Modelling dynamic roughness in rivers during floods

A.J. Paarlberg, C.M. Dohmen-Janssen, S.J.M.H. Hulscher & R.M.J. Schielen
University of Twente, Department of Water Engineering and Management, PO Box 217, 7500 AE Enschede, the Netherlands, phone: +31-53-489 3911, fax: +31-53-489 5377, email: a.j.paarlberg@ctw.utwente.nl

A.P.P. Termes
HKV Consultants, Lelystad, the Netherlands

ABSTRACT: Although dune dynamics and associated hysteresis effects vary for different flood wave types, calibrated roughness coefficients of many hydraulic models only depend on the discharge. Thus, hydraulic simulation models may yield incorrect water level predictions, if they are applied to flood waves and discharges for which they were not calibrated. This paper presents a new physically-based method to determine the main channel roughness by predicting dune dimensions during a flood wave using an idealized mathematical dune development model. Model results show that the shape of a flood wave influences dune dynamics and thus roughness development. Although hysteresis in dune height is larger for a sharp-peaked flood wave, the total increase in dune height is larger for broad-peaked flood waves. The proposed modelling approach yields physical insight into the effects of time-dependent dune development on the main channel roughness coefficient in hydraulic models, which could serve as starting point for future model calibrations.

1 INTRODUCTION

In the Netherlands, hydraulic models are used to predict water levels in the main rivers. Based on the simulation results it is decided whether the flood protection levels are still met. The flow resistance of the main channel is largely determined by the presence of dunes on the bed, which typically develop in sand-bed rivers, if the bed shear stress exceeds the threshold of sediment motion. The dunes that form in the river Rhine in the Netherlands have heights in the order of 10-30% of the flow depth in the main channel and the length is many times the flow depth (typically 1-8 for the river Rhine) (Fig. 1). Generally, the dune length linearly increases with the flow depth, and the migration rate is inversely proportional to dune height.

Figure 2a shows measured dune heights during the 1998 flood in the river Rhine near the Pannerdensche Kop (Fig. 1) as a function of discharge. A clear hysteresis effect can be observed, which occurs because it requires time for the dunes to adapt to the changing flow conditions by means of sediment transport. After the discharge peak, the dunes continue to grow about 20% in height.

It is expected that this hysteresis effect of dune development also has its impacts on water levels. Unfortunately, we lack a situation in which measurements on both dunes and water levels are available. However, Figure 2b shows a clear hysteresis effect in water levels in the river Meuse in the Netherlands. This effect can be attributed to (*i*) accelerations and decelerations during the passage of a flood wave (i.e. the Jones formula, see e.g. Perumal et al. 2004) and (*ii*) dunes forming on the bed during the passage of a flood wave.

Recently, the main channel roughness coefficients in the hydraulic simulation model Sobek were calibrated as a function of the discharge, to better represent water levels for the complete flood waves (Udo et al. 2007). However, this still implies that the calibration is specific for the conditions for which the model was calibrated (e.g. the peak discharge, flood wave shape). Effectively, the effects of dune development, the hysteresis effect in dune height and all other (model) errors end up in the roughness coefficient. In other words, the roughness coefficient acts as *garbage bin* of hydraulic models.

Dunes develop as a complex interaction between the flow, the sediment transport and the bed morphology. Modelling these interactions in response to unsteady flow is complicated, and especially hysteresis in dune dimensions are still difficult to predict with sufficient accuracy, in such a way that the effects can be incorporated in simulation models for operational water management purposes. In some hydraulic models, the roughness coefficient of the main channel is based on dune dimensions which are predicted using empirical relationships; these predictors assume dunes to be in equilibrium with flow conditions, and therefore always need to be calibrated (e.g. Warmink et al. 2007). Wilbers (2004) included hysteresis effects (time-lags) in dune development, following the approach of Allen (1976), with a calibrated adaptation constant. Giri et al. (2007) presented a numerical morphodynamic simulation model which was able to predict stage-discharge relationship under flume conditions. However, the complicated flow model results in extremely large computational times, and makes the model infeasible for operational water management purposes.

