes. Although the statistics were not fully resolved, the measured probability distribution of step length matched well with the distribution shown by Lajeunesse et al. (2010), for flat sediment beds.

Contrary to expectation, it was found that along dunes the mean step length at the trough (lower shear stress) is nearly the same as at the crest (higher shear stress). However, it is known and also observed during the present experiments that, due to strong turbulent generation in the lee of dune crests, much larger fluctuations in shear stress occur in the dune trough (with flow reattachment) than on the dune crest. Flow reattaches at the trough, and the turbulent bursts resulting from this move particles over great distances. This compensates for the lower average shear stress in this area. Furthermore it was found that in both areas the particle velocity is about 10% of the average streamwise velocity.

The average step lengths found in the experiments were markedly lower than the results which follow from the formula for step length of Sekine & Kikkawa (1992) which was derived for flat bed. This confirms that sediment movement along dunes and flat beds are different.

2. How can the modelling of dunes be improved in an idealized dune model?

The model proposed by Paarlberg et al. (2009) is computationally cheap, and can predict equilibrium dunes well. However, it cannot predict all morphologies, in particular low-angle dunes and upper-stage plane bed are not included. This has to do with how the flow separation zone is modelled. Once flow separation is triggered, it remains activated and all sediment that reaches the crest is deposited on the lee side. In this way the lee side always remains steep, it is not possible to model dune lee slopes between 10° and 30° and also the transition to upper-stage plane bed from the dune regime is blocked.

In this research two alternative bed load formulations have been introduced, one takes the original equilibrium bed load formula of Meyer-Peter & Müller (1948) and forces spatial lag with a simple relaxation equation, while the other replaces this equilibrium formula with a sediment pick-up and deposition model, for example as described by Nakagawa & Tsujimoto (1980).

By choosing this type of bed load model with inherent spatial lag (in both cases controlled by the step length parameter) and by no longer representing the flow separation zone with a separate parameterized model (Paarlberg et al., 2009), the modelling of fully-developed dunes has been improved; the dune lee side can freely develop without further intervention to a certain lee side angle between a few degrees and 30°. Although the model has not been validated thoroughly, it was shown that with a realistic step length parameter α it can reproduce the experimental results of Venditti et al. (2005a, 2005b) well.

It has been further shown that if the step length is increased to higher values, the model is able to completely wash out a fully formed dune, thereby enabling the modelling of a transition to upper-stage plane bed without the need for more complex hydrodynamic/sediment modelling.

Because the Nakagawa & Tsujimoto (1980) bed load model is closer to the actual physical processes, this model has been chosen to continue with. In general it has been shown that spatial lag processes associated with bed load transport can have a strong effect on the resulting dune morphologies in a flume.

3. How can a step length model be derived that combines bed load and suspended load processes and, implemented in the idealized dune model of Paarlberg et al. (2009), enables the modelling of dune dynamics due to a flood wave?

In reality the step length is not constant but it changes with increasing flow strength. For low discharge with small shear stress step lengths will be relatively low and dunes can develop and grow. With increasing flow strength the step length will also increase, and the spatial lag between shear stress and transport increases as well. When the spatial lag is high enough the dunes start washing out, until they are completely gone and the upper-stage plane bed regime is reached. To model this process, Shimizu et al. (2009) have introduced a step length model that increases step length when the dimensionless grain shear stress exceeds 0.5 (i.e. when the transitional regime is reached) until it equals 0.8 (i.e. when the upper-stage plane bed is reached).

This step length model has been implemented in the new dune evolution model, and tuned so that it can run a synthetic flood wave calculation scenario, as used earlier by Shimizu et al. (2009) with a complex 2DV k-ε dune evolution model, until similar results are obtained. Because suspended load was not modelled explicitly, a significantly higher step length was needed in the present model to model it implicitly. This means that step length was then actually applied to total load: bed load and suspended load. The total load step length has been made depth-dependent, because step length of suspended sediment scales with water depth. With this adjustment the idealized dune model was able to simulate the transition to upper-stage plane bed in a similar way as the complex k-ε dune evolution model. Compared with the results of Shimizu et al. (2009), the transition regime and the upper-stage plane bed regime were reached at the same moments in time, and dune dimensions were approximately equal.

A flood wave similar to the Rhine flood wave in 1998, as reported by Julien et al. (2002), has been modelled with river slope and sediment characteristics representative for the Waal. It was shown that, although dune heights are still overestimated, the model is able to represent the bedform hysteresis as it was observed in the Waal river. Simulations with slightly higher discharges than in 1998 showed that a sudden transition to upper-stage plane bed occurs. This indicates that this kind of event may occur for river situations with high discharges. However, further model development and calibration is still needed to improve further its quantitative performance and to make it ready for practical use. In general it was confirmed that spatial lag processes can have a strong effect on the resulting dune morphologies, but in the field situation only for length scales that are more appropriate for suspended transport.

