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Modelling non-equilibrium bed load in a parameterized dune evolution model

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ABSTRACT: The bed of a river goes through various stages of development as the flow strength increases. 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, but for lowland rivers only the mentioned regimes are relevant. Dunes are the most common bedforms in lowland river channels consisting of sand and gravel. Dunes influence water levels significantly, because they impose roughness on the flow. In general, increasing bedform dimensions lead to increasing water levels. While there are various models that describe the interaction between flow, sediment and bed form properties well, there are few that are able to describe all the transitions from a lower-stage plane bed through an upper-stage plane bed. Also, there is a need for fast calculation of bedform evolution and the effects that they have on hydraulic roughness, in order to be useful for operational flood forecasting models (during floods bedforms develop rapidly). 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 dune evolution model of Paarlberg et al. (2009) was specifically set up to fit this goal. It is a 2DV-model with only bed load transport and assumes constant eddy-viscosity. To predict the characteristic evolution of dunes, a parameterization of the flow separation zone was implemented. The model then was able to predict dune length and height well while remaining computationally cheap.

However, this model is unable to predict a transition to an upper-stage plane bed, because there is no way for the sediment transport and shear stresses to be out of phase. Therefore another way to handle sediment transport is implemented, inspired by the model of Shimizu et al. (2009). In this paper a lag distance is introduced directly in the model of Paarlberg et al. (2009). The effects on bed morphologies and development characteristics of using this non-equilibrium transport relation versus the previous equilibrium transport relation are explored.

In general dune heights become smaller than with the original model. Flow separation is suppressed and thereby dune height. Dune lengths become (much) larger, though for small lag distances the predicted dune lenght shows an improved agreement with the measured dune length. Water depths slightly decrease. The results show the potential of this way of modelling non-equilbrium bed load to be able to predict a transition to plane bed.

In the future the model will be further refined by improving the relation between shear stress and the step-length of transported material. In this light experiments will be undertaken by the authors to better capture the processes that trigger the transition to an upper-stage plane bed. With this, the model will be validated further.

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. 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). For this research the focus is on the hydraulic roughness of the main channel, which is largely determined by the bed morphology. The bed of a river goes through various stages of development as the flow strength increases. 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, but for lowland rivers only the mentioned regimes are relevant. River dunes are the dominant bedforms in many rivers, and form in beds with sedimentsizes ranging from silt to gravel (Kostaschuck 2000; Wilbers and Ten Brinke, 2003; Best, 2005; Jerolmack and Mohrig, 2005; Kleinhans et al., 2007). The height is in the order of 10 - 30% of the water depth and their length is in the order of 10 times their heights. They migrate in downstream direction and are of asymmetrical shape with mild stoss side slopes and steep lee side slopes, often reaching the angle of repose (about 30°). For steep lee side slopes, a flow separation zone develops behind the dune. Here the flow near the bottom is reversed due to a recirculating eddy that develops in this zone. Under flood conditions the bed is highly dynamic; dunes grow and decay as a result of the changing flow conditions. River dunes increase the hydraulic roughness significantly, because their shape causes form drag. Water level forecasts during a high river water discharge therefore depend on accurate predictions of the evolution of river dune dimensions.

Due to practical reasons the main channel roughness is often used as a calibration parameter to match observed and modelled water levels. For example in models of the Rhine branches in the Netherlands (Wasantha Lal, 1995; Werner, 2004; Van den Brink et al., 2006). The hydraulic roughness is often calibrated as a constant parameter, though sometimes it is calibrated as a function of discharge. Although the latter method is an improvement over the former, it still means hysteresis effects are disregarded. This means that the calibrated roughness values are unrealistic, 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 dune evolution modelling.