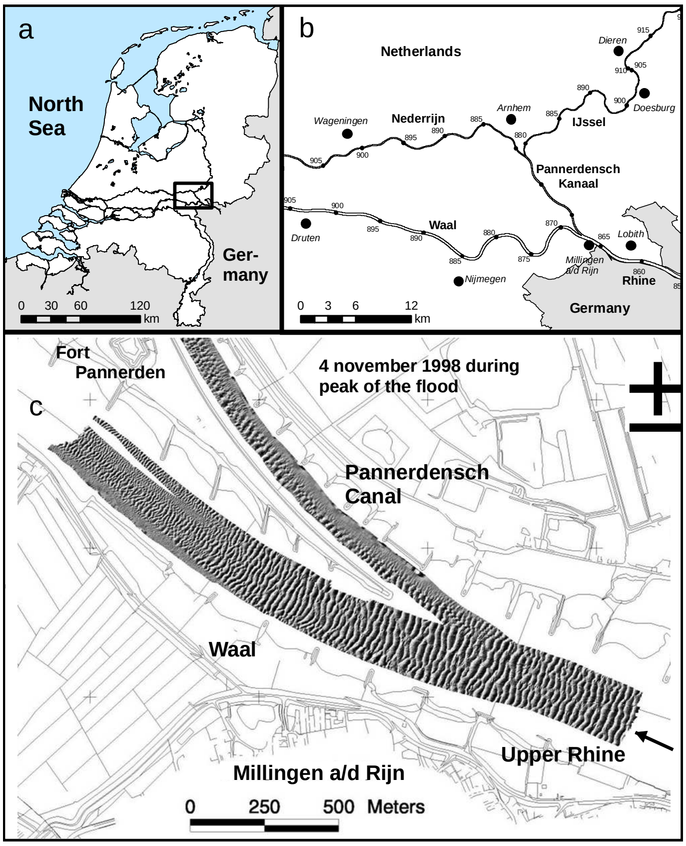

Figure 1: Measurements of dunes at the Pannerdensche Kop bifurcation in the river Rhine. (a) location in the Netherlands; (b) major river branches of the river Rhine; (c) detailed multibeam measurements during peak of the 1998 flood, with dune heights of 1-2 m and lengths of upto 50 m in an average water depth of about 10 m (picture courtesy (c): Antoine Wilbers).

This paper aims to develop a physically-based approach to incorporate the effects of dune development during floods on water levels in the hydraulic model Sobek, over the full time scale of a flood wave. To this end, the hydraulic simulation model Sobek is coupled with an idealized mathematical dune development model. We will investigate to what extent this impacts water level predictions over the entire range of flood waves, compared with an earlier model calibration.

The outline of this paper is as follows. In Section 2, the dynamic roughness model is introduced and the various submodels are discussed. In this paper we use a calibrated Sobek model of the river Waal as case study, and apply the model for two types of flood waves, i.e. a sharp- and a broad-peaked flood wave; this reference case is presented in Section 3. Section 4 presents dune dynamics and water levels during the two types of flood waves. The paper ends with a discussion and conclusions in Sections 5 and 6, respectively.

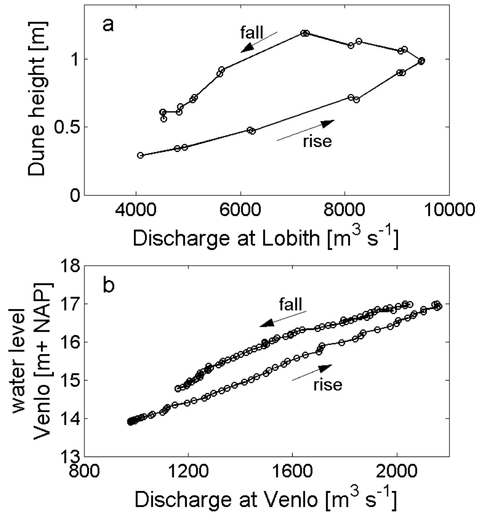

Figure 2: (a) Hysteresis effect in dune height in the river Rhine near the Pannerdensche Kop during the 1998 flood (Rijkswaterstaat, Wilbers & Ten Brinke 2003); (b) hysteresis in water level in the river Meuse at Venlo during februari 2002 flood (Termes 2004). NAP is the Dutch ordinance datum.

2 DYNAMIC ROUGHNESS MODEL

Paarlberg et al. (2006, subm.) developed a physics-based idealized mathematical model to predict temporal dune evolution. This model is now linked with Sobek to form a *dynamic roughness* model. With this model water levels in natural river settings can be computed, explicitly accounting for dune roughness. A model overview is presented in Figure 3. In short, computed dune dimensions are translated into a roughness coefficient for the main channel, and if this coefficient changes with more than 10%, Sobek computes updated water levels. This procedure continues until an entire flood wave is simulated. The different submodels are discussed in the remainder of section 2.

2.1 *Sobek model*

Sobek solves the 1-D cross-sectional integrated shallow water equations. The river Rhine is divided into trajectories of a certain length, and cross-sections are defined roughly every 500 m, to take large-scale variations in bed levels and river non-uniformity in stream-direction into account. This introduces local water level differences and different conveyance capacities of floodplains along the river, enabling to simulate natural river settings. The specific Sobek model used in this paper will be discussed in Section 3.

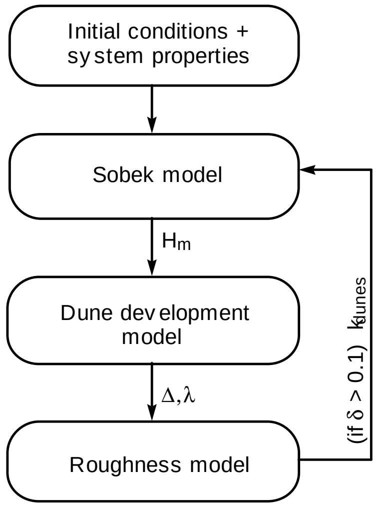

Figure 3: Overview of the dynamic roughness model. A simulation is initialized by specification of a flood wave, system properties (such as grain size), and initial dune dimensions (giving a roughness coefficient with Eq. 1). The flow depth in the main channel (H_m) computed by Sobek, is used as input for the dune development model. If the relative change in roughness (δ) exceeds 10%, a new Sobek computation is performed.

