COMPARISON OF TWO BED FORM MODELS TO PREDICT BED FORM ROUGHNESS FOR FLOOD MODELLING

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ABSTRACT

The hydraulic roughness of the main channel of most lowland rivers is dominated by bed forms. River bed forms act as roughness to the flow, thereby significantly influencing the water levels, which are essential for flood forecasting. We compared a time-lag model and a physically based pickup and deposition model to predict dynamic bed form evolution during a flood wave in the flume and the field. The results showed that the explicit computation of bed form and associated roughness predictions perform equally well as a calibrated model for the flume case, but slightly less for the field case. We were able to explain a large part of the roughness of the main channel that is normally calibrated. Using a physically-based roughness prediction improves the accuracy of the modelled water levels for operational flood forecasting.

Keywords: Bed forms, hydraulic roughness, flood modelling

1. INTRODUCTION

Water level forecasts are essential for flood protection management. Hydrodynamic models are applied to predict water levels. However, model outcomes are inherently uncertain. Recent studies have shown that the hydraulic roughness of the main channel is one of the largest sources contributing to the uncertainty in water levels (Warmink et al. 2013). Therefore, accurate estimates of main channel roughness can potentially increase the accuracy of water level predictions.

The river bed is highly dynamic: bed forms grow and decay as a result of changing flow conditions. Knowledge of bed form evolution and associated roughness is limited. Currently, in most hydrodynamic models the hydraulic roughness is used as a calibration coefficient. Therefore, the roughness is assumed constant or a function of the discharge. However, in many bed form dominated rivers, a clear hysteresis between bed form geometry and discharge is observed, which occurs because there is a time-lag between changing flow conditions and the size of the bed forms. After the discharge peak, bed forms continue to grow about 20% in height (Paarlberg et al. 2010). This effect is currently not taken into account in the calibration and, therefore, in operational water level modeling for flood safety management. The objective of this study was to explicitly model the dynamic bed form evolution and roughness during a discharge wave. Firstly we applied two bed form evolution models to a discharge wave in a flume and secondly, we applied one of these models to the 1995 peak discharge wave in the river Rhine and compared it to the calibrated model.

2. DATA

Many flume experiments are available that show bed form dimensions under different discharge conditions (e.g. Guy et al. 1966, Venditti 2005). However, most of these measurements have been carried out for a constant flow discharge, so these data do not show the hysteresis effect. We used the flume data from Wijbenga and Van Nes (1986), who carried out an excellent experiment with a discharge wave (**Error! Reference source not found.**). The discharge wave was scaled to historical discharge waves in the Dutch river Rhine. Wijbenga and Van Nes (1986) repeated the test 9 times and measured the bed form evolution and associated flow characteristics, averaged over the 9 tests. The discharge ranged between 0.03 and 0.15 m3/s resulting in water depths, h ranging between 0.15 and 0.47 m. The width of the flume was 1.5 m for the discharge step experiments and 0.5 m for the discharge waves. The measuring section was 30 m long. Bed material consisted of uniform sand with D50 = 0.78 mm.

Table 1. Flume data from Wijbenga and Van Nes (1986) for a discharge wave.

[test ID]	q [m^2/s]	h [m]	W [m]	H_0 [m]	L_0 [m]	H_{max} [m]	L_{max} [m]
T43	0.064-0.288	0.15-0.47	0.5	0.043	0.99	0.080	1.22

For the field case, we modelled the discharge wave of 1995, which is one of the largest recorded discharges in the river Rhine, because extensive dune dimension data were available by Wilbers and Ten Brinke (2003). They measured the dune dimensions at two location in the Upper Rhine in the Netherlands (just upstream of the first bifurcation point) and one location at the Waal, close to the TielWaal measurement station (Figure 1).

3. METHOD

The 1D SWE model SOBEK was used to compute the hydrodynamics and coupled this model with two different dune evolution models. We used the same approach for both the flume and field case following the approach presented by Paarlberg and Schielen (2012). For the field case, the cross sections were defined approximately every 500 m, so large scale variations in river geometry are accounted for (Paarlberg and Schielen, 2012). We used the Sobek model for the three main distributaries in of the river Rhine in the Netherlands. We defined the upstream boundary conditions as an upstream water level at Lobith (at the Dutch-German border) corresponding to a discharge of 12400 m3/s and at the downstream boundaries as the observed water levels.