5.3 RECOMMENDATIONS

This research project has resulted in increased knowledge and understanding of processes related to dune evolution, and the modelling of dunes was improved. Morphological development was represented in an idealized bedform evolution model in a more physics-based way by including pick-up and deposition processes along with varying step length. Inevitably this also leads to defining more research directions as well. It is recommended to continue with this modelling approach, and 1) improve step length knowledge for dune situations, 2) improve the modelling of dune length within an idealized model, 3) investigate the relative contributions of bed load and suspended load (models) to processes like a transition to upper-stage plane bed, and 4) use the idealized bedform evolution model with the proposed sediment transport concepts within a flood model. Besides improving on the proposed concepts, it is recommended to 5) do a thorough review of how a transition to upper-stage plane bed relates to certain empirical (non-dimensional) parameters to help assess how close the conditions in certain rivers are to a transition to upper-stage plane bed. Finally, it is recommended to 6) use (concepts of) the sediment transport model in this thesis to improve significantly different types of dune model, and models for other types of morphological development. These six recommendations are elaborated further in the following.

1. Step length knowledge for dune situations

Firstly, the detailed sediment motion along dunes is a subject that warrants further study. We now have a first idea of how bed load properties vary along 2D dunes under low flow strength. For higher flow strength and more irregular dunes these properties will probably vary more; turbulent events become stronger and so in general flow becomes more irregular as well. The relation between (the stochastics of) turbulent events and parameters like step length is very interesting in that regard. This needs very detailed hydrodynamic measurements near the bottom, as well as detailed recording of particle movement, for varying conditions with high and low flow strength. An instrument like the Acoustic Concentration and Velocity Profiler (ACVP) as used by Nasqhband et al. (2014a) and camera techniques can be used for the former. Though it may not get the best results in the bed load layer itself, it will give a very good idea of the turbulent structures directly above it. An alternative is to use a dune evolution model like that of Nabi et al. (2010, 2012a, 2012b, 2013a, 2013b), which employs a very detailed hydrodynamics and sediment transport module. Simulating a fixed dune shape in such a model, enables the numerical study of the behaviour of small amounts of mobile sand along the dune while limiting computational requirements. In this way, this type of advanced dune evolution model can function as a sort of virtual laboratory with somewhat idealized physics.

2. Dune length within an idealized model

An important aspect of dune evolution modelling is the behaviour of dune length under varying discharge, and the importance of dune length characteristics for hydraulic roughness. The focus of the present research was on dune height, because it has a stronger influence on roughness. Under varying discharge, it was therefore simply assumed that dune length scales directly with the water depth with a constant ratio. Measurements show that this is a reasonable assumption, but in reality the ratio between dune length and water depth can change during a flood wave and a dune field in general does not have a single representative dune length. Both the behaviour of *average* dune length as well as the effects of the *distribution* of dune length may be taken into account in order to further improve the prediction of hydraulic roughness.

3. The relative contributions of bed load and suspended load to processes like a transition to upper-stage plane bed

The contributions of bed load and suspended load to events like a transition to upper-stage plane bed should be studied further. The detailed properties of transport modes in such an event should be studied further experimentally; when is bed load dominant, when is suspended load dominant, and how can this be predicted? Also the role of bed load and suspended load can be studied further by employing models such as developed by Nabi et al. (2010, 2012a, 2012b, 2013a, 2013b). A less computational time-intensive alternative was developed by Naqshband et al. (2015), and simulates bed load as well as suspended load. However, while suspended load was modelled with pick-up and deposition processes, the bed load model was still an equilibrium model. This could be replaced by a pick-up and deposition model for bed load. Further study of different combinations of bed load and suspended load models is therefore possible, which also entails the further improvement of the dune evolution model.

4. An idealized model with non-equilibrium transport concepts within a flood model

A goal of this research was the improvement of dune evolution modelling specifically within the context of (operational) flood modelling. The new bedform evolution model is still computationally cheap, and is in principle able to model flood waves for flume situations and river scenarios. However, still work has to be done in further model development (calibration/validation), using existing laboratory data and especially using existing bed for evolution data in rivers (e.g. Sieben, 2004).

5. The predictive power of (non-dimensional) parameters on a transition to upper-stage plane bed and predicting such a transition without a dune evolution model

The current model version has shown the large effect the sudden disappearance of bedforms may have on water levels for high discharges in a river. Although it is not certain if the model predicts this transition to upper-stage plane bed correctly and at the correct discharge, it clearly shows the importance of being able to know if and when such an event occurs. Tools are needed that can help in assessing how close conditions in a certain river are to a transition to upper-stage plane bed. In the absence of a thoroughly calibrated dune evolution model that can calculate the extreme future river flood scenarios in a reasonable time, other ways of gaining this knowledge can be considered. A thorough review of the available empirical knowledge from flumes and the field regarding the occurrence of dunes for various sets of dimensionless parameters associated with sediment and flow behaviour is recommendable. Extensive literature exists on how dune regimes and dune dimensions relate to parameters like the Froude number, suspension number and Shields number, but this knowledge should be further integrated. A challenge in that regard lies in incorporating the lag processes inherent in dune dynamics, as most of the empirical data applies to equilibrium situations. Approaches like that of Coleman et al. (2005) combine equilibrium predictors of dune dimensions with a time-dependent lag model, which may be a promising way to tackle this issue.