2.2 *Dune development model*

The dune development model is based on the two-dimensional vertical (2-DV) hydrostatic shallow water equations, with a constant eddy viscosity over the flow depth and a partial slip condition at the bed. Flow separation is included in a parameterized way. In the region of flow separation, the separation streamline forms an artificial bed (Paarlberg et al. 2007), enabling to compute the hydrostatic flow over the dunes. A simple sediment transport relationship including gravitational bed-slope effects is applied, to determine bed evolution.

The dune development model uses the reach-averaged bed slope, the average flow depth in the main channel (as computed by Sobek) and the bed material (represented as D_{50}) as inputs (Fig. 3). To minimize computational effort, the dune development model employs periodic boundary conditions, and one dune is simulated in the domain. Two coefficients of the turbulence model which determine the eddy viscosity and the resistance at the bed were calibrated on the basis of flume experiments (Paarlberg et al., subm.). In this paper, the model is applied with the same coefficients (see discussion).

Since the dune development model simulates one dune in the domain, the dune length is changed by changing the length of the domain. This length is chosen on the basis of a numerical linear stability analysis, and is mainly controlled by the water depth in our model. If the water depth changes by 1%, a linear stability analysis is performed using small amplitude sinusoidal disturbances with different wave lengths on a flat bottom as topography (see also Paarlberg et al., subm.). An example result of the stability analysis is shown in Figure 4. From this analysis a fastest growing wave length can be found, which is used as domain length (effectuated by adapting the horizontal distance between grid-points in horizontal direction).

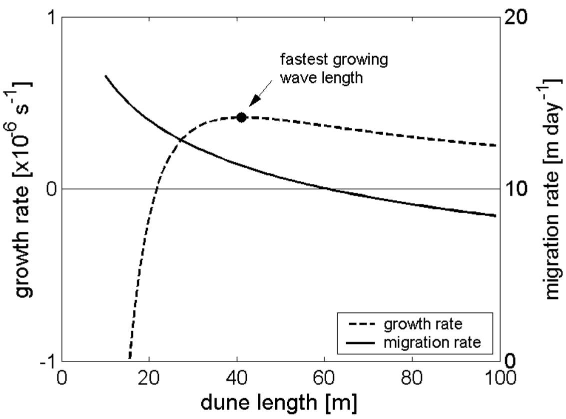

Figure 4: Results of a linear stability analysis for a main channel flow depth of 6 m. Short waves are stable while a wave length of ~40 m is most instable.

2.3 *Roughness model*

The total roughness height of the main channel (k_{total}) can be divided into a contribution of grains (k_{grain}) and dunes (k_{dunes}), according to the method of Einstein & Barbarossa (1952). We extend it with a contribution due to uncertainties ($k_{uncertain}$), originating from (model) errors that are incorporated in calibrated roughness coefficients (i.e. in the *garbage bin*):

$$k_{total} = k_{grain} + k_{dunes} + k_{uncertain} \tag{1}$$

Generally, the roughness due to dunes is dominant over the grain roughness and the uncertainties, and therefore the latter two are neglected in the simulations presented in this paper. We specify the dune roughness height according to Van Rijn (1993) as:

$$k_{dunes} = 1.1\gamma\Delta\left(1 - \exp\frac{-25\Delta}{\lambda}\right) \tag{2}$$

with roughness correction factor γ (see below), Δ the dune height and λ the dune length.

The dune development model is 2-DV and assumes that dunes form uniformly over the complete main channel width, that all dunes have the same height, and that all available energy directly contributes to the formation of the dunes. Therefore, it is anticipated that our dune development model predicts maximum dune dimensions, rather than average dune dimensions, which most likely control the total flow resistance due to dunes. This argues that γ in Eq. (2) should be smaller than unity. Indeed, Van Rijn (1993) proposed a correction coefficient γ of 0.7 to better reproduce field measurements, since his original relationship was mainly based on flume tests. However, this does not yet correct for the fact that our model predicts maximum dune dimensions rather than average dune dimensions. Van der Mark et al. (2007) analyzed flume data and found that the average dune height is more or less half of the maximum dune height. In anticipation of the model results (Section 4), the dune aspect ratio (Δ/λ) is more or less constant, meaning that the dune roughness linearly depends on the dune height for a certain aspect ratio (Eq. 2). Therefore, we use a value of γ=0.35 (=0.70/2) as default value for the correction factor. In the discussion, the sensitivity to this parameter is investigated.

3 REFERENCE MODEL AND SCENARIOS

3.1 *Representative river Waal model*

We set-up a simple 60-km long straight channel with floodplains in Sobek, having a uniform cross section (Fig. 5) of a relatively straight trajectory in the river Waal (river km 885.23-900.88) (Fig. 1). Roughness coefficients are chosen uniform over the entire channel. To minimize the influence of the downstream stage-discharge relationship on the results, the average water depth (H_m) at the upstream boundary of the channel is used as input for the dune development model. The grain size and channel slope are uniform over the entire channel, and specified as 1 mm and 0.76x10^{-4} (both based on conditions in the river Waal), respectively.

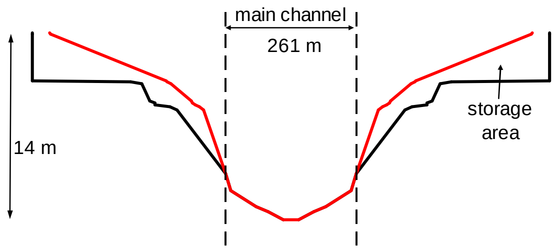

Figure 5: Cross section for the Sobek model, based on relatively straight section in the river Waal (river km 895, Fig. 1b).