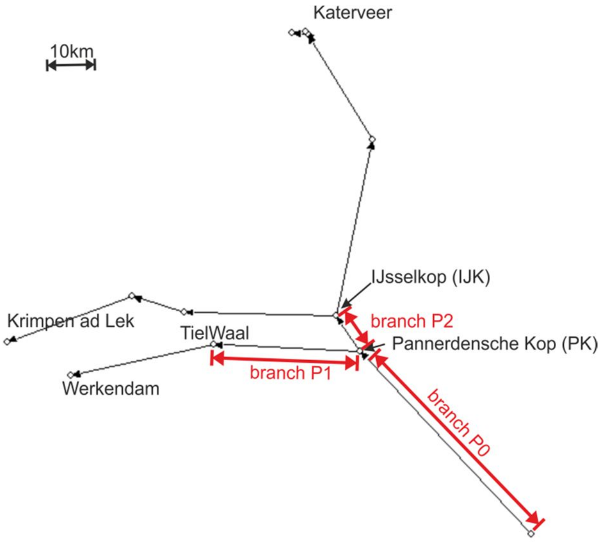


Figure 1 Sobek model schematization of the Rhine distributaries in the Netherlands. The roughness was computed for the three branches: P0, P1 and P2.

3.1 Analytical time-lag bed form evolution model

To predict the dune dimensions, we use the analytical time-lag approach presented by Coleman et al. (2005). This dune evolution model predicts the (non-equilibrium) dune dimensions based on only data of the water levels. Coleman et al. (2005) adopted the commons scaling relationship for sand-wave development from an initially flat bed from Nikora & Hicks (1997) valid for $0.01 < t/t_e < 1$:

$$\frac{P}{P_e} = \left(\frac{t}{t_e}\right)^{\gamma}$$

where P is the average value of dune length or height, P_e is the equilibrium value, t is time, t_e is the time to achieve P_e, and γ is a growth rate parameter, resulting in different growth rates for dune height and dune length (Warmink, 2014). For flume data the equilibrium dune dimensions were predicted using H=0.33h and L=6.28h, where h is water depth following Yalin (1992). For the field conditions, the Allen (1968) predictor was used for equilibrium dune dimensions. Several equilibrium predictors were tried, but these provided the best results.

Coleman et al. (2005) used flume data to derive an empirical equation to predict the time-to-equilibrium for dunes, based on shear velocity, u_*, water depth, h, the Shields number, θ, and critical Shields number, θ_{cr}:

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

3.2 Physically-based bed form evolution model

Dune dimensions with the dune evolution model based on Paarlberg et al. (2009), using the reach averaged slope, water depth from Sobek and the D50 from Wilbers and Ten Brinke et al. (2003). The dune evolution model solves the water flow over the dune using the 2DV shallow water equations with hydrostatic pressure assumption. Compared to the original Paarlberg model, sediment transport is now computed using the pickup and deposition model based on Van Duin et al. (2015). This model essentially introduces a space-lag between bed shear stress and sediment deposition.

3.3 SobekDune model

In our modelling approach, we imposed the discharge in Sobek to compute the water depths, given an initial roughness. For this water depth, the dune dimensions and associated roughness were computed for the six branches not controlled by structures (the bed form roughness for the branch from IJsselkop to Krimpen a.d. Lek was set as the calibrated roughness). The empirical roughness model of Van Rijn et al. (1984) was used with a correction coefficient to account for the variability of dune heights of y=0.7 (following Van Rijn, 1993). If at time, t, the water depths or roughness changed more than 5% compared to the start of the run, the water levels are re-computed using the updated roughness. These steps were repeated until the end of the discharge series. The results of the SobekDune model are compared to the calibrated Sobek model, without the bed evolution module using the calibrated roughness. The simulation period was from December 1st 1994 to February 28 1995, with the peak discharge on January 31 1995.

4. RESULTS

4.1 Flume results

Figure 2 shows the results of the SobekDune model flume discharge wave using the Coleman dune dimensions predictor compared to the calibrated Sobek model run and the observed roughness (based on water level slope). This figure shows that the water levels from the SobekDune model are similar to the water levels from the calibrated Sobek model. This implies that we can accurately predict the roughness without the need for calibration. Furthermore, the time-lag prediction is slightly improved using the SobekDune model, which is shown the smaller errors during the peak of the discharge wave.