6. Pick-up, deposition and step length modelling in other contexts

Dunes can be modelled with a cellular automaton model as well; Knaapen et al. (2013) adopt the model for desert dunes of Bishop et al. (2002) for that purpose. The Knaapen et al. (2013) model also employs pick-up and deposition processes, which suggests that prediction of a transition to upper-stage plane bed is possible. In this model step length is used as one of the input parameters. The model of Seuren et al. (2014) builds on this concept, and uses the step length model of Sekine & Kikkawa (1992) to calculate the input step length from hydrodynamic conditions. However, the model still lacks a link with hydrodynamics during the model run itself, as step length is assumed to be constant. This shows that there are opportunities to apply (concepts of) the transport model used in this thesis in significantly different types of dune evolution model. It would be interesting to further develop this type of model, and find if and how it can predict a transition to upper-stage plane bed. This would require either adding a flow model, or at least a module that roughly predicts how flow changes due to the hydraulic roughness of the morphology and how that in turn influences the movement of sediment along the bed.

The pick-up and deposition model of Nakagawa & Tsujimoto (1980) and similar non-equilibrium bed load models could be valuable in other aqueous areas besides the main channel of rivers as well. This is especially the case for the morphological phenomena occurring under non-equilibrium conditions, like the initiation and washing out of sand ripples on sea beds. While the spatial scales and ratio between bedform height and water depth are different than for river dunes, also here a spatial lag between maximum shear stress and maximum bed load transport should contribute to growth and decay. Pick-up and deposition models are already used for scour studies, for example by Zhang et al. (2015) who model local scour around spur dykes for uniform and non-uniform beds.

When the upper-stage plane bed is reached and flow strength is further increased, eventually antidunes can grow. It would be interesting to study the prediction of these forms and how they are affected by pick-up and deposition processes relating to bed load and suspended load.

REFERENCES

Abbot J. E. and Francis J.R.D. (1977). Saltation and suspension trajectories of solid grains in a water, Philos. Trans. R. Soc. London A., 284, pp. 225–254.

Allen, J.R.L. (1968). The nature and origin of bed-form hierarchies. Sedimentology, 10, pp. 161-182.

Allen, J.R.L. (1974). Reaction, relaxation and lag in natural sedimentary system: general principles, examples and lessons. Earth Science Review, 10, pp. 263-342.

Allen, J.R.L. (1978). Computational methods for dune time-lag: Calculations using Stein's rule for dune height. Sedimentary Geology, 20(3), pp. 165-216.

Bagnold R.A. (1956). The flow of cohesionless grains in fluids. Phil. Trans. R. Soc. London A, 249, 235–297.

Best J. (2005). The fluid dynamics of river dunes: A review and some future research directions, J. Geophys. Res., 110, F04S02, doi:10.1029/2004JF000218.

Bishop, S.R., H. Momiji, R. Carretero-González, & A. Warren (2002). Modelling desert dune fields based on discrete dynamics. Discrete Dynamics in Nature and Society, 7(1), 7-17.

Bridge, J.S. & J.L. Best (1988), Flow, sediment transport and bedform dynamics over the transition from dunes to upper stage plane beds, Sedimentology, 35, 753–764.

Casas, A., G. Benito, V.R. Thorndycraft, M. Rico (2006). The topographic data source of digital terrain models as a key element in the accuracy of hydraulic flood modelling. Earth Surface Processes and Land Forms, 31, pp. 444-456.

Charru, F., H. Mouilleron, O. Eiff (2004), Erosion and deposition of particles on a bed sheared by a viscous flow, Journal of Fluid Mechanics, 519, pp. 55–80.

Claudin P., F. Charru, B. Andreotti (2011). Transport relaxation time and length scales in turbulent suspensions. Journal of Fluid Mechanics, 671, pp. 491–506.

Coleman, S., M. Zhang, T. and Clunie, (2005). Sediment-Wave Development in Subcritical Water Flow. Journal of Hydraulic Engineering, 131(2), 106–111.

Colombini, M. (2004). Revisiting the linear theory of sand dune formation. Journal of Fluid Mechanics, 502, pp. 1-16, doi:10.1017/S0022112003007201

Colombini, M. & A. Stocchino (2012). Three-dimensional river bedforms. Journal of Fluid Mechanics, 695, pp. 63-80, doi:10.1017/jfm.2011.556

Deltacommissie (2008). Samen werken met water. Deltacommissie.

Deltanet (2014). Simplified map of the Dutch-Belgian Rhine-Meuse-Scheldt delta from the Rhine, Meuse and Scheldt page. Retrieved from: http://www.deltanet-project.eu/rhine-meuse-and-scheldt

Dottori, F., M.L.V. Martina, and E. Todini (2009). A dynamic rating curve approach to indirect discharge measurement. Hydrology and Earth System Sciences, 13.6, pp. 847-863.

Einstein, H.A. (1950). The bed load function for sediment transportation in open channel flows. Technical bulletin, No. 1026, U.S. Department of Agriculture, Soil Conservation Service.

Engelund, F. (1966), Hydraulic resistance of alluvial streams, J. Hydraul. Div. Am. Soc. Civ. Eng., 92(2), pp. 315–326.

Engelund, F. (1970). Instability of erodible beds. J. of Fluid. Mech., Vol. 42, pp. 225-244.

Engelund, F. & J. Fredsøe (1974), Transition from dunes to plane bed in alluvial channels, Ser. Pap. 4, 56 pp., Inst. of Hydrodyn. and Hydraul. Eng., Tech. Univ. of Den., Lyngby.