In the past, many approaches have been used to model dune dimensions, varying from equilibrium dune height predictors (e.g. Yalin, 1964; Allen, 1978; Van Rijn, 1984) to different forms of stability analyses (e.g. Kennedy, 1963; Engelund, 1970; Fredsøe, 1974; Yamaguchi & Izumi, 2002). Recently, models have been developed that calculate the turbulent flow field over bedforms, in some cases in combination with morphological computations (e.g. Shimizu et al., 2001; Nelson et al., 2005; Tjerry & Fredsøe, 2005; Giri & Shimizu, 2006; Shimizu et al., 2009; Nabi et al., 2010). These models are valuable to study detailed hydrodynamic processes, but are computationally intensive. This is due to the complexity of turbulent flow, particularly in the flow separation zone behind the leeside of the dunes. Also there are few models that are able to describe all the transitions from a lower-stage plane bed through an upper-stage plane bed. For example, the model of Shimizu et al. (2009) is able to predict these transitions.

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. To that end Paarlberg et al. developed a dune evolution model in which the flow and sediment transport at the flow separation zone is modelled in a parameterized way (see Paarlberg et al., 2009; 2007). 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.

In addition, this model has been coupled with an existing hydraulic model to form a 'dynamic roughness model' (Paarlberg et al., 2010). The time-dependent dune evolution during a flood wave is explicitly taken into account for determining the roughness due to bedforms, instead of the common method of calibrating bedform roughness (as a function of discharge). 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 (Paarlberg et al., 2010). This shows that application of models like this leads to more realistic predictions.

The dune evolution model still has some drawbacks. A main drawback is that the model is unable to predict a transition to an upper-stage plane bed, because there is no way for the sediment transport and shear stresses to be out of phase. This is an important process in the transition of one bedform regime to another (Kennedy, 1963; Nakagawa & Tsujimoto, 1980; Shimizu et al., 2009). In the case of the transition to an upper stage plane bed this is explained as follows. Bed shear stress along a dune will be maximum at the crest and decrease on the leeside. If transport follows that pattern, the crest can't erode. However, if transport and shear stress are out of phase the maximum transport occurs away from the crest the crest will erode. This is because more transport occurs after than before the crest.

Therefore another way to handle sediment transport is implemented, inspired by the model of Shimizu et al. (2009). This model uses the pick-up and deposition formulation of Nakagawa & Tsujimoto (1980). The pick-up is determined from local bed shear stress. The sediment is deposited from the pick-up point with a conceptually derived function, which uses a mean step length, exponentially decreasing with distance. By handling the transport like this a lag distance between shear stress and sediment transport is introduced. In this paper this lag distance is introduced directly in the model of Paarlberg et al. (2007, 2009). The effects on bed morphologies and development characteristics of using this non-equilibrium transport relation versus the previous equilibrium transport relation will be explored.

2 NON-EQUILIBRIUM BED LOAD TRANSPORT

Assuming that equilibrium between shear stress and transport is present, the formula devised by Meyer-Peter and Müller (1948) can be directly applied. As Nakagawa & Tsujimoto (1980) argue, a lag distance between flow properties (and thereby bed shear stress) and sediment transport is the principal cause of bed instability. They further identify two sources of this lag distance. The first is the spatial distribution of bed shear stress, which is handled in the Paarlberg et al. (2009) model by applying the transport formula to the *local* bed shear stress. The second is the probability distribution of sediment particle step length, which is the distance travelled from dislodgement to rest according to Einstein (1950). This effect is not taken into account in the original model. Francis (1973), Fernandez Luque & Van Beek (1976) and Sekine & Kikkawa (1984) have done experiments to determine the dependence of particle step length on various parameters under flat bed conditions. The latter authors have used this data to make a numerical model of saltation of particles (Sekine & Kikkawa, 1992). All computed values are no more than two times larger or smaller than the observed values. Their model shows that the mean step length can vary between near zero and about 350 times the particle diameter, mostly dependent on friction velocity (positively) and settling velocity (negatively). The data shows a range of approximately 40 to 240 times the particle diameter.