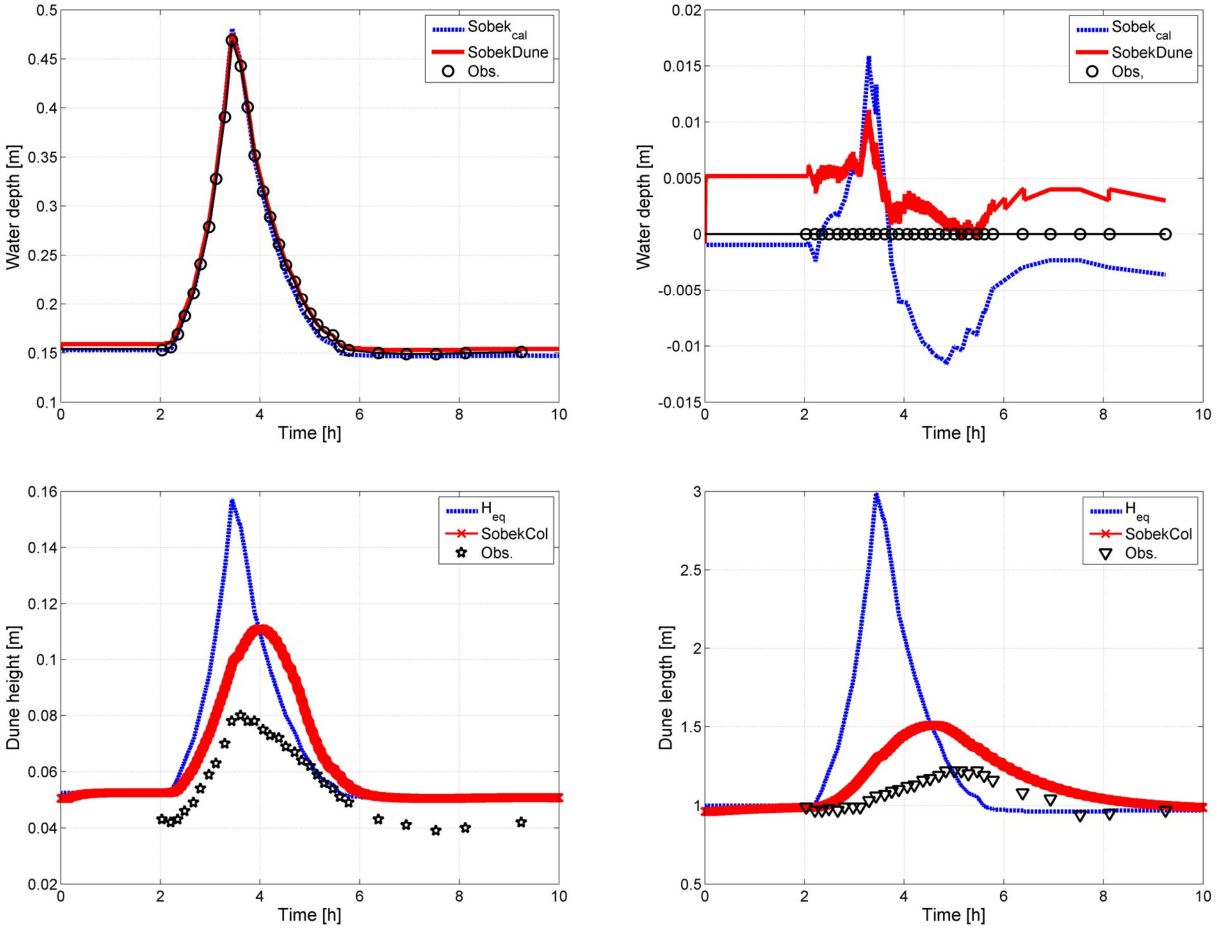


Figure 2. Top: observed, calibrated and predicted (SobekDune) water depth (left) and differences (right). Bottom two figures show the predicted dune height and length using the equilibrium predictor and the Coleman predictor compared to the observations.

Figure 3 shows the results of the pickup and deposition model. The dune height is slightly overestimated, but the water levels are quite well predicted. This is probably caused by the inaccuracies in the roughness predictor. The results show that also this model is capable of replicating the calibrated roughness and improves the prediction of the water levels around the peak discharge, because the time-lag is included in the computation.