Engelund, F. & J. Fredsøe (1982). Sediment ripples and dunes. Ann. Rev. Fluid Mech, Vol. 14, pp. 13-37.

Fernandez Luque, R. & R. Van Beek (1976). Erosion and transport of bed sediment. Journal of hydraulic research, 14 (2), pp. 127-144.

Francis, J.R.D. (1973). Experiment on the motion of solitary grains along the bed of a water stream. Proceedings of the Royal Society of London, A332, pp. 443-471.

Fread, D.L., (1982). A Dynamic Model of Stage-Discharge Relations Affected by Changing Discharge. NOAA Technical Memorandum NWS HYDRO-16, National Weather Service, Silver Spring, Maryland.

Fredsøe, J. (1974). On the development of dunes in erodible channels. Journal of Fluid Mechanics, 64, pp. 1-16.

Fredsøe, J. & F. Engelund (1975). Bed configurations in open and closed alluvial channels, Ser. Pap. 8, 39 pp., Inst. of Hydrodyn. and Hydraul. Eng., Tech. Univ. of Den., Lyngby.

Galappatti G. & C.B. Vreugdenhil (1985). A depth-integrated model for suspended sediment transport. Journal of Hydraulic Research, 23, pp. 359–377. doi: 10.1080/00221688509499345.

Giri, S. & Y. Shimizu (2006). Computation of sand dune migration with free surface flow. Water Resources Research, 42.

Giri, S., S. Van Vuren, W. Ottevanger, K. Sloff & A. Sieben (2008). A preliminary analysis of bedform evolution in the Waal during 2002-2003 flood event using Delft3D. In Proceedings of MARID-2008. Leeds, UK

Henderson, F. M. (1996). Open channel flow, Macmilliam Series in Civil Engineering, Macmilliam eds., New York, USA, pp. 522.

Hulscher, S.J.M.H. (1996). Tidal-induced large-scale regular bedform patterns in a three-dimensional shallow water model. Journal of Geophysical Research, Vol. 101(C9), 20,727-20,744.

Jerolmack, D.J. & D. Mohrig (2005). A unified model for subaqueous bedform dynamics. Water Resources Research, 41.

Jones, B.E. (1915). A method of correcting river discharge for a changing stage. U.S. Geological Survey Water Supply Paper, 375-E, pp. 117– 130.

Julien, P.Y. & G.J. Klaassen, 1995. Sand-dune geometry of large rivers during floods. J. Hydr. Eng, Vol. 121, No. 9, pp. 657-663.

Julien, P.Y., Klaassen, G.J., Ten Brinke, W.B.M., Wilbers, A.W.E. (2002). Case study: bed resistance of Rhine river during 1998 flood. Journal of Hydraulic Engineering 128, 1042-1050

Kennedy, J.F. (1963). The mechanics of dunes and antidunes in erodible-bed channels. J. of Fluid. Mech., Vol. 16, pp. 521-544.

Kleinhans, M.G., L.C. Van Rijn (2002). Stochastic Prediction of Sediment Transport in Sand-Gravel Bed Rivers. Journal of Hydraulic Engineering, 128, pp. 412-425.

Kleinhans, M.G., A.W.E. Wilbers and W.B.M. Ten Brinke (2007). Opposite hysteresis of sand and gravel transport upstream and downstream of a bifurcation during a flood in the River Rhine, the Netherlands. Netherlands Journal of Geosciences - Geologie en Mijnbouw, 86 (3), pp. 273–285.

Knaapen, M. A. F., J. Willis, and J. H. Harris. "Modeling Dune dynamics in situations with bimodal sediment distributions." MARID IV (2013): 153-158.

Kostaschuk, R. (2000). A field study of turbulence and sediment dynamics over subaqueous dunes with flow separation. Sedimentology, 47, pp. 519–531.

Kostaschuk R., D. Shugar, J. Best , D. Parsons , S. Lane , R. Hardy, O. Orfeo. (2010). Suspended sediment transport and deposition over a dune: Río Paraná, Argentina. Earth Surface Processes and Landforms 34: 1605–1611. DOI: 10.1002/esp.1847

Kroy, K., G. Sauermann, and H. J. Herrmann (2002), Minimal model for aeolian sand dunes, Phys. Rev. E, 66(3), 031302, doi:10.1103/PhysRevE.66.031302.

Lajeunesse, E., L. Malverti, and F. Charru (2010), Bed load transport in turbulent flow at the grain scale: Experiments and modelling. Journal of Geophysical Research, 115, F04001, doi:10.1029/2009JF001628.

Lefebvre, A., V.B. Ernstsen, & C. Winter (2011). Influence of compound bedforms on hydraulic roughness in a tidal environment. Ocean Dynamics,61(12), 2201-2210.

Maddux, T.B., J.M. Nelson, S. R. McLean (2003a), Turbulent flow over three-dimensional dunes: 1. Free surface and flow response, J. Geophys. Res., 108(F1), 6009, doi:10.1029/2003JF000017.

Maddux, T.B., S.R. McLean, J. M. Nelson (2003b), Turbulent flow over three-dimensional dunes: 2. Fluid and bed stresses, J. Geophys. Res., 108(F1), 6010, doi:10.1029/2003JF000018.