In this paper a range of *constant* mean step lengths and their effect on the model results will be examined. This means that the effect of flow properties (friction and settling velocity, et cetera) are not taken into account yet, but it does enable us to investigate the effect of this lag distance under dune conditions. It must also be noted that there is no experimental work on step lengths under dune conditions. It is likely that observations of step lengths for dunes will differ from existing observations (generally done for flat beds) as the effects of the upwards slope, avalanching at the crest and (possible) flow separation after the crest must have influence on the distribution of step length. This is another reason to first try a simpler approach. In the future experiments will be done to get a better idea of step length distribution under dune conditions.

3 MODEL SET-UP

3.1 *General set-up*

The basis of the present model is the dune evolution model developed by Paarlberg et al. (2009), which is based on the numerical model of Hulscher (1996). To predict the time evolution of offshore sand waves, different versions of the Hulscher (1996) model have been developed (Van den Berg and Van Damme, 2005; Németh et al., 2006; 2007, Van den Berg, 2007). Paarlberg et al. (2009) extended the process-based morphodynamic sand wave model of Németh et al. (2006) with a parameterization of flow separation, to enable simulation of finite amplitude river dune evolution.

Flow separation is forced in the model when the leeside slope exceeds 10°. The form of the flow separation zone (see Figure 1) behind the dune and the effect it has on flow, bed shear stress distribution and the sediment transport is included in a parameterized way using experimental data of turbulent flow over two-dimensional subaqueous bedforms (Paarlberg et al. 2007). In the flow separation zone the bed shear stress is assumed to be zero and all the sand transport that reaches the crest of the dune is avalanched under the angle of repose on the leeside of the dune (Paarlberg et al., 2009). This enables the model to predict river dunes with their characteristic shape and realistic dimensions without resolving the complex recirculating flow in the flow separation zone and remaining computationally cheap.

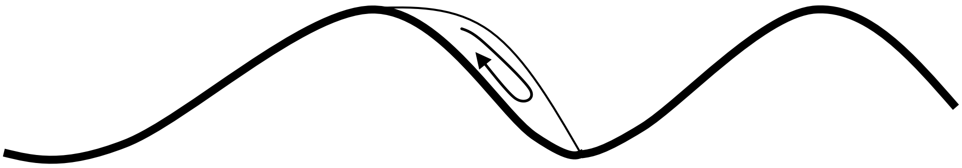

Figure 1 Schematization of the flow separation zone (flow from left to right)

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. From a numerical stability analysis during simulation the length of the fastest growing disturbance is determined and taken as the domain and (implicitly) dune length.

3.2 *Flow model*

In general the flow is forced by the difference in water level across the domain. Though 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 but 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.

3.2.1 *Governing equations*

The flow in the model of Paarlberg et al. (2009) is described by the two-dimensional shallow water equations in a vertical plane (2-DV), assuming hydrostatic pressure conditions. Using a scaling analysis on 2-DV Navier-Stokes equations, Paarlberg et al. (2008) show that for small Froude numbers 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 (1) and (2).

$$u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-g\frac{\partial \varsigma}{\partial x}+A_v\frac{\partial^2 u}{\partial z^2}+gi \qquad (1)$$

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \qquad (2)$$

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, and g and A_v denote the acceleration due to gravity and the vertical eddy viscosity respectively.

3.2.2 *Boundary conditions*

The boundary conditions are defined at the water surface (z=h) and at the bed ($z=z_b$). The boundary conditions at the water surface are (3) no flow through the surface and (4) no shear stress at the surface. The kinematic boundary condition at the bed is (5) that there is no flow through the bed.

$$\left.\frac{\partial u}{\partial z}\right|_{z=h} = 0 \tag{3}$$

$$u\left.\frac{\partial \zeta}{\partial x}\right|_{z=h} = w \tag{4}$$

$$u\left.\frac{\partial z_b}{\partial x}\right|_{z=z_b} = w \tag{5}$$

As basic turbulence closure, a time- and depth-independent eddy viscosity is assumed, leading to a parabolic velocity profile. In order to represent the bed shear stress correctly for a constant eddy viscosity, a partial slip condition at the bed (6) is necessary.

$$\tau_b = A_v \left.\frac{\partial u}{\partial z}\right|_{z=z_b} = Su_b \tag{6}$$

In this equation τ_b ($m^{2/}s^2$) is the volumetric bed shear stress 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), Van den Berg and Van Damme (2005), and Van den Berg (2007).