3.2 *Flood wave scenarios*

Floodwaves in the river Rhine are variable in shape, with rapid or gradual changes in discharge over time. Figure 6 gives a representation of two typical flood wave shapes which are analyzed in this paper. The sharp-peaked flood wave (Fig. 6a) is a schematic representation of the flood wave that occurred in the river Waal in october/november 1998 which had a maximum discharge of ~6.000 m^3/s. The wave is characterized by a sharp peak, i.e. the high discharge occurs for a small period of time. For the broad-peaked flood wave (Fig. 6b), the high discharge occurs for a longer period of time. These shape differences may influence dune dynamics, since for the broad wave the rising and falling stages are shorter, while the dunes have more time to adapt to the higher discharge. Note that both flood waves have the same duration (i.e. 30 days).

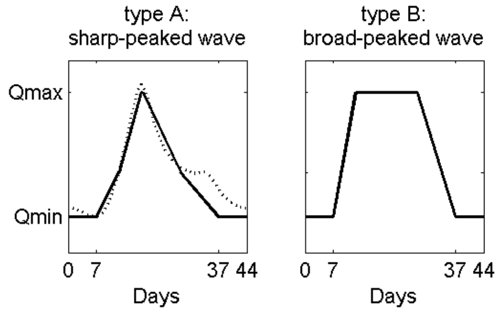

Figure 6: Two types of flood waves analyzed in this paper. Qmax (=6.000 m^3/s) and Qmin (=1.333 m^3/s) are the maximum and minimum discharge, respectively. The dotted line in the left plot gives the hydrograph for the 1998 flood in the river Waal.

Generally, dune dimensions at the start of a flood wave are not known, but in the simulation model initial dune dimensions have to be specified. We have chosen to start a simulation with an initial dune height of 2 cm. To investigate the differences in dune development for different initial conditions, every model simulation will consist of two subsequent flood waves of identical shape with periods of 1 week constant low discharge in between. For the first wave, dunes have to develop from very small sinusoidal disturbances, while for the second wave, the dune height is more or less in equilibrium with flow conditions, at the start of the wave.

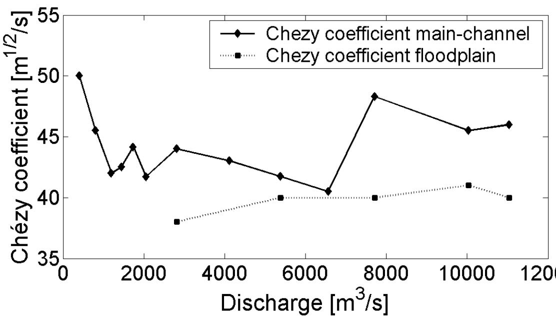

Figure 7: Calibrated Chézy coefficients of the main channel and the floodplain as a function of discharge (data from Udo et al. 2007).

3.3 *Main channel and floodplain roughness*

Figure 7 shows calibrated Chézy coefficients for the same river trajectory as from which the cross-section was chosen (Fig. 5). For discharges higher than about 7.000 m^3/s in the river Waal, the Sobek model is calibrated on the basis of computation results of the 2DH hydraulic model Waqua of the river Rhine in the Netherlands (Van den Brink et al. 2006, Udo et al. 2007), since no measurements are available above this discharge. This might explain the sudden increase in Chézy coefficients at higher discharges in Figure 7. We use a discharge-independent value of 38 m$^{1/2}$/s for the Chézy coefficient in the floodplains, since below 6.000 m^3/s (the maximum discharge used in this paper) it hardly varies (Fig. 7).

4 RESULTS DYNAMIC ROUGHNESS MODEL

4.1 *Dune dynamics for sharp-peaked flood wave*

Wilbers & Ten Brinke (2003) observed that in the river Waal, the dune length remains fairly constant during the 1998 flood, i.e. about 40 m. They argue that this is caused by a combination of grain size distribution over the river width and distance between groynes. However, for other river sections such as the Upper Rhine between Lobith and the Pannerdensche Kop, the dune length may vary during floods. Therefore, model simulations are performed for both constant and variable dune length.

Figure 8 shows simulated dune dynamics for two subsequent sharp-peaked flood waves, with constant dune length (i.e. 40 m) and with variable dune length (i.e. based on linear stability analysis). For constant dune length, we observe a small effect of dune heights responding to variations in the discharge (Fig. 8b), and the maximum dune height occurs slightly after the peak discharge with a time-lag of about 3 days (the hysteresis effect will be discussed in Section 4.2). During the rising stage of a flood wave, the flow depth in the main channel increases and, as a result, also the dune length that is most unstable (the fastest growing mode) increases (Fig. 8a). Elongating dunes have smaller bed slopes and grains can be transported up-slope easier, resulting in higher dunes (Fig. 8b). For variable dune length, the dune height can become upto 40% higher than for constant dune length.