Meyer-Peter, E. & R. Müller (1948). Formulas for bed-load transport. Proceedings of the 2nd IAHR congress, Vol. 2, pp. 39–64.

Morvan, H., D. Knight, N. Wright, X. Tang, A. Crossley (2008). The concept of roughness in fluvial hydraulics and its formulation in 1D, 2D and 3D numerical simulation models. Journal of Hydraulic Research, 46(2), pp. 191-208.

Nabi, M., H.J. De Vriend, E. Mosselman, C.J. Sloff, Y. Shimizu (2010) – Simulation of subaqueous dunes using detailed hydrodynamics. River, Coastal and Estuarine Morphodynamics: RCEM 2009.

Nabi, M. (2012a), Computational modelling of small-scale river morphodynamics, PhD thesis, Delft Univ. of Technol., Delft, Netherlands.

Nabi, M., H.J. de Vriend, E. Mosselman, C.J. Sloff, Y. Shimizu (2012b), Detailed simulation of morphodynamics: 1. Hydrodynamics model, Water Resour. Res., 48, W12523, doi:10.1029/2012WR011911.

Nabi, M., H.J. de Vriend, E. Mosselman, C.J. Sloff, Y. Shimizu (2013a), Detailed simulation of morphodynamics: 2.Sediment pickup, transport, and deposition, Water Resour. Res., 49, 4775–4791, doi:10.1002/wrcr.20303.

Nabi, M., H.J. de Vriend, E. Mosselman, C.J. Sloff, Y. Shimizu (2013b), Detailed simulation of morphodynamics: 3. Ripples and dunes, Water Resource Research, 49, doi:10.1002/wrcr.20457.

Nakagawa, H. & T. Tsujimoto (1980). Sand bed instability due to bed load motion. Journal of the Hydraulics Division, 106(12), pp. 2029-2051.

Naqshband, S., J.S. Ribberink, D. Hurther, and S.J.M.H. Hulscher (2014a), Bed load and suspended load contributions to migrating sand dunes in equilibrium, J. Geophys. Res. Earth Surf.,119, 1043–1063, doi:10.1002/2013JF003043.

Naqshband, S., J.S. Ribberink, S.J.M.H. Hulscher (2014b). Using Both Free Surface Effect and Sediment Transport Mode Parameters in Defining the Morphology of River Dunes and Their Evolution to Upper Stage Plane Beds., J. Hydraul. Eng., 140(6), 06014010.

Naqshband, S., O.J.M. van Duin, J.S. Ribberink, S.J.M.H. Hulscher (2015). Modeling river dune development and dune transition to upper stage plane bed. Earth Surface Processes and Landforms, doi:10.1002/esp.3789.

Nelson, J.M., A.R. Burman, Y. Shimizu, S.R. McLean, R.L. Shreve, M. Schmeeckle (2005). Computing flow and sediment transport over bedforms. River, Coastal and Estuarine Morphodynamics: RCEM 2005, 2, pp. 861–872.

Nemeth, A.A. (2003). Modelling offshore sand waves. Ph.D. thesis, University of Twente, Enschede, the Netherlands.

Németh, A.A., S.J.M.H. Hulscher, and R.M.J. van Damme (2006). Simulating offshore sand waves, Coastal Engineering, 53, pp. 265-275, doi:10.1016/j.coastaleng.2005.10.014.

Niño, Y., & M.H. Garcia (1994). Gravel saltation: 1. Experiments. Water Resources Research, 30, pp. 1907–1914.

Niño Y. & M.H. Garcia (1998). Using Lagrangian particle saltation observations for bedload sediment transport modelling. Hydrological Processes, 12, pp. 1197-1218.

Nittrouer J.A., D. Mohrig, M.A. Allison, A.-P.B. Peyret (2011). The lowermost Mississippi River: a mixed bedrock-alluvial channel. Sedimentology 58. 1914–1934. DOI: 10.1111/j.1365-3091.2011.01245.

Paarlberg, A.J., C.M. Dohmen-Janssen, S.J.M.H. Hulscher, J. van den Berg and A.P.P. Termes (2006). Modelling morphodynamic evolution of river dunes. Proc. River Flow 2006, Ferreira, Alves, Leal and Corsado (eds), Taylor & Francis Group, London, ISBN 0-415-40815-6, pp. 969-978.

Paarlberg, A.J., C.M. Dohmen-Janssen, S.J.M.H. Hulscher and P.Termes (2007). A parameterization of flow separation over subaqueous dunes. Water Resour. Res., 43, W12417, doi:10.1029/2006WR005425.

Paarlberg, A.J., C.M. Dohmen-Janssen, S.J.M.H. Hulscher and P.Termes (2009). Modeling river dune evolution using a parameterization of flow separation. Journal of Geophysical Research, Vol. 114, pp. F01014.

Paarlberg, A.J., C.M. Dohmen-Janssen, S.J.M.H. Hulscher, P. Termes, R. Schielen (2010). Modelling the effect of time-dependent River dune evolution on bed roughness and stage. Earth Surfaces Processes and Landforms, 35, pp. 1854-1866.