3.2.3 *Equilibrium transport model*

In the original dune evolution model only bed load transport is taken into account. The equilibrium bed load transport is calculated by applying the formula of Meyer-Peter and Müller (1948) including gravitational bed slope effects. Below this formula is given in dimensional form (as volumetric bed load transport per unit width, m^2/s):

$$q_{b;e} = \begin{cases} \beta\left(\tau_b(x) - \tau_c(x)\right)^n \left(1 + \eta \frac{\partial z_b}{\partial x}\right)^{-1} & \text{if} \quad \tau > \tau_c \\ 0 & \text{if} \quad \tau \le \tau_c \end{cases} \tag{7}$$

where $\tau_c(x)$ is the local critical (volumetric) bed shear stress (m^2/s^2), n=3/2 and $\eta=\tan(\varphi)^{-1}$ with the angle of repose $\varphi=30°$. The proportionality constant β (s^2/m) describes how efficiently the sand particles are transported by the bed shear stress (Van Rijn, 1993) and its value can be estimated with

$$\beta = \frac{m}{\Delta g} \tag{8}$$

where $\Delta=\rho_s/\rho-1=1.65$ (ρ_s/ρ is the specific grain density), and m is an empirical coefficient which is set to 4 by Paarlberg et al. (2009) based on analysis done by Wong and Parker (2006). The local, critical bed shear stress $\tau_c(x)$, corrected for bed slope effects, is given by the following equation:

$$\tau_c(x) = \tau_{c0} \frac{1 + \frac{\partial z_b}{\partial x}}{\sqrt{1 + \left(\frac{\partial z_b}{\partial x}\right)^2}} \tag{9}$$

with τ_{c0} the critical bed shear stress for flat bed, defined by equation (10). In this equation θ_{c0} is the critical Shields parameter and D_{50} is the median grain size.

$$\tau_{c0} = \theta_{c0} g \Delta D_{50} \tag{10}$$

3.2.4 *Spatial lag in transport*

Here the model differs from the model presented by Paarlberg et al. (2009). In addition to calculating the equilibrium transport and taking that as the actual transport, the following relation is applied:

$$\frac{dq_b}{dx}=\frac{q_{b;e}-q_b}{\Lambda} \tag{11}$$

where q_b is the actual sediment transport and Λ is the mean step length. This is determined by:

$$\Lambda=\alpha D_{50} \tag{12}$$

where α is a constant determining the mean step length (see introduction). It should be noted that equation 11 needs a boundary condition (at x=0) whereas only a periodic boundary condition is defined. Therefore a value is guessed for x=0 and the rest of the values are determined using equation 11 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 a new guess is made. This process is repeated until a satisfactory result is found (i.e. when the periodic boundary condition is met).

3.2.5 *Bed evolution*

The bed evolution is modelled using the Exner equation given by (13), where the sediment transport rate is calculated from equation (11) and ε_p=0.4 is the bed porosity.

$$\left(1-\varepsilon_p\right)\frac{\partial z_b}{\partial t}=-\frac{\partial q_b}{\partial x} \tag{13}$$

It should be noted that in the case of flow separation this equation is only applied outside the flow separation zone. In the separation zone the bed transport at the crest of the dune is deposited on the leeside of the slope under the angle of repose (i.e. avalanched). So, an integral form of equation (13) is used for the lee slope of the dune.

