Explicit computation of dynamic bed form roughness for operational flood modelling using a time-lag approach

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Introduction

Accurate forecasts of water levels are essential for flood protection management. Hydrodynamic models are applied to predict water levels, which are used to estimate the risk of flooding, the design of dikes and assure timely warning. 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.

Under flood conditions the river bed is highly dynamic; bed forms grow and decay as a result of the changing flow conditions. Knowledge of bed form evolution and associated roughness is limited. Most flood prediction models are calibrated using a constant and uniform roughness coefficient. 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; Warmink, 2014). This effect is currently not taken into account in operational water level modeling for flood safety management.

Data

We modelled the discharge wave of

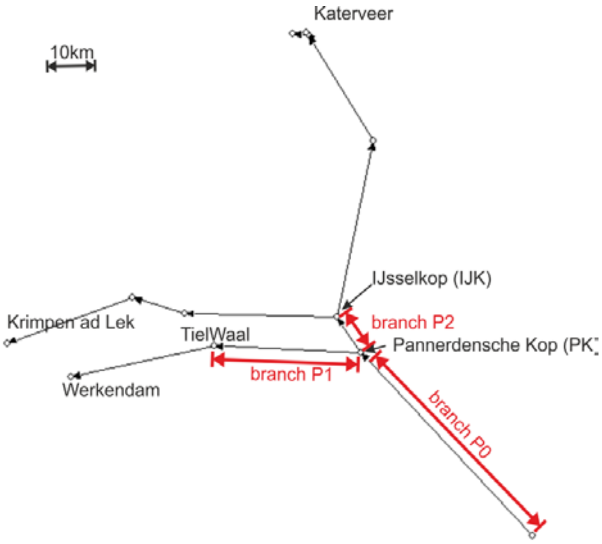

Figure 1. Sobek model schematization of the Rhine distributaries in the Netherlands. The roughness was computed for the three branches: P0, P1 and P2.

October/November 1998, because extensive dune dimension data were available by Frings and Kleinhans (2008). They measured the dune dimensions at three locations at Pannerdensche Kop (Figure 1, Table 1).

Table 4. Data from Frings and Kleinhans (2008) for the three branches at PK.

Sect.	Q_{peak} [m^3/s]	h_{peak} [m]	S_{mean} [m/m]	H_{max} [m]	L_{max} [m]	D_{50} [mm]
P0	9413	12.7	2.8e^{-4}	1.2	33.1	3.1
P1	6172	10.5	0.8e^{-4}	0.48	12.5	1.1
P2	3302	11.2	0.8e^{-4}	0.49	16.6	7.2

** Maximum dunes (H,L) occurred not at the same time as maximum discharge.*

Method

As a test case, we followed the Sobek model approach presented by Paarlberg and Schielen (2012). Cross sections were defined approximately every 500 m, so large scale variations in river geometry are accounted for. We used the Sobek model for the three main distributaries of the river Rhine in the Netherlands with the upstream boundary at Ruhrort, Germany (Figure 1).

Coleman et al. (2005) bed form 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. The Allen (1968) predictor was used for equilibrium dune dimensions.

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, θcr:

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

SobekDune model

We imposed the observed 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 three branches connecting to the PK bifurcation point. 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 modelling period. The results of the SobekDune model are compared to the calibrated Sobek model, without bed evolution.

Results

Both dune height and dune length are overestimated by the equilibrium predictor, which consequently results in an overestimation using the Coleman model (Figure 2).But, the time-lag was well represented.

The SobekDune model yields similar water levels as the calibrated Sobek model, but without the need for calibration. It shows a slower increase (more time-lag) of the roughness during the rising limb of the flood wave. The resulting water levels show a similar trend. The SobekDune and calibrated water levels show an error of around 20 and 30 cm, respectively, before to the flood wave (Figure 3). The peak water level was overestimated by 40 cm using the SobekDune model and by 60 cm for the calibrated Sobek model.

Conclusions

We conclude that

- The Coleman method can predict bed form evolution during a flood wave, but its accuracy mainly depends on an appropriate model to predict the equilibrium bed form dimensions.
- The Coleman dune model coupled with Sobek can explain a large part of the bed form roughness that is normally calibrated in a field situation.

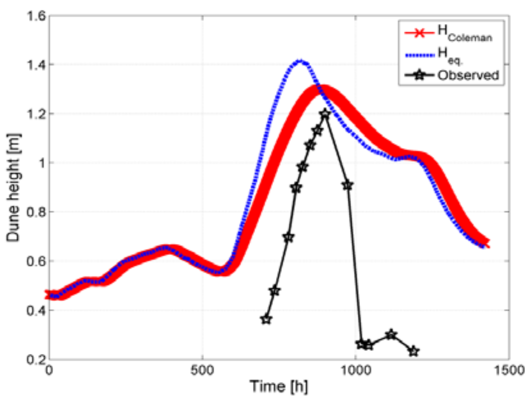

Figure 2. Dune height predicted by Coleman using observed water levels just upstream of PK (Upper Rhine branch).

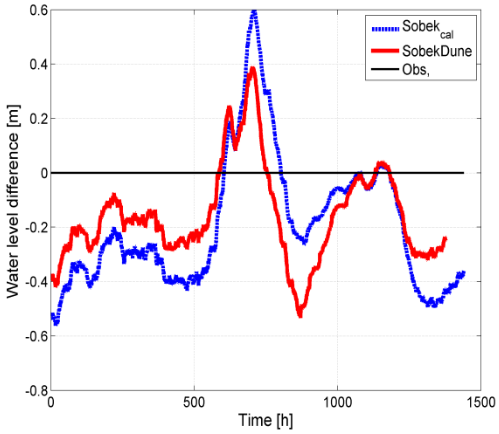

Figure 3. Water level differences from the SobekDune model for location P0.

In future work we will apply more detailed physically based models to predict dynamic bed form roughness.

Acknowledgements

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References

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

Coleman et al. (2005) Sediment-wave development in subcritical water flow, DOI: 10.1061/(ASCE)0733-9429(2005)131:2(106))

Frings, R.M. & Kleinhans, M.G., 2008. Complex variations in sediment transport at three large river bifurcations during discharge waves in the river Rhine. *Sedimentology* 55, 1145-1171

Nikora V.I., & Hicks D.M. 1997. Scaling relationships for sand wave development in unidirectional flow. *Journal of Hydraulic Engineering*, 123, 12, 1152–1156, doi: 10.1061/(ASCE)0733-9429(1997)123:12(1152).

Paarlberg et al. (2010) Modeling the effect of time-dependent river dune evolution on bed roughness and stage, DOI: 10.1002/esp.2074

Paarlberg A.J. & Schielen. 2012. Integration of a dune roughness model with a large-scale flow model. *Proceedings River Flow 2012*.

Warmink, J.J. 2014. Dune dynamics and roughness under gradually varying flood waves, comparing flume and field observations. Advances in GeoSciences 39, 115-121. DOI: 10.5194/adgeo-39-115-2014