Evolution of bed form height and length during a discharge wave

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Abstract

This research focusses on modeling the evolution of bed form during a discharge wave for application in operational flood forecasting. The objective of this research was to analyze and predict the bed form evolution during a discharge wave in a flume experiment. We analyzed the data of a flume experiment and show that dune length is determined by development of secondary bed forms during the receding limb of the discharge wave. Secondly, three models were compared to predict the bed form evolution: an equilibrium model, a time-lag model and the physically-based, numerical model of Paarlberg et al. (2010). We show some preliminary results and show that the numerical model seems promising for modeling bed form evolution for operational flood forecasting.

1. INTRODUCTION

Accurate forecasts of flood levels are essential for flood management. While a lot of improvements have been made in the field of hydraulic modeling, the roughness values of the main channel and floodplains are still largely uncertain (Warmink et al., 2007, 2012a). This research focusses on the roughness of the main channel, which is mainly determined by the bed forms that develop on the river bed.

Rivers dunes are the dominant bed forms in many rivers. The height is in the order of 10 - 30% of the water depth and their length in the order of 10 times their heights. Under flood conditions the bed is highly dynamic; dunes grow and decay as a result of the changing flow conditions.

River bed forms act as roughness to the flow, thereby significantly influencing the water levels. Accurate and fast computer models are required to predict daily water level forecasts for operational flood management and forecasting. It is essential to predict the time evolution of bed forms and assess their influence on the hydraulic roughness.

Observations in flumes and in the field have shown that dunes of different lengths and amplitude co-exist (Carling et al., 2000; Warmink et al. 2012b). Carling et al. (2000) described the morphodynamics of bed forms in the river Rhine under supply limited conditions. They distinguished three scales of bed forms, ripples, small dunes (length < 5 m) and large dunes (length > 10 m) and show that the latter two strongly interact.

Recently, several successful attempts were made to model bed form evolution and associated roughness using detailed numerical modeling (e.g. Giri and Shimizu, 2006, Nabi, 2010). However, these models require long computational times and are therefore not applicable for operational flood management.

Paarlberg et al. (2009, 2010) developed a process-based model for bed form evolution that requires limited computational effort. This model accounts for flow separation and is able to predict bed form development towards equilibrium conditions.

The objective of this research was to analyze and predict the bed form evolution during a discharge wave. Firstly, the data of a flume experiment were

analyzed to determine the most important processes in dune evolution during a discharge wave. Secondly, three models were compared to predict the bed form evolution: an equilibrium model, a time-lag model and the physically-based, numerical model of Paarlberg et al. (2010).

2. OBSERVATIONS FROM DATA

Many flume experiments are available that show the height of bed forms under different discharge conditions (e.g. Guy et al. 1966, Wijbenga and Van Nes 1986, Venditti 2005). However, most of these measurements were carried out for a constant flow discharge. These data do not show the hysteresis effect. We used the flume data from Wijbenga and Van Nes (1986) who imposed a discharge wave in the flume (scaled to observed discharge waves in the Dutch river Rhine) and measured the bed form evolution and associated flow characteristics. The discharge ranged between 0.03 and 0.15 m^3/s resulting in water depths, h ranging between 0.15 and 0.47 m. The width of the

flume was 0.5 m and the measuring section was 30 m long. Bed material consisted of uniform sand with D50 = 0.78 mm.

Figure 1 shows the observed and predicted dune heights, Δ (m) and lengths, Λ (m). The predicted dune dimensions are computed using Coleman et al. (2005) see section 3 and the equilibrium predictors of Yalin (1964) where h is water depth (m):

$$\Delta = 0.33\,h \qquad\qquad (1)$$
$$\Lambda = 6\,h \qquad\qquad (2)$$

The dune dimensions predicted by Yalin indicate the variation in water depth. The observed dune height shows a small time-lag and is clearly lower than the equilibrium dune height (predicted using eq (1)). This time-lag and attenuation of the dune height is commonly observed under a discharge wave in the field.

The observed dune length shows a similar trend, with a time-lag and attenuation compared to predicted equilibrium dune length. However, the time-lag and attenuation are larger for dune length than for dune height. This shows that dune length has a much longer adaptation time than dune height.
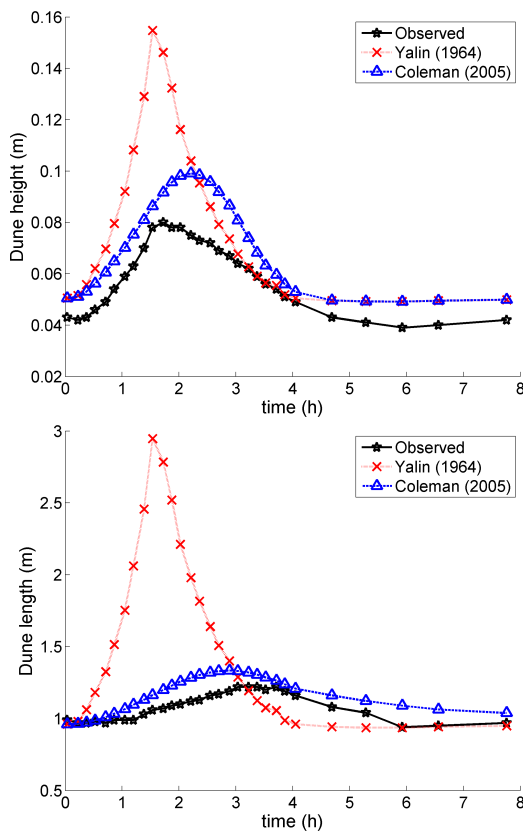
Figure 2 shows the detailed bed profiles measured by Wijbenga and Van Nes (1986) during the discharge wave. The vertical axis shows the normalized time for Twave=3.5h. The right panel shows the normalized discharge, Q, dune height, Δ and dune length, Λ. The left panel shows the corresponding bed profiles at different times during the discharge wave. Initially, at t/Twave=0, a flat bed with small bed forms is visible. As discharge increases dunes grow both in height and length. At t/Twave≈0.5, the bed pattern consists of regular large dunes. Few, small secondary dunes are visible in the bed profiles on top of the primary dunes. In due time, these regular bed forms become longer and lower. After t/Twave=1.24, the regular dunes becomes more irregular and individual dunes are difficult to distinguish. At t/Twave=2, the bed profile is similar to the initial bed profile.

Figures 2 and 3 show that initially, dune length is relatively small and as discharge increases, both the dune height and length grow. However, dune height grows faster than dune length. Just after the peak of the discharge wave, dune height is at its

Figure 1. Observed and predicted dune height (top) and length (bottom) from Wijbenga and Van Nes

maximum, while dune length is still growing. At a certain point during the receding limb of the discharge wave, secondary dunes start to develop on top of the primary dunes. At this point, the primary dunes decrease in height, while the secondary dunes grow in height. At the same time, both the primary and secondary dunes grow in length. However, because the secondary dunes grow, they erode the underlying primary dune, leading to reduction of the average dune length as shown in the right panel of figure 2. Figure 3 also shows that at T/t=0.06 many short dunes exist. The small ones grow in length (t/T=0.5) and at t/T>=1.25 both long and short dunes co-exist. This implies that the secondary dunes become dominant and 'took over' the primary dunes. This process is reflected in the observed dune length and essential for describing dune evolution during a discharge wave.

3. TIME-LAG APPROACH

As a first attempt to predict dune evolution under a discharge wave, we used the time-lag method following Coleman et al. (2005). Coleman et al. (2005) adopted the commons scaling relationship for sand-wave development from an initially flat bed from Nikora & Hicks (1997):

$$\frac{P}{P_e} = \left(\frac{t}{t_e}\right)^{\gamma} \quad \text{(for } 0.01 < \frac{t}{t_e} < 1 \text{)} \tag{3}$$

where P is the average value of dune length or height, P_e is the equilibrium value (using Yalin, 1964; eq. (2)), t is time, t_e is the time to achive P_e, and γ is a growth rate parameter. Coleman et al. (2005) derived a relation for γ, based on many flume experiment with a discharge step. They showed that growth rate was different for dune height and dune length and only depended on sediment size, D:

$$\gamma_H = 0.22 D_*^{0.22} \approx 0.37 \tag{4}$$

$$\gamma_L = 0.14 D_*^{0.33} \approx 0.32 \tag{5}$$

with

$$D_* = D_{50} / \left(g(s-1)/\upsilon^2\right)^{1/3} \tag{6}$$

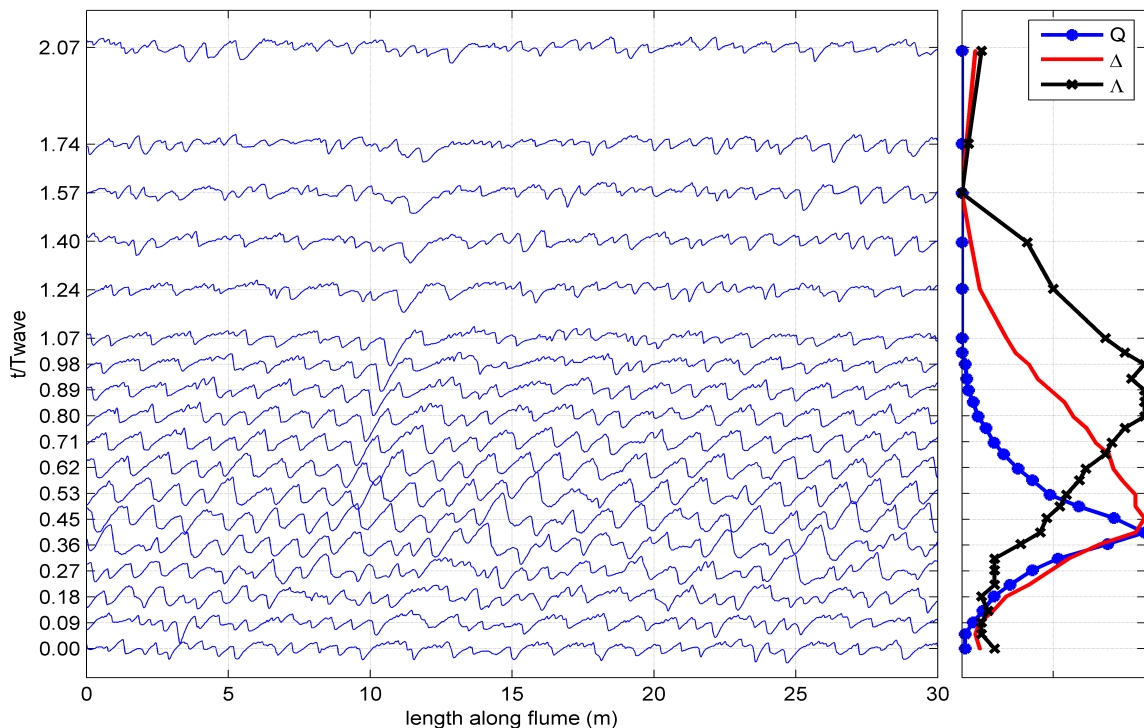Using this approach for the data from Wijbenga & Van Nes (1986) yielded γ_H=0.42 and γ_L = 0.37.

Figure 2. Left: measured bed profiles from test 5 of Wijbenga and Van Nes (1986). Right: corresponding discharge (Q), dune height (Δ) and dune length (Λ) at the same time during the discharge wave (t/Twave). The black solid lines connect individual dune troughs

Coleman et al. (2005) used their data to derive for dunes (7):

$$t_e\left[\frac{u_*}{D_{50}}\right] = 2.05 \cdot 10^{-2}\left[\left(\frac{D_{50}}{h}\right)^{-3.5}\right]\left[\left(\frac{\theta}{\theta_{cr}}\right)^{-1.12}\right]$$

Coleman et al. (2005) assumed that the times to equilibrium are equal for dune height and dune length, based on flume experiments with a sudden step in discharge that show that after a certain period of time (after a perturbation in the flow) dunes reach their equilibrium. However, observed dune heights during a flood wave from Wijbenga and Van Nes (1986) show that the maximum dune height is reached long before the maximum dune length is reached (Warmink et al. 2012b; Figure 2). Calibration showed that for dune height, the t_e values need to adapted with a factor 0.01 to yield realistic dune heights for the Wijbenga and Van Nes (1986) data. Figure 1 shows the predicted dune height (a) and length (b) using this time-lag approach. The times to equilibrium from equation (7) ranged between 250,000 to 27,000,000 seconds, which is 3 to 320 days. These values seem unrealistic, but resulted in a reasonably good fit to the observed dune dimensions.

Calibration of t_e for dune height was required, which is not feasible and limits the practical applicability for flood forecasting. Furthermore, the process of overtaking of the primary dunes by

the secondary dunes is not taken into account.

4. NUMERICAL MODELING

We used the model developed by Paarlberg et al. (2009, 2010) to reproduce the observed dune evolution of Wijbenga & Van Nes (1986). The Paarlberg et al. (2009) model consists of a flow module, a sediment transport module and a bed evolution module. Flow and bed morphology are solved in a decoupled manner. The flow is described by the two-dimensional shallow water equations in a vertical plane (2-DV), assuming hydrostatic pressure conditions. The model applies a parameterization of the flow separation zone. In the region of flow separation, the separation streamline forms an artificial bed (Paarlberg et al. 2009), which enables the computation of the hydrostatic flow over the dunes. Paarlberg et al. (2009) used the model with a domain length equal to the wave length of the fastest growing mode as determined by a stability analysis (see Paarlberg et al. 2009). This wave length and thereby the domain length changes during the model run, as the flow depth adjusts to the evolving dune. Effectively, the Paarlberg et al. (2009) model computes the lag-time and associated attenuation of the dune height, based on an imposed discharge and equilibrium dune length. We used the dune length predicted by Yalin (eq. 2) as input for the
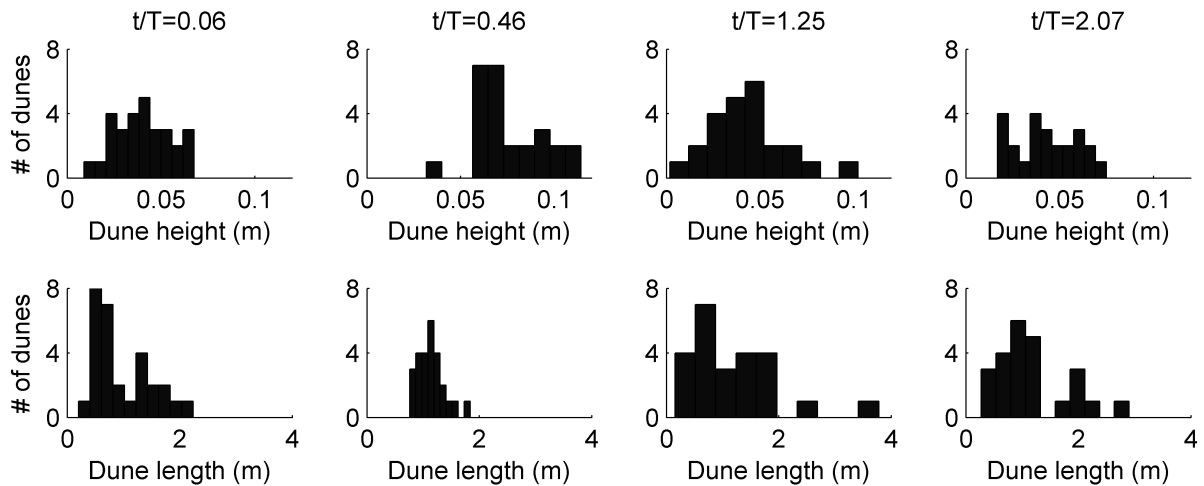

Figure 3. Histograms of dune height and length of profiles in Figure 2, for four times during the discharge wave. The total number of dunes in the flume was 29, 26, 24, 24, respectively. At the peak of the discharge wave (t/T=0.46), dune height is at its maximum, while dune length keeps growing after the peak. The variation in dune length, indicating the amount of secondary bed forms is smallest during the peak.

model instead of the stability analysis, which yielded similar results, but reduces computational time.

For the computation of the discharge wave, the Paarlberg et al. (2009) model was coupled with a 1D hydrodynamic model, Sobek, based on a schematization of the flume. This coupled model is referred to as SobekDune (Paarlberg et al. 2012). Dune dimensions were calculated with the dune evolution model of Paarlberg et al. (2009), using the reach-averaged channel slope, the average water depth in the main channel (as computed by Sobek) and the bed material as inputs (Paarlberg and Schielen, 2012). The model was calibrated by adapting the partial slip model to match the observed discharge. The calibration parameters $\beta 1$ and $\beta 2$ were adapted using flow A as reported by Venditti et al. (2005) following Paarlberg et al. (2009).

The dune roughness coefficient of the main channel is specified as a Nikuradse roughness height. This roughness height is translated into a Chézy coefficient for use in Sobek using White-Colebrook. Following Van Rijn (1984), the roughness height of the bed can be found from a summation of a contribution due to grains (k_grains) and due to dunes (k_dunes). Following Paarlberg and Schielen (2012), we adopted the roughness predictor of Van Rijn (1984) for the relation between computed dune dimensions and bed roughness:

$$k_{dunes} = 1.1\Delta\left(1 - \exp\left(\frac{-25\Delta}{\Lambda}\right)\right) \qquad (8)$$

where Δ is dune height (m) and Λ is dune length (m). The dune length for computing the roughness was derived using Coleman et al. (2005).

Figure 4 shows the results of the SobekDune model compared to the dune dimensions that were observed and predicted by the Yalin (eq. 1-2) and Coleman (eq 3-7) models. The left frame of Figure 4, shows that the model is capable of reproducing the time-lag in the dune height. Also, the dune height is attenuated compared to the equilibrium dune height predicted by the Yalin model, However, SobekDune overestimates the dune height. This might be caused by erroneous values of the partial slip model coefficients, which were not recalibrated for the Wijbenga and Van Nes (1986) data. In further research, the model will be recalibrated. Adaptation of these parameters will result in a decrease of the flow velocity and therefore a decrease in the sediment transport and dune height.

The dune height predicted using the Coleman et al. (2005) model shows a better fit to the observed dune height. However, it should be noted that this model it is not physically based and therefore has less predictive capacity.

5. ROUGHNESS IMPLICATIONS

The right frame of Figure 4 shows the roughness evolution during the discharge wave in the flume, based on the dune dimensions of the three models of Yalin, Coleman and SobekDune. The observed roughness is based on measured water level slope during the flume experiment. The roughness due to the three models is computed using eq. (8) with the predicted dune dimensions as input.

The roughness based on the dune dimensions from the equilibrium model of Yalin does not show a time-lag. Furthermore, the roughness is slightly underpredicted due to an overprediction of the dune length. The roughness based on the dune
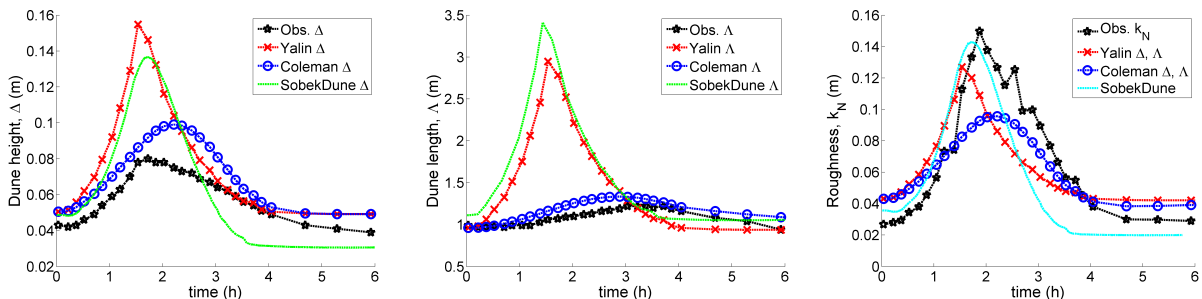

Figure 4. Observed and predicted dune height (left), dune length (middle) and Nikuradse roughness (right) for the three models of Yalin (1964), Coleman et al. (2005) and SobekDune.

dimensions from the Coleman model are slightly lower than the observed roughness values, although the dune dimensions are well represented. This might indicate that the Van Rijn (1984) model underpredicts the roughness for this case.

The roughness based on dune dimensions from SobekDune are similar to the observed roughness values. However, it should be noted that these are only preliminary results and the dune height is overestimated by the SobekDune model.

6. DISCUSSION

The benefit of the SobekDune model is that it is physically-based and can be applied to other conditions as well, while the Coleman model required calibration for the dune height. However, a thorough analysis of validity of the calibration coefficients for the SobekDune model is still required.

Based on these preliminary results, the SobekDune model seems promising for computation of the evolution of bed forms under varying discharge. It represents both the time-lag and attenuation in the dune height, which are essential for prediction of the hydraulic roughness and resulting water levels. The computational time is small compared to existing physically based models for bed form evolution (e.g. Giri and Shimizu, 2006, Nabi, 2010), which makes it feasible for use in operational flood forecasting.

The flattening of the primary dunes and overtaking by the secondary dunes as observed in the data from Wijbenga and Van Nes (1986) is not represented in the three models. In further research, we will include the flattening of the primary dunes and generation of secondary dunes during the receding limb of the discharge wave in the SobekDune model to better simulate the physical processes in bed form evolution in rivers. This potentially increases the predictive capacity of the model and might increase the accuracy of roughness and water level predictions for operational water level predictions.

7. CONCLUSIONS

The objective of this research was to predict and model bed form evolution during a discharge wave. We compared three models: an equilibrium model, a time-lag model and a numerical model

for a discharge wave in a flume experiment. We conclude that:

1) The adaptation time for dune length is much larger than for dune height for lower-regime conditions during a discharge wave.
2) Primary dunes are eroded by superimposed secondary dunes that develop during the receding limb of the discharge wave.
3) The time-lag approach of Coleman et al. (2005) yielded realistic result for dune dimension prediction during a discharge wave, however, calibration of the time-to-equilibrium was required for dune height.
4) The SobekDune model seems promising for modeling bed form evolution during a discharge wave, although the modeling results are preliminary.

In further research, we will include the physical processes observed in the flume experiment to increase the accuracy of roughness and water level predictions for operational flood forecasting.

8. ACKNOWLEDGMENT

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