4 RESULTS

For the reference case one of the experiments carried out by Venditti et al. (2005) is taken. The measured parameters can be found in the table below.

Table 1 Measured parameters of Venditti Flow A (Venditti et al, 2005)

Name	Venditti Flow A
α [-]	N/A
h_i [m]	0.152
i [10^{-4}]	12
q [m^2/s]	0.077
D_{50} [mm]	0.5
l_e [m]	1.3172
Δ_e [m]	0.048
h_e [m]	0.17
$\theta_{c;0}$ [-]	0.050

New parameters in this table are h_i (initial water depth), q (discharge per unit width), l_e (equilibrium dune length), Δ_e (equilibrium dune height) and h_e (equilibrium water depth).

4.1 *Varying mean step length*

First the effect of mean step length on the model results is studied. In the table below these results can be found, with the first result being the results with zero phase lag from the model as presented in Paarlberg et al. (2009). The step length is varied between 25 and 300 times the median grain size. The lower range is chosen as such that the mean step length Λ is always larger than the horizontal spatial step Δx. The domain is divided in 120 horizontal and 25 vertical points. Making the horizontal resolution even finer (up until 1200 horizontal points) did not change the outcomes.

Table 2 Model results for varying mean step length

α [-]	Δ_e [m]	l_e [m]	h_e [m]	u_{avg} [m/s]	Λ [cm]	Δx [cm]
N/A	0.049	1.04	0.179	0.43	N/A	0.87
25	0.032	1.43	0.160	0.48	1.25	1.19
50	0.034	1.80	0.161	0.48	2.50	1.50
75	0.037	2.14	0.162	0.48	3.75	1.79
100	0.039	2.49	0.163	0.47	5.00	2.07
150	0.042	3.09	0.164	0.47	7.50	2.58
200	0.046	3.74	0.164	0.47	10.0	3.12
250	0.031	3.06	0.159	0.49	12.5	2.55
300	0.018	3.06	0.155	0.50	15.0	2.55

The new parameter in this table is the average velocity u_{avg} (m/s). From the table it can be seen that the original model comes very close to the values found in the experiment of Venditti et al. (2005), see table 1. The equilibrium dune height and water depth are very close and though the dune length differs about 30% it is still a reasonable result. To get an idea of the dune evolution, in the figure below the evolving bed morphology without a phase lag (left) and with a lag distance (α=25; right) can be seen. The figure clearly shows a different resulting dune morphology. The dunes without a lag distance have a characteristic shape with a slope at the angle of repose, due to flow separation. Flow separation was interrupted for the simulation with a lag distance (this is explained later), so the dunes remain more sinusoidal. Also, without a lag distance the dunes seem to evolve and grow faster, which can also be attributed to the presence of flow separation (after a certain while).

