River dune dynamics in regulated rivers

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Abstract
The river bed of lowland rivers typically consists of river dunes. These dunes are the major source of roughness for the river flow and so, changes in their dimensions affects the roughness significantly. During floods these dunes grow in length and height. Numerical model studies and laboratory experiments have shown that for extreme discharges these dunes will wash out, i.e upper stage plain bed (USPB), decreasing the water level. In this study we investigate at which locations along the river Rhine, flattening of the dunes or USPB are most likely to occur, using the data-based relationship found by Naqshband et al. (2014a). The flood hydrodynamics is generated by WAQUA. Next, we will apply the steplength approach of van Duin et al (2017) to model this transitions on river scale and assess the water level reduction. Potentially, this USPB may lead to a self-regulation process in rivers decreasing water levels at the extreme discharges which may occur due to climate changes.

1. Introduction

Figure 1 shows river dunes in the dutch rivers Waal and Upper Rhine. These main channel dunes are the major source of roughness for the river flow. During floods these dunes are dynamic: they migrate downwards and grow in length and height. These enlarged dunes make the roughness increase significantly, blocking the flow and thereby increasing the water height. Numerical model studies and laboratory experiments have shown that for extreme discharges these dunes will wash out (Naqshband et al., 2014b), i.e upper stage plain bed (USPB). This will lead to a significant decrease in water level. At this moment the bed transition models are not calibrated yet for real river situations, so it is unknown at which water discharge exactly this transition will happen. It is suspected that USPB might have been present in the Meuse near Heusden in the Netherlands (Adriaanse, 1986). However it is still unknown whether USPB can develop under Dutch design conditions. In this study we investigate at which locations along the river Rhine, flattening of the dunes or USPB are most likely to occur, using the data-based relationship found by Naqshband et al. (2014a). This study aims to find out whether and where USPB may occur under design conditions in the Netherlands.

2. Method

To find out whether USPB can occur in the Netherlands two analyses are performed. The first analysis uses flow and sediment characteristics to calculate Froude and Suspension numbers along the Dutch river system (Eq. 1 & 2).

$$Fr = \sqrt{u/gh} \tag{1}$$

$$Suspension\ number = u_*/w_s \tag{2}$$

Where; u is the flow velocity; g is the gravitational acceleration; h is the water depth; u_* is the shear velocity and w_s is the fall velocity. The flow characteristics are obtained from a WAQUA-simulation with a discharge of 16,000 m^3/s at Lobith. The sediment characteristics are obtained from measurements performed by RWS (Ten Brinke, 1997).

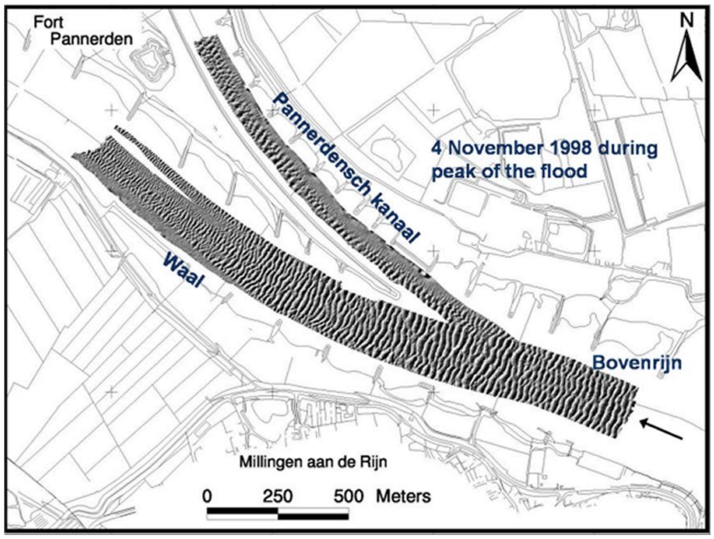

Figure 1. Dunes at the Pannerdensche Kop in the Upper Rhine during a flood (Wilbers & Ten Brinke, 2003)

We introduce the USPB-index for determining the most probable location for USPB. This index is a dimensionless indicator allowing the comparison of different locations on their probability to develop USPB. The USPB-index is computed as the shortest dimensional distance to the dashed line in Fig. 2. The indices are determined for every location in the Rhine branches and the Meuse with an interval of 20 meters along the river. Values above the dashed in line in Fig.2 are formulated as negative values, this allows to state that the location with the lowest USPB-index is the most-USPB-probable location.

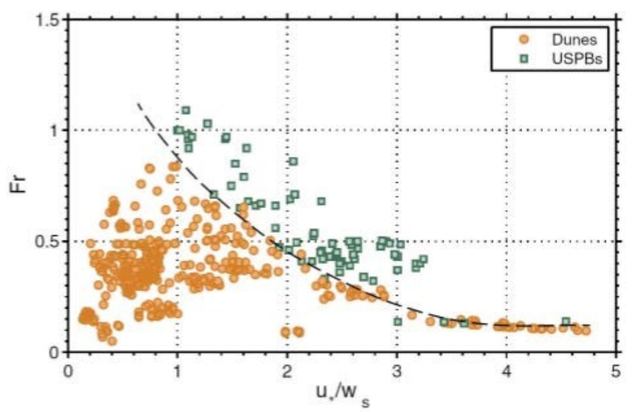

Figure 2: Observed bed forms with Froude and Suspension numbers (Naqshband et al., 2014a).

The second analysis incorporates the dynamic behaviour of dune development, using the morphodynamic model of Van Duin et al. (2017). Firstly, the model is calibrated upon observed equilibrium dune heights in flume conditions (Coleman et al., 2005; Naqshband et al., 2014b). Secondly, the model is calibrated on river scale with observed dune heights in the Waal in 2002 and 2003 (Sieben, 2004). This second calibration is performed on the observed dune heights, by adapting the coefficients that influence the eddy viscosity and partial slip (beta-coefficients). Because there are no actual observations of USPB, the dashed line in Fig. 2 is used to calibrate the moment of the transition to USPB.
The re-calibrated model of Van Duin et al. (2017) is then applied to the location with the lowest USPB-index. We used the hydrodynamic conditions in the Rhine belonging to design discharge wave of 16,000 m^3/s to evaluate development of USPB.

3. Results

3.1 USPB-index

We found that the IJssel just upstream of Kampen (river kilometre 994) was the most probable location for USPB. The USPB-index was above zero (0.03), which means in the dune regime in Fig. 2, so it is expected that dunes still will be present, though an onset to flattening is expected.

3.2 Results of the calibrations for field conditions

Adapting the step-length-model gave good results for flume conditions (Nash-Sutcliff=0.7) and adapting the beta-coefficients to 0.245 gave reasonable results for the calibration for field conditions (NS=0.3). The simulated water depths were in range with the observations. These results were considered sufficiently accurate to have confidence in the model to predict if USPB conditions can be achieved.

3.3 Upper Stage Plane Bed development under the design discharge

We applied the fully calibrated model to the Ijssel, near Kampen. The