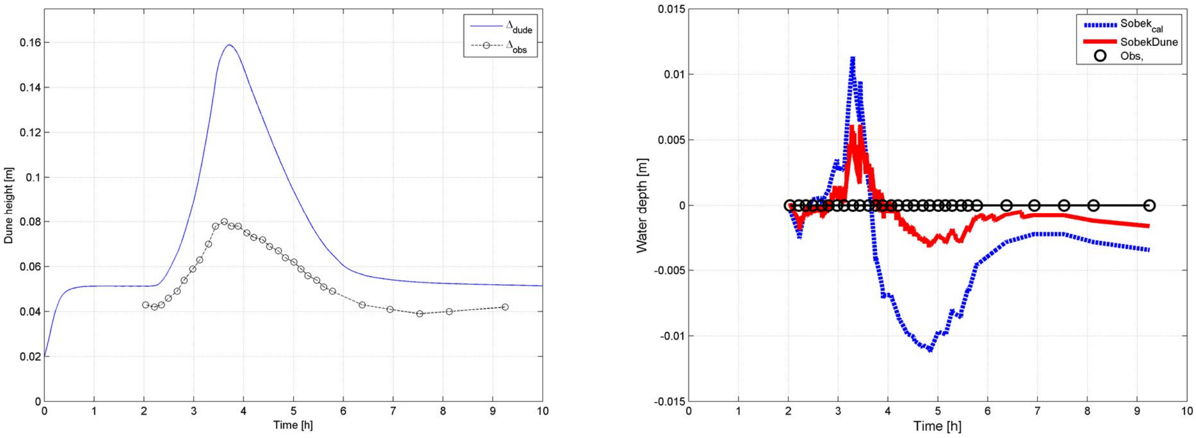
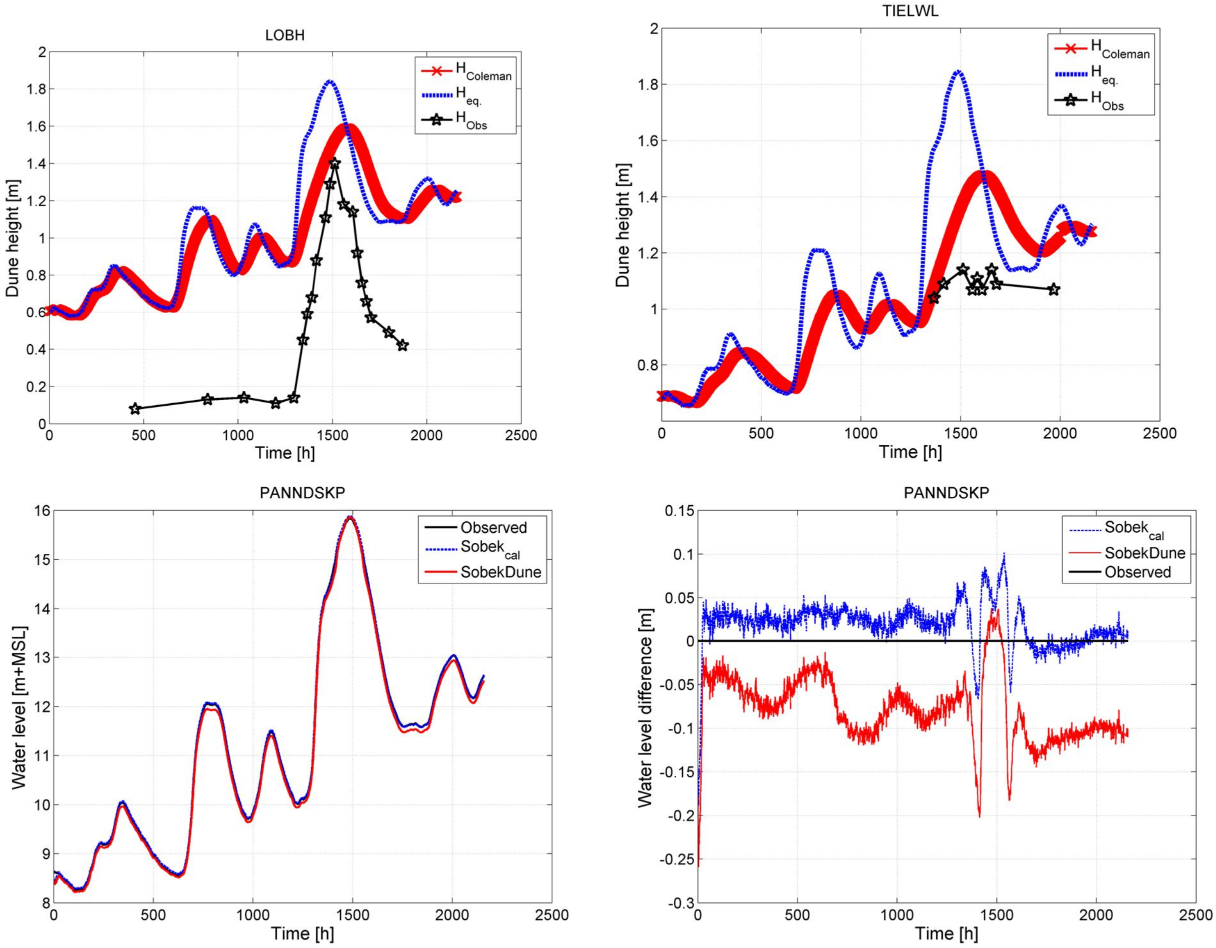