Paarlberg, A.J. (2012). SOBEKduin: Integratie duinruwheidmodel in SOBEK. Report PR2177.10 (in Dutch), HKV Consultants, Lelystad, Netherlands.

Paarlberg, A.J., & R.M. Schielen (2012). Integration of a dune roughness model with a large-scale flow model. In Proc. of River Flow (pp. 155-161).

Parsons DR, Best JL, Hardy RJ, Kostaschuk R, Lane SN, Orfeo O. (2005). The morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: results from simultaneous multibeam echo sounding and acoustic Doppler current profiling. Journal of Geophysical Research 110: F04S03. DOI: 10.1029/2004JF000231

Richards, K. (1982). Rivers, form and process in alluvial channels. Methuen and Co., New York, 358p.

Rouse, H. (1937). Modern conceptions of the mechanics of fluid turbulence. Transactions of the American Society of Civil Engineers Vol. 102(1), pp. 463-505.

Sekine, M., and H. Kikkawa (1984). Transportation mechanism of bed-load in an open channel. Proceedings of the Japanese Society of Civil Engineering., 351, pp. 69-75 (in Japanese).

Sekine, M., and H. Kikkawa (1992). Mechanics of Saltating Grains II. Journal of Hydraulic Engineering, ASCE, 118 (4), pp. 536-558.

Seuren, J.M., O.J.M. van Duin, J.J. Warmink, M.A.F. Knaapen, S.J.M.H. Hulscher (2014). River dune predictions, comparison between a parameterized dune model and a cellular automation dune model. In D.C.M. Augustijn & J.J. Warmink (Eds.), Proceedings NCR-days 2014, Enschede, October 2-3, pp 69-70.

Shimizu, Y., M.W. Schmeeckle, J.M. Nelson (2001). Direct numerical simulations of turbulence over two-dimensional dunes using CIP methods. Journal of Hydroscience and Hydraulic Engineering, 19(2), pp. 85-92.

Shimizu, Y., S. Giri, I. Yamaguchi, J. Nelson (2009). Numerical simulation of dune-flat bed transition and stage-discharge relationship with hysteresis effect. Water Resources Research, 45.

Sieben, J. (2004). Characterization of bed levels with statistical equivalency. Proceedings of MARID2004, Marine Sandwave and River Dune Dynamics, 1 & 2 April 2004, Enschede, the Netherlands, pp. 276-283.

Smith, J.D. & S.R. McLean (1977), Spatially-averaged flow over a wavy surface, J. Geophys. Res., 82, 1735– 1746.

Soulsby, R. (1997). Dynamics of marine sands: a manual for practical applications. Thomas Telford.

Southhard, J.B. & L.A. Boguchwal (1990). Bed configurations in steady unidirectional water flows. Part 2. Synthesis of flume data. Journal of Sedimentary Research, Vol. 60.

Southhard, J.B. (1991). Experimental Determination of Bed-Form Stability. Annual Review of Earth and Planetary Sciences, Vol. 19, pp. 423-455.

Sterlini, F. (2009). Modelling sand wave variation. Ph.D. thesis, University of Twente, Enschede, the Netherlands.

Ten Brinke, W.B.M., A.W.E. Wilbers, and C. Wesseling (1999), Dune growth, decay and migration rates during a large-magnitude flood at a sand and mixed sand-gravel bed in the Dutch Rhine river system, in Fluvial Sedimentology VI, edited by N. D. Smith and J. Rogers, Spec. Publ. Int. Assoc. Sedimentol., 28, 15–32.

Tjerry, S. & J. Fredsøe (2005). Calculation of dune morphology. Journal of Geophysical Research - Earth Surface, 110.

Tsujimoto, T., A. Mori, T. Okabe, T. Ohmoto (1990). Non-equilibrium sediment transport: a generalized model. Journal of Hydroscience and Hydraulic Engineering, 7 (2), pp. 1-25.

Van den Berg, J. (2007). Nonlinear Sandwave Evolution. Ph.D. thesis, University of Twente, Enschede, the Netherlands.

Van den Berg, J. (2012). Non-linear process based modeling of offshore sand waves. Continental Shelf Research, 37, pp. 26-35.

Van den Brink N.G.M., D. Beyer, M.J.M. Scholten, E.H. van Velzen (2006). Onderbouwing hydraulische randvoorwaarden 2001 van de Rijn en zijn takken. RIZA report 2002·015 (in Dutch), RIZA, The Netherlands.

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen & S.J.M.H. Hulscher (2012). Particle step length variation along river dunes. In R.M. Munoz (Ed.), Proceedings of the International conference on fluvial hydraulics, San Jose, Costa Rica, 5-7-September 2012 (pp. 493-497). London, UK: CRC Press Taylor & Francis Group.

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen and S.J.M.H. Hulscher. (2013). Modelling sediment pick-up and deposition in a dune model. Van Lancker, V. and Garlan, T. (Eds), MARID 2013. Fourth International Conference on Marine and River Dune Dynamics. Bruges, Belgium, 15-17 April 2013. Royal Belgian Institute of Natural Sciences and SHOM. VLIZ Special Publication 65 – Flanders Marine Institute (VLIZ). Oostende, Belgium. 338p. ISSN 1377-0950. ISBN 978-2-11-128352-7.