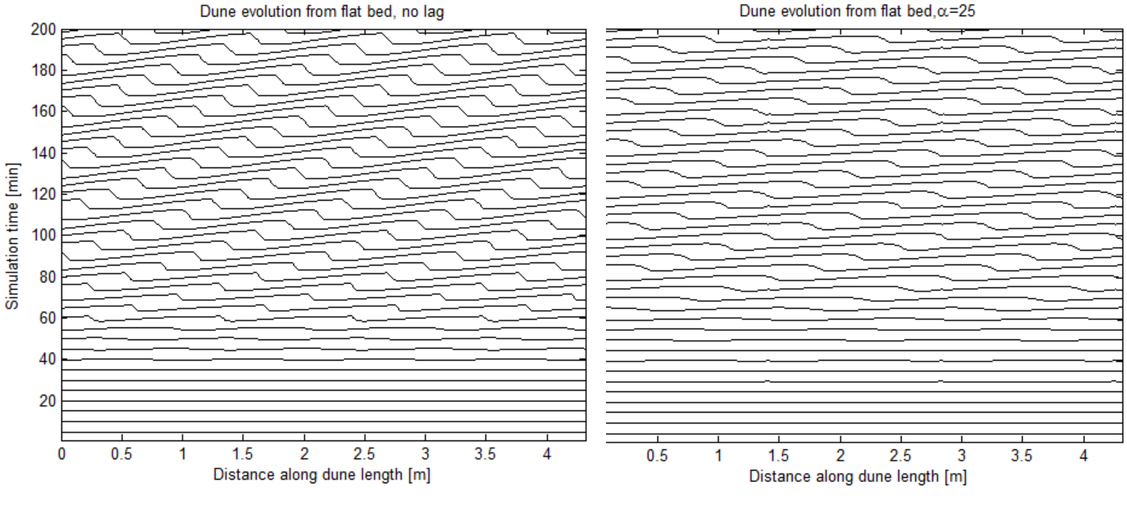

Figure 2 Dune evolution without (left) and with lag distance (α=25; right)

For the runs with a lag distance the dune heights are of the same order of magnitude as the experimental result but all smaller. This shows that the lag distance has a suppressing influence on the dune height. This is probably caused because flow separation is suppressed. The model results show that the dune becomes steep enough for flow separation (i.e. the leeside slope exceeds 10°), but this is always quickly countered by the effects of spatial lag. Flow separation plays an important role in dune evolution; it enables the dune to become higher than without flow separation (Nelson et al., 1995; Sumer et al., 2003). Because the original model would have no transport in the flow separation zone and the transport at the crest would be avalanched, the dune could not flatten. Now due to the spatial lag sediment does deposit in the flow separation zone, enabling the dune to flatten. The separation criterion is then no longer met and flow separation ceases. This process can also be observed by combining equation 11 and 13.

$$\left(1-\varepsilon_p\right)\frac{\partial z_b}{\partial t} = -\frac{q_{b;e}-q_b}{\Lambda} \tag{14}$$

In the flow separation zone the equilibrium transport is zero (because the bed shear stress is set to zero). This means that the bottom change (left hand side of equation 14) is directly determined by the bed transport divided by the lag distance. When this transport is high enough the rise of the bed in the flow separation zone will flatten out the dune, lowering the angle of the leeside. The relation between α and dune height is however not very straightforward. First dune height increases with increasing α, but for values of α greater than 200 it starts decreasing again.

For the lowest value of α, the resulting dune length (1.4 m) is closer to the experimental result (1.3 m) than the original result (1.0 m). But, for increasing α, the dune length becomes larger and larger, reaching its maximum at α=200 (3.7 m, almost 3 times too high) and then becoming smaller again. The dune length is a direct result of the stability analysis carried out to determine the fastest growing wavelength. The overestimation of dune length for greater lag distances will have to be explored further. But, conceptually it is promising that the introduction of a small lag distance (step length) in the sediment transport leads to an improved prediction of the dune length.

Water depths are of the same order of magnitude as the original result and the experimental result. The difference is about 10% at worst, but the calculated depths are always lower than the original calculation without phase lag and the experimental results. This is probably because due to smaller dune heights and the absence of flow separation less roughness is imposed, velocities can become higher (see also the average velocity results) and therefore water depths can become lower for the same discharge (note that the water level difference over the domain forces the flow, discharge is checked afterwards; see 3.2).

4.2 *Varying discharge*

The discharge has been varied as well, but then with a constant value of the mean step length α=100. This was done to see if the effect of lag distance itself is enough to suppress dune growth with increasing stream power. In reality it is expected that for large discharges dune heights will actually become smaller again. The results can be seen in the table below (the Shields parameter is calculated roughly with $\theta = h_s * i / (\Delta * D_{50})$).

