River dune predictions: Comparison between a parameterized dune model and a cellular automaton dune model

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Introduction

River dunes are of great importance for the determination of water levels, especially during flood events. They have a large influence on the hydraulic roughness and thereby on water levels. In addition, dune formation could affect the navigability of rivers and propagation of dunes could uncover pipelines or other constructions beneath the river bed. That is why many have tried and are still trying to model dimensions and propagation of dunes under various conditions (e.g. Van Rijn, 1984; Nabi et al., 2013).

Because fast calculations are essential during an upcoming flood event, there is a need for fast model predictions. The focus of this research is on a parameterized dune model (Paarlberg et al., 2009) and the cellular automaton dune model (CA model) HR Wallingford is experimenting with (Knaapen et al., 2013). Both models are relatively fast in their calculations they do however, have a fundamentally different approach to predict river dunes. This research reveals the performance of these two models tested under various conditions.

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

Adjusting the CA model

The initial CA model is based on stochastic rules; there is no link between sediment transport and flow characteristics within the model. Therefore we adapted the CA model before comparing it with the parameterized dune model. We added a length scale by linking the model parameters to a distance instead of a number of cells and assuming a fixed domain. In this way parameters and the domain itself are defined in meters and no longer in number of cells. The moved sediment within the model is determined by counting the number of slabs and the distance travelled. The amount of moved sediment is used to add a time scale to the model by relating it to the sediment transport according to Meyer-Peter and Müller (1948). Additionally we linked model parameters of the CA model to the characteristics of the experimental data. We used the formula of Cheng and Chiew (1998) to relate flow characteristics with the pickup probability of the CA model (Eq. 1).

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

where P is the pickup probability, θ is the shields parameter and C_L denotes a constant that is assumed to be 0.25. Sekine and Kikkawa (1992) proposed a relation between the shear and settling velocity and the step length of saltating grains. We used their formula to relate flow characteristics with the step length of the CA model (Eq. 2).

$$\lambda = \alpha_2\left(\frac{u_*}{v_S}\right)^{\frac{3}{2}} * \left[1 - \frac{\left(\frac{u_{*C}}{v_S}\right)}{\left(\frac{u_*}{v_S}\right)}\right] \quad (2)$$

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

$$\lambda = \frac{\Lambda}{D} \quad (3)$$

where Λ is the step length in [m] and D the grain size in [m]. The adjustments led to new input parameters for the model; these are the step length, pickup probability, shadow distance and sediment transport.

Comparison of the model performances

We tested the performance of the parameterized dune model and the CA model using sixteen flume experiments to determine their predictive value for prediction of dune dimensions and migration rates. Both models show problems for predicting migration rates. The parameterized dune model overestimates the observed migration rates about three times, while predictions of the CA model are about three times smaller than the observed migration rates in general. Results of predicted dune heights are presented in Fig. 2. On average, predictions of dune dimensions are lower than observed for both models. With a root-mean-square error of the dune height and length of 0.036 m and 0.82 m for the CA model against 0.044 m and 0.77 m for the parameterized dune model predictions are comparable.

A part of the midsection of the CA model is plotted against the predicted dune profile of the parameterized dune model for one of the experiments. Results are presented in Fig. 1 to show the differences in dune profiles. The skew shape of the dune profile predicted by the parameterized dune model is not clearly represented in the profile of the CA model. Runs with longer simulation times have shown that the predicted dune shape in the CA model becomes more asymmetric like the dunes predicted by the parameterized dune model. This indicates that longer run times are required to simulate equilibrium dunes as predicted by the parameterized dune model and observed in the field.

Conclusions and recommendations

In this study a non-dimensional CA model is made dimensional. The CA model is tested for the first time in the way as presented here, by adding time and length scales to the model.

There is no other research to compare results with. Results seem promising and show predictions that are reasonable; however in general the predictions are slightly underestimated.

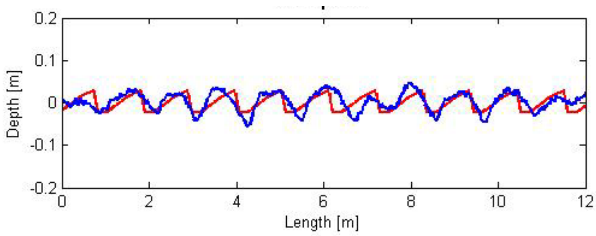

Figure 1. Predicted dune profiles. Red line represents the parameterized dune model, blue line the CA model, flow direction from left to right.

The model has potential and recommended improvements are:

- Linking the shear velocity to flow characteristics to improve the relation of the CA model with the flow characteristics.
- Adding an equilibrium state, to overcome the infinite growth and merging of dunes until a single dune covers the domain.

References

Cheng, N.-S., and Y.-M. Chiew (1998). Pickup probability for sediment entrainment. J. Hydraul. Eng., 124, pp. 232-235.

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

Meyer-Peter, E., and R. Müller (1948). Formulas for bed-load transport. Proceedings of the 2nd meeting of the Int. Assoc. for Hydraul. Res., Stockholm.

Nabi, M., H.J. Vriend, E. Mosselman, C.J. Sloff, and Y. Shimizu (2013). Detailed simulation of morphodynamics: 3. Ripples and dunes. Water Resour. Res., 49.

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. J. Geophys. Res., 114.

Sekine, M. and H. Kikkawa (1992). Mechanics of saltating grains. II. J. Hydraul. Eng., 118, pp. 536-558.

Van Rijn, L.C. (1984). Sediment transport part III: Bedforms and alluvial roughness. J. Hydraul. Eng., ASCE, 110(12), pp. 1733-1754.

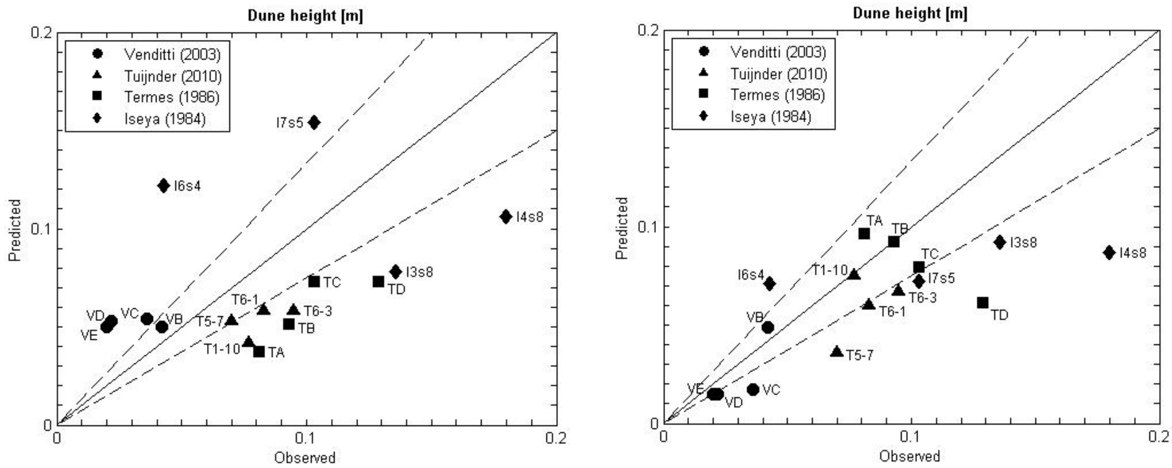

Figure 2. Observed dune heights versus predicted values parameterized dune model (left) and CA model (right).