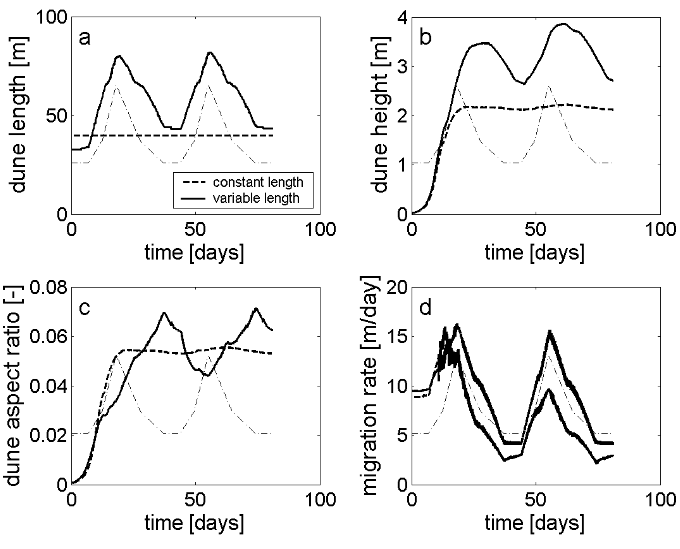

Figure 8: Result for two subsequent sharp-peaked flood waves (Fig. 6) (discharge variation sketched in subplots with dash-dotted lines). a) dune length; b) dune height; c) dune aspect ratio (ratio of dune height to dune length); d) migration rate.

The dune aspect ratio during the modelled flood wave varies roughly between 0.05 and 0.07 (Fig. 8c), which is well within the range of values from literature (e.g. Bennett & Best 1995, Carling et al. 2000). In the river Rhine, also lower values around 0.04 are reported (Julien & Klaassen 1995, Wilbers & Ten Brinke 2003). However, as discussed in Section 3.3, the dune height might be over-predicted for natural river settings because the dunes are not uniformly distributed over the river. This explains the slightly high dune aspects ratios. For the second discharge wave (of the two subsequent waves in a simulation), the dune aspect ratio is lowest during the peak of the flood wave, since the dune length is at a maximum at that stage. Thus changes in length have more influence on the dune aspect ratio than changes in dune height, mainly because the dune length differs about 100% between low and high discharge, and the dune height differs about 40% between these discharges. This indicates that a proper modelling of dune length is very important for accurate modelling of dune development, since the dune aspect ratio is important for roughness predictions (Eq. 2).

Figure 8d shows that the migration rate is highly variable and especially responds to a changing discharge. This is not surprising, since for increasing discharge and flow depth the bed shear stress and thus the sediment transport increase. With a more or less constant dune height, an increasing sediment transport rate also yields that the migration rate increases. Wilbers & Ten Brinke (2003) assume a relationship between dune length and migration rate with higher migration rates for longer dunes. If the dune length varies during the flood wave we find a similar trend (Fig. 8a and d). However, the relationship is less strong than Wilbers & Ten Brinke (2003) observed, since longer dunes are also higher, reducing the migration rate if we assume that all sediment that passes the dune crest deposits evenly at the dune lee (as is done in the dune development model). For constant dune length it seems that the flow depth (or bed shear stress) is the controlling parameter on the migration rate.

4.2 *Hysteresis effect in dune height*

Figure 9a-b show the dune height as a function of discharge for constant dune length for the two different flood wave types. For the broad-peaked flood wave, the dunes do not really respond to the changing discharge during rising and falling stage, since these periods are relatively short (Fig. 6b). In contrast, for the sharp-peaked flood wave, the hysteresis effect is more pronounced, especially for the first discharge wave, when the dune height is still growing towards the equilibrium height at the start of the wave (Fig. 6a). Since the dune length is constant, only the forcing or flow depth changes during the flood wave. However, the dune height does not differ much between the low and the high discharge (Fig. 9a-b). Probably, this is because a maximum dune aspect ratio is obtained for the flow and sediment conditions (conform Carling et al. 2000) and the dune height only changes due to small nonlinear effects if the water depth changes strongly between the low and high discharge.

For variable dune length, the hysteresis effects in dune height are more pronounced for both flood wave shapes (Fig. 9c-d) compared to the case with constant dune length. This is a direct result of the observation in Section 4.1 that dunes change in height if the dune length changes (i.e. more of less constant dune aspect ratio). For the second wave of the sharp-peaked flood wave, we clearly observe the hysteresis loop with a maximum dune height difference of about 1.2 m. Also, the maximum dune height occurs if the discharge is already falling. For the broad-peaked flood wave, the dunes become slightly less high during the rising stage of the second wave than is the case for the sharp-peaked flood wave (Fig. 9c-d). However, the relatively long period of high discharge for the broad-peaked flood wave yields higher dunes at the start of the falling stage for this flood wave shape. This is important for practice since at the end of the flood wave the relict dunes are higher which may cause problems for e.g. shipping activities.