Figure 3. Left: dune height from the pickup and deposition model compared to the observations. Right: water level differences compared to the observation for the calibrated and SobekDune model.

4.2 Field results

Figure 4 shows the results of the Coleman model for the Dutch Rhine distributaries. The dune dimensions are poorly predicted using the Coleman model, because the equilibrium predictor fails to predict the small dune dimensions that are observe before the peak (Figure 4, top left). This was also observed for other locations and in observations during other discharge events. Despite the overestimation of dune height and length, the SobekDune model performs reasonably well for water level predictions. This is probably caused by the correction factor in the roughness predictor, which was also shown in the flume to results in well predicted water depths, while dune dimensions were overestimated (figure 3).



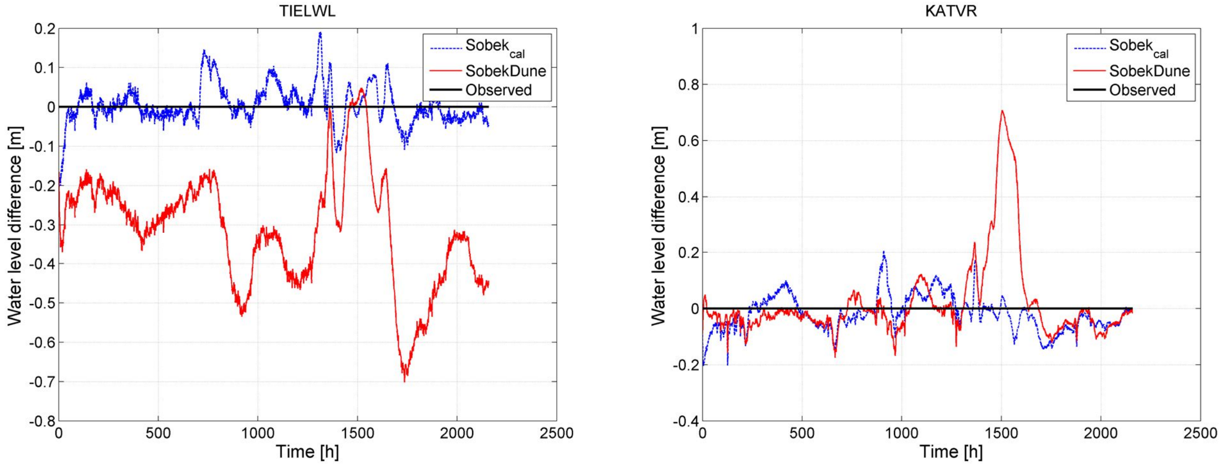


Figure 4. Top: dune heights at Lobith and TielWaal from the Coleman model compared to the observations. Middle and bottom figures: water levels and water level differences for the stations Pannerdesche Kop (PK), TielWaal along the Waal and Katerveer along the IJssel.

5. CONCLUSIONS

In this study we aimed at explicit computation of the bed form roughness. We compared the Coleman and pickup and deposition bed form models for the flume case and applied the Coleman model to the field case. We have shown that both the Coleman and pickup-and-deposition models improve the prediction of the time-lag and associated water depths in the flume case. The Coleman method did not perform as expected for the field case, but this is probably caused by the difficulty in the determination of the equilibrium dune height that is used for the Coleman predictor. The application of the physically based pickup-and-deposition model is promising, because it does not depend on empirical equations. Finally, we have shown that explicit computation of bed form evolution can explain a large part of the roughness that is usually calibrated. Calibration will always remain necessary, but using the knowledge of bed form evolution and including this in the prediction can largely improve the accuracy of water level predictions, especially in circumstances where calibration data is scarce.

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