Van Duin, O.J.M., S.J.M.H. Hulscher, J.S. Ribberink & C.M. Dohmen-Janssen (submitted). Which bed load transport formulations allow modelling the transition from dunes to upper-stage plane beds?

Van Rijn, L.C. (1984a). Sediment transport part I: bed load transport. Journal of Hydraulic Engineering, 110, pp. 1431–1456.

Van Rijn, L.C. (1984b). Sediment transport part III: Bedforms and alluvial roughness. Journal of Hydraulic Engineering, 110(12), pp. 1733-1754.

Van Rijn L.C. (1993). Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. AQUA: Amsterdam.

Venditti, J.G. (2003). Initiation and development of sand dunes in river channels. PhD thesis, University of Britisch Columbia, Canada.

Venditti, J.G., M.A. Church, S.J. Bennett (2005a). Bedform initiation from a flat sand bed. Journal of Geophysical Research, 110.

Venditti, J.G., M. Church, and S.J. Bennett (2005b), Morphodynamics of small-scale superimposed sand waves over migrating dune bedforms, Water Resour. Res., 41, W10423, doi:10.1029/2004WR003461.

Venditti, J.G., M.A. Church, and S.J. Bennett (2005c), On the transition between 2D and 3D dunes, Sedimentology, 53, doi:10.1111/j.1365- 3091.2005.00748.x.

Venditti, J.G. (2007), Turbulent flow and drag over fixed two- and three-dimensional dunes, J. Geophys. Res., 112, F04008, doi:10.1029/2006JF000650.

Vidal, J.-P., S. Moisan, J.-B. Faure, D. Dartus (2007). River model calibration, from guidelines to operational support tools. Environmental Modelling & Software, 22, pp. 1628–1640.

Warmink, J.J., M.J. Booij, H. van der Klis, S.J.M.H. Hulscher (2007). Uncertainty in water level predictions due to various calibrations. Proceedings of CAIWA 2007, Pahl-Wostl C (ed.), Basel, Switzerland, 12–15 November 2007; 1–18.

Warmink, J.J., M.J. Booij, H. Van der Klis, S.J.M.H. Hulscher (2012). Quantification of uncertainty in design water levels due to uncertain bed roughness in the Dutch river Rhine. Hydrological Processes 27(11) 1646-1663. DOI: 10.1002/hyp.9319

Warmink, J.J. (2013) Modelling dune evolution under a discharge wave. In: NCR-Days 2013, 03-10-2013 - 10-10-2013, Delft (pp. 3:17 - 3:18).

Warmink, J.J., M.W. Straatsma, F. Huthoff, M.J. Booij, S.J.M.H. Hulscher (2013). Uncertainty of design water levels due to combined bedform and vegetation roughness in the Dutch river Waal. Journal of Flood Risk Management 6(4) 302-318. DOI: 10.1111/jfr3.12014

Warmink, J.J., C.M. Dohmen-Janssen, J. Lansink, S. Naqshband, O.J.M. van Duin, A.J. Paarlberg, A.P.P. Termes, S.J.M.H. Hulscher (2014). Understanding river dune splitting through flume experiments and analysis of a dune evolution model. Earth Surface Processes and Landforms. DOI: 10.1002/esp.3529

Warmink, J.J., R.M.J. Schielen (2014). Explicit computation of bedform roughness for operational flood modelling, a case study for the river Rhine. In A.J. Schleiss et al. (Eds.) Proceedings River Flow 2014, Lausanne, Switzerland, pp 375-380.

Warmink, J.J., O.J.M. van Duin, S. Naqshband (2015). Comparison of two bedform models to predict bedform roughness for flood modelling. Proceedings of the 36th IAHR World Congress, 28 June – 3 July, 2015, The Hague, The Netherlands.

Wasantha Lal, A.M. (1995). Calibration of riverbed roughness. Journal of Hydraulic Engineering. 121(9): 646-671.

Werner, M. (2004). Spatial flood extent modelling: a performance-based comparison. PhD thesis, Delft University of Technology, Nether- lands.

Wilbers A. (2004). The Development and Hydraulic Roughness of Subaqueous Dunes, Netherlands Geographical Studies 323. Utrecht University: Utrecht; 224 pp.

Wilbers A.W.E., W.B.M. Ten Brinke (2003). The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. Sedimentology, 50, pp. 1013–1034.

Wong, M. & G. Parker (2006). Reanalysis and correction of bed-load relation of Meyer-Peter and Müller using their own database. Journal of Hydraulic Engineering, 132 (11), pp. 1159–1168.

Yalin, M.S. (1964). Geometrical properties of sand waves. J. of Hydr. Div. ASCE, Vol. 90, pp. 105-119.

Yamaguchi, S. & N. Izumi (2002). Weakly nonlinear stability analysis of dune formation. Proceedings of River Flow 2002, pp. 843-850.

Zhang, H., Mizutani, H., Nakagawa, H., & Kawaike, K. (2015). Euler–Lagrange model for local scour and grain size variation around a spur dyke. International Journal of Multiphase Flow, 68, 59-70.

PUBLICATIONS

PEER-REVIEWED JOURNAL PAPERS

Van Duin, O.J.M., S.J.M.H. Hulscher, J.S. Ribberink & C.M. Dohmen-Janssen (2015, submitted). Which bed load transport formulations allow modelling the transition from dunes to upper-stage plane beds?

Naqshband, S., **O.J.M. van Duin**, J.S. Ribberink, S.J.M.H. Hulscher (2015). Modeling river dune development and dune transition to upper stage plane bed. Earth Surface Processes and Landforms, doi:10.1002/esp.3789.

Warmink, J.J., C.M. Dohmen-Janssen, J. Lansink, S. Naqshband, **O.J.M. van Duin**, A.J. Paarlberg, A.P.P. Termes, S.J.M.H. Hulscher (2014). Understanding river dune splitting through flume experiments and analysis of a dune evolution model. Earth Surface Processes and Landforms. DOI: 10.1002/esp.3529

CONFERENCE PAPERS AND ABSTRACTS

Warmink, J.J., **O.J.M. van Duin**, S. Naqshband (2015). Comparison of two bedform models to predict bedform roughness for flood modelling. Proceedings of the 36th IAHR World Congress, 28 June – 3 July, 2015, The Hague, The Netherlands.

Seuren, J.M., **O.J.M. van Duin**, J.J. Warmink, M.A.F. Knaapen, S.J.M.H. Hulscher (2014). River dune predictions, comparison between a parameterized dune model and a cellular automation dune model. In D.C.M. Augustijn & J.J. Warmink (Eds.), Proceedings NCR-days 2014, Enschede, October 2-3, pp 69-70.

Van Duin, O.J.M. & S.J.M.H. Hulscher (2014). Modelling the transition from dunes to the upper-stage plane bed. In A.J. Schleiss, G. De Cesare, M.J. Franca & M. Pfister (Eds.), River Flow 2014 (pp. 1067-1074). Londen: Taylor & Francis Group.

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen & S.J.M.H. Hulscher (2013). Modelling pick-up and deposition in a dune model. In: A. Crosato (ed.) Teaming up with nature and nations. Book of Abstracts NCR-Days 2013, October 3-4, Delft, The Netherlands. NCR Publication 37-2013. ISSN 1568-234X

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen and S.J.M.H. Hulscher. (2013). Modelling sediment pick-up and deposition in a dune model. Van Lancker, V. and Garlan, T. (Eds), MARID 2013. Fourth International Conference on Marine and River Dune Dynamics. Bruges, Belgium, 15-17 April 2013. Royal Belgian Institute of Natural Sciences and SHOM. VLIZ Special Publication 65 – Flanders Marine Institute (VLIZ). Oostende, Belgium. 338p. ISSN 1377-0950. ISBN 978-2-11-128352-7.

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen & S.J.M.H. Hulscher (2012). Particle step length variation along river dunes. In R.M. Munoz (Ed.), River Flow 2012: Proceedings of the International conference on fluvial hydraulics, San Jose, Costa Rica, 5-7- September 2012 (pp. 493-497). London, UK: CRC Press Taylor & Francis Group.

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen & S.J.M.H. Hulscher (2011). Modelling non-equilibrium bed load in a parameterized dune evolution model. In Shao, X., Z. Wang and G. Wang (Ed.), Proceedings of the 7th IAHR Symposium on River, Coastal and Estuarine Morphodynamics. Beijing, China: Tsinghua University Press.

Van Duin, O.J.M., J.S. Ribberink, C.M. Dohmen-Janssen & S.J.M.H. Hulscher (2010). River dune evolution and the transition to plane beds. In E. Stouthamer (Ed.), NCR-days 2010. Book of abstracts (pp. 1-2). Delft: NCR.

ABOUT THE AUTHOR

Olav Jacob Maarten van Duin was born in Delft, on the 9th of February, 1984. After living in Pijnacker for 10 years, he moved with his parents and sister Elin to Bathmen. After the final years of primary school, it was time for secondary school (gymnasium) at the Geert Groote College (later Etty Hillesum Lyceum) in Deventer. At the age of 18, a trek to Enschede was undertaken to study at the University of Twente. Here he obtained his bachelor's degree in Civil Engineering & Management in 2007, with a thesis on decision support systems in water management and the criteria related to generating models for such systems. The research was carried out at HydroLogic in Amersfoort. After that, he worked part time at HydroLogic during his further studies and obtained his master's degree in Water Engineering & Management *cum laude* in 2009, with a thesis on the analytical modelling of tidal flow in a semi-enclosed basin. This research was done as an 'internal' internship at the WEM department.

To further delve into the intricacies of water and sand, Olav started his PhD research at the University of Twente. The research project was about the sediment transport processes along river dunes and how they influence the dune morphology. This work entailed laboratory work for 4 months at the Technical University of Braunschweig, as well as work on modelling sediment and dune behaviour. During this time Olav published in various journals and conference proceedings with various co-authors. Besides research, Olav was involved in teaching Bachelor and Master students of the studies he had previously undertaken. This included supervising Bachelor and Master students during their final assignments, as well as the courses Fluid Dynamics, Mathematical Physics of Water Systems, River Dynamics and Hydraulic Engineering. Currently, Olav works at the applied research institute Deltares in Delft.

Apart from studies and work, Olav is/was involved in assorted volunteer work, a range of musical endeavours, some sports, some committees, and various other shenanigans which unfortunately don't fit on the page anymore.