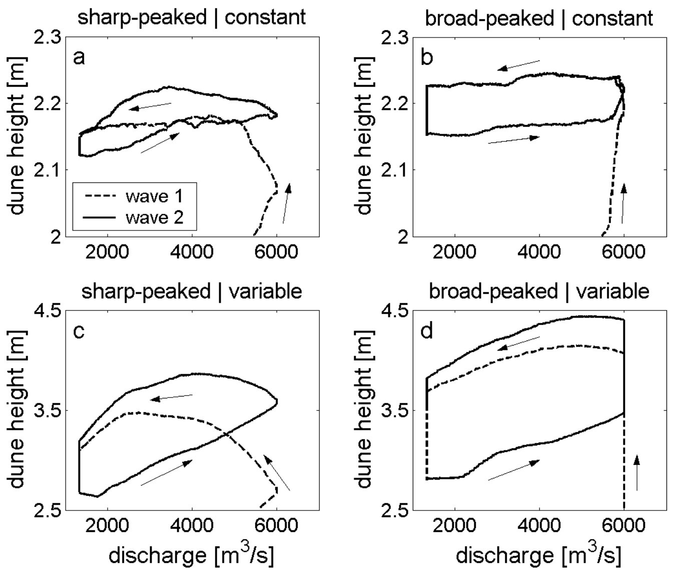

Figure 9: Hysteresis in dune height, for the two types of flood waves (Fig. 6). Results for both constant dune length (a-b), and variable dune length (c-d) are shown (note different scales on y-axis). In the figures, the two subsequent flood waves in each simulation are plotted separately (see legend of subplot a).

4.3 *Effects on hydraulic parameters*

Changing dune dimensions over time and the hysteresis effect in dune height also yield hysteresis in roughness height since the roughness coefficient of the main channel is directly linked to both dune height and dune length (Eq. 2). Figure 10 compares Chézy coefficients computed with the new dynamic roughness model and the values of the originally calibrated model. Obviously, the dynamic roughness model over-predicts the main channel roughness, for both types of flood waves. The over-prediction is larger for variable dune length, which is directly linked to higher dunes for these cases (Fig. 9). For constant dune length, the roughness coefficient at the peak discharge is predicted quite well, but the hysteresis effect in roughness is very small, which is due to the dune height being almost constant during the second wave (Fig. 9a-b).

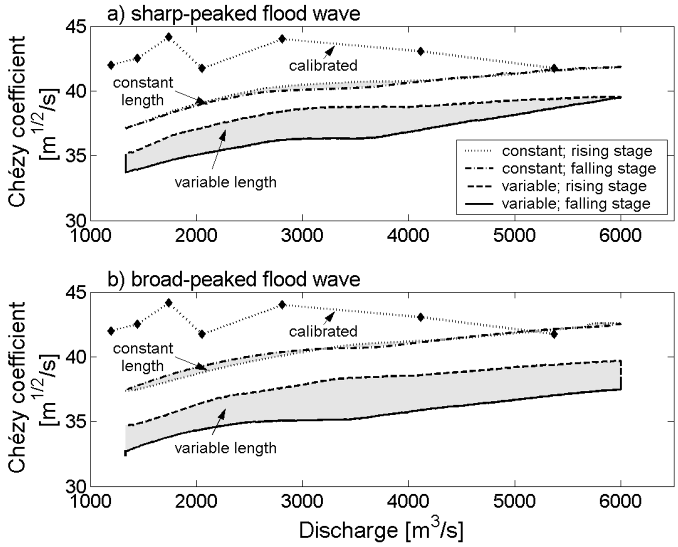

Figure 10: Chézy coefficients of the main channel computed by the dynamic roughness model, compared to the calibrated values (diamond symbols) for (a) sharp-peaked flood wave, and (b) broad-peaked flood wave. Results for both constant and variable dune length are shown, for the second wave in a flood wave.

To analyze the performance of the dynamic roughness model presented in this paper, computed water levels are compared to the originally calibrated model in which the roughness coefficients are a function of discharge. The unsteadiness effects due to accelerations and decelerations during the passage of the flood wave are included. Figure 11 shows the deviation between the water levels computed with the dynamic roughness model and the original stage-discharge relationship for both flood wave types. The over-prediction of main channel roughness yields higher water levels, as computed by the dynamic roughness model, for all cases analyzed in this paper. The oscillating behaviour observed in Figure 11 can be understood as follows. The main channel roughness differs between the dynamic roughness model and the calibrated model yielding different water levels for a certain discharge. Due to the used cross section this implies that certain areas become flooded or empty at different discharges. This effect is not taken into account in the analysis in Figure 11.

Water level differences between the new model and the originally calibrated model are largest at low discharge, if most water is conveyed through the main channel, and lowest at peak discharge. This is attributed to the aspects that (*i*) in practice hydraulic models are calibrated on peak discharges, and (*ii*) the relative influence of the main channel roughness decreases at higher water levels. Dunes reach their maximum dimensions after the peak discharge (Fig. 9) and decrease in dimensions slowly after they have reached their maximum dimensions. This causes that for variable dune length, differences in flow depth are larger for the falling stage than for the rising stage. Differences in water depth can be upto 1 m for low discharge (Fig. 11), which is about 15% in this case. For the broad-peaked flood wave, effects are even larger than for the sharp-peaked flood wave, since dunes are also higher for that case.