Table 3 Model results for varying discharge with α=100

q [m^2/s]	Δ_e [m]	l_e [m]	h_e [m]	θ [-]
0.03	0.018	1.953	0.085	0.12
0.09	0.045	2.599	0.181	0.26
0.15	0.060	3.055	0.254	0.37
0.21	0.073	3.435	0.317	0.46
0.27	0.085	3.777	0.375	0.54
0.33	0.097	4.119	0.427	0.62
0.5	0.126	4.917	0.563	0.82
1.1	0.193	7.235	0.948	1.38
1.7	0.268	9.135	1.265	1.84

As expected, dune height, dune length and water depth increase for increasing discharge. However at some point (Shields parameter larger than about 1.1; Engelund, 1967) it is expected that the heights will decrease again and this does not occur. This means that by itself the lag distance cannot trigger a transition to a plane bed in this model. In fact, as can be seen in the graph below there is even no evidence that the dune heights will decrease for an even higher Shields value.

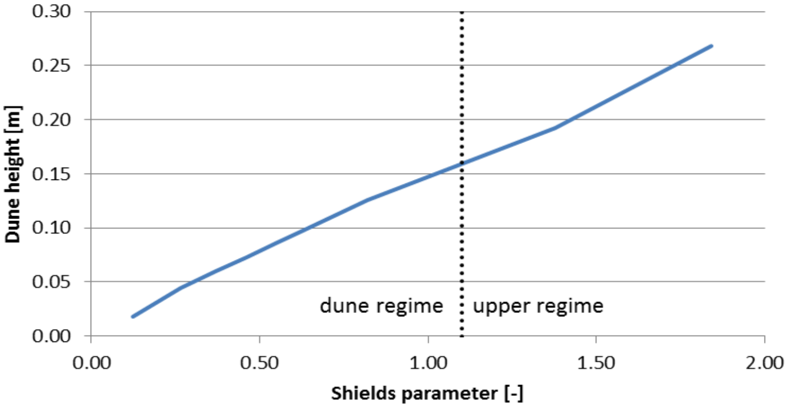

Figure 3 Dune height as a function of Shields parameter with $\alpha=100$

5 CONCLUSIONS

This paper has explored the potential of using a non-equilibrium bed load formulation in a model for predicting dune evolution in a computationally cheap way. The introduction of spatial lag shows that all dune heights are close to the original result but smaller than before (regardless of the spatial lag distance) due to the suppression of flow separation. Though lag distances are small compared to the dune length, it has significant effect. This is because spatial lag changes the dynamics of the flow separation zone and the dune leeside the most, and lag distances are significantly large compared to the length of the dune leeside. The effect spatial lag has on dune heights is not straightforward, as dune height does increase for increasing spatial lag distance, but decreases again for the larger distances. For the case under review the prediction of dune length is better than before with a small spatial lag, but for larger lags it greatly differs. Water depths become somewhat smaller, but within a reasonable range. Increasing discharge with a constant lag distance does not lead to a suppression of dune height, so that by itself is not enough to trigger a transition to plane bed.

It is expected that if the step length is made a function of the friction velocity and therefore varies for increasing discharge, varies during a model run and along the dune, the model results may become more precise and a transition to plane bed may become possible. For example, for increasing discharge, friction velocities will increase. If α then also increases it will first lead to higher dune heights, but at a certain point they will drop again. This would follow the pattern of expected dune evolution: at a certain high discharge dunes will flatten and disappear again. Also, if the step length can vary along a dune it will likely become highest at the crest (as velocities become highest there). This means that the leeside slope will become less steep due to the sediment spreading out over a larger distance. Flow separation will then be suppressed and the dune can break up again.

6 FUTURE WORK

The model will be further refined by improving the relation between bed shear stress and the step-length of transported material. This will probably entail the implementation of a full pick-up and deposition model (e.g. Nakagawa & Tsujimoto, 1980) as done by Shimizu et al. (2009). For this more information is needed on how (mean) step length varies along the dune. In this light experiments will be undertaken by the authors to better capture the processes that trigger the transition to an upper-stage plane bed. With this the model will be validated further.

7 ACKNOWLEDGEMENTS

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