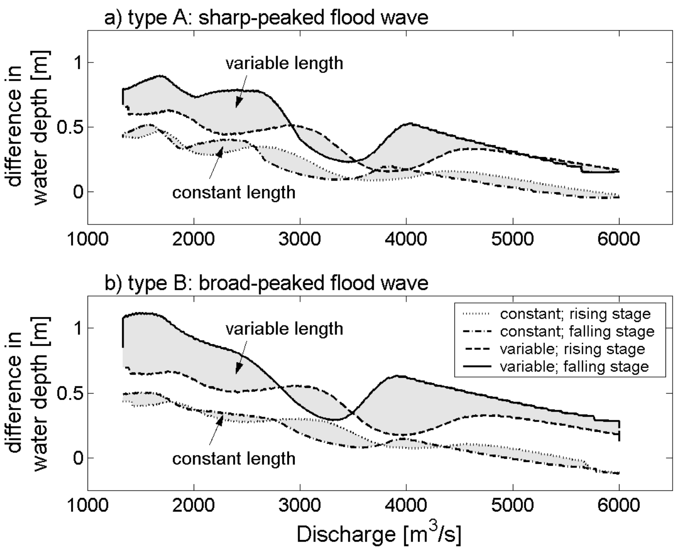

Figure 11: Differences of the stage-discharge relationships between the the dynamic roughness model and the originally calibrated model for (a) sharp-peaked flood wave, and (b) broad-peaked flood wave (for the second wave, conform Fig. 10).

5 DISCUSSION

The roughness coefficients and water depth are generally over-predicted by the new dynamic roughness model, compared to the calibrated model, especially for low discharge. There could be three main causes for these differences: 1) the dune dimensions are predicted incorrectly, 2) the translation of dune dimensions into a roughness coefficient is incorrect, or 3) in the calibrated model the term $k_{uncertain}$ in Eq. (1) is large. We will discuss these issues here.

The dune development model employs periodic boundary conditions, and the flow is forced by the channel slope and water depth. The two required coefficients for the turbulence model, which determine the eddy viscosity and bed resistance, are based on a calibration for flume conditions (see Paarlberg et al., subm.). The water depth, channel slope and these two coefficients determine the discharge that is 'forced' through the domain. For larger water depths in field situations, this approach tends to underpredict the discharge that is modelled in the dune development model (i.e. velocities are too low), compared to that used in Sobek. This might indicate that a recalibration is required. However, computed dune dimensions for the sharp-peaked flood wave (based on 1998 flood wave shape) and constant dune length compare quite well with measured dimensions, if we take into account that the dune development model predicts maximum dune dimensions rather than average dune dimensions.

Table 1. Sensitivity analysis for roughness correction factor γ for sharp-peaked flood wave and variable dune length. C_m is the main channel Chézy coefficient, and H_{diff} represents the difference in flow depth between the dynamic roughness model and the calibrated model (conform Fig. 10). [..] indicates that a certain parameter is averaged over a wave.

Case	γ	Δ_{max} *m*	[Δ] *m*	[λ] *m*	[Δ/λ]	[C_m] $\sqrt{m/s}$	[H_{diff}] *m*
calibrated model						42.7	
γ reference	0.35	3.86	3.32	60.3	0.055	36.6	0.53
γ -50%	0.18	3.72	3.15	57.5	0.055	41.7	0.09
γ +50%	0.53	3.96	3.42	62.2	0.055	33.5	0.82

The second issue is related, since a roughness correction coefficient γ=0.35 was introduced into Eq. (2) to represent the roughness of the average dune dimensions (Section 2.3). Table 1 gives the results of a sensitivity analysis for the sharp-peaked flood wave and variable dune length by varying the value of γ (parameters are averaged over the second wave). Dune dimensions are marginally influenced, but hydraulic parameters change significantly. The Chézy coefficients and water depth differences as function of discharge do not really change, but the results change in absolute sense, meaning that the stage discharge relationships shift upwards or downwards depending on γ. If the value of γ is halved, differences between the originally calibrated model and the dynamic roughness model (H_{diff}) become much less, both in terms of Chézy coefficients and differences in water depth (Tab. 1). This indicates that future research is required on this parameter, focussing on how irregularity in dunes can be taken into account in this model. More insights on this aspect might be obtained by calibrating hydraulic models for situations where also dune dimensions are known.

The third issue relates to the term $k_{uncertain}$ in Eq. (1), which contains uncertainties in the roughness coefficient or model errors. This term is not taken into account for the comparisons made in this paper, since it is not known for the calibrated model. The dune development model shows that for the sharp-peaked flood wave, at the end of the wave, dunes of significant height are present (independent on the roughness correction coefficient γ), which might be relevant information for shipping activities. This information can not be obtained from calibration of water levels and discharge as is done in current practice. Instead, the resistance caused by these higher dunes might be incorporated into the term $k_{uncertain}$.

The new dynamic roughness model provides more insight in the part of the main channel roughness coefficient, associated to time-development and hysteresis effects of dunes. Future work should aim on further reducing the uncertainties in the roughness coefficient of the main channel. This could be done by recalibrating main channel roughness coefficients on the term $k_{\mathrm{uncertain}}$, and including the dynamic roughness caused by dunes using the approach presented in this paper.

6 CONCLUSIONS

This paper presents an approach to include dune dynamics into the hydraulic model Sobek, which can be applied on river-reach spatial scale and flood wave time scale. The dune development model reduces the computational effort to a minimum, but retains the most essential processes on a physical basis. In contrast to empirical models, this allows to apply the model to situations for which it was not calibrated, with more confidence.

Time-lag in dune height development is captured by the model. This results in a hysteresis effect in dune height and main channel roughness, which differs for different flood wave types, especially if the dune length varies significantly. Predicted dune aspect ratios are well within range with other research, and dunes appear to develop to a more or less constant aspect ratio (i.e. ~0.055), which causes the dune height to become approximately constant if the dune length is constant.

Differences in flow depths between the new dynamic roughness model and the originally calibrated model are significant, especially at low discharge, but depend on the roughness correction factor γ. Due to the hysteresis effect in dune roughness, flow depths are significantly different between the rising and the falling stage. A broad-peaked flood wave with variable dune length leads to more effects on water levels, since dunes have ample time to adapt to the high discharge. Thus, for a hydraulic model with calibrated roughness coefficients it is important to know the underlying shape of the flood wave that is used for calibration. In the new dynamic roughness model, this effect is automatically accounted for, since dune dynamics are explicitly modelled.

Future work should aim on further reducing the uncertainties in roughness coefficient of the main channel. In this way, the elements that end-up in the *garbage bin* of hydraulic models might be reduced.

ACKNOWLEDGEMENTS

This research is supported by the Technology Foundation STW, applied science division of NWO and the technology program of the Ministry of Economic Affairs (Project No. 06222).

REFERENCES

Allen, J.R.L. 1976. Computational models for dune time-lag: general ideas, difficulties and early results. *Sedimentary Geology*, 15: 1–53.

Bennett, S.J. & Best, J.L. 1995. Mean flow and turbulence structure over fixed, two-dimensional dunes: implications for sediment transport and bedform stability. *Sedimentology*, 42 (3): 491–513.

Carling, P.A., Gölz, E. Orr, H.G. & Radecki-Pawlik, A. 2000. The morphodynamics of fluvial sand dunes in the River Rhine, near Mainz, Germany. I. Sedimentology and morphology. *Sedimentology*, 47: 227–252.

Einstein, H.A. & Barbarossa, N.L. 1952. River channel roughness. *Transaction ASCE*, 117: 1121–1146.

Giri, S., Yamaguchi, S., Shimizu, Y. & Nelson, J. 2007. Simulating temporal response of bedform characteristics to varying flows. *In*: Dohmen-Janssen and Hulscher (Eds.), *Proc. of RCEM 2007, Enschede, the Netherlands*, (2): 939–947. Taylor & Francis Group, London.

Julien, P.Y. & Klaassen, G.J. 1995. Sand-dune geometry of large rivers during floods. *Journal of Hydraulic Engineering*, 121 (9): 657–663.

Paarlberg, A.J., Dohmen-Janssen, C.M., Hulscher, S.J.M.H. Van den Berg, J. & Termes, A.P.P. 2006. Modelling morphodynamic evolution of river dunes. *In*: Ferreira, Alves, Leal, and Corsado (Eds.), *Proc. of Riverflow 2006*: 969–978. Taylor & Francis Group, London.

Paarlberg, A.J., Dohmen-Janssen, C.M., Hulscher, S.J.M.H. & Termes P. 2007. A parameterization of flow separation over subaqueous dunes. *Water Resources Research*, 43 (W12417).

Paarlberg, A.J., Dohmen-Janssen, C.M., Hulscher, S.J.M.H. & Termes, A.P.P. subm. Modelling dune development using a parameterization of flow separation. *Submitted to Journal of Geophysical Research – Earth Surface.*

Perumal, M., Shrestha, K.B. & Chaube, U.C. 2004. Reproduction of hysteresis in rating curves. *Journal of Hydraulic Engineering*, 130 (9): 870–878.

Termes, A.P.P. 2004. Herziening Qh-relaties Venlo en Megen en afleiding Qh-relaties Belfeld-beneden en Lith-boven. Tech. Rep. PR902 (in Dutch), HKV Consultants, Lelystad, the Netherlands.

Udo, J., Bakker, M. & Termes, P. 2007. SOBEK-model Rijn; hydraulische calibratie. Report PR1158 (in Dutch), HKV Consultants, Lelystad, the Netherlands.

Van den Brink, N.G.M., Beyer, D., Scholten, M.J.M. & van Velzen E.H. 2006. Onderbouwing hydraulische randvoorwaarden 2001 vaan de Rijn en zijn takken. RIZA report 2002.015 (in Dutch), RIZA, the Netherlands.

Van der Mark, C.F., Blom, A. & S.J.M.H., Hulscher 2007. Variability in bedform characteristics using flume and river data. *In*: Dohmen-Janssen & Hulscher (Eds.), *Proc. of RCEM 2007, Enschede, the Netherlands*, (2): 923–930. Taylor & Francis Group, London.

Van Rijn, L.C. 1993. *Principles of sediment transport in rivers, estuaries and coastal seas*. AQUA Publications.

Warmink, J.J., Booij, M.J., van der Klis, H. & Hulscher S.J.M.H. 2007. Uncertainty in water level predictions due to various calibrations. *In*: C. Pahl-Wostl (Ed.), *Proc. of CAIWA 2007, Basel, Switserland*: 1–18.

Wilbers, A.W.E. 2004. *The development and hydraulic roughness of subaqueous dunes*. PhD thesis, University of Utrecht, Utrecht, the Netherlands.

Wilbers, A.W.E. & Ten Brinke, W.B.M. 2003. The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. *Sedimentology*, 50: 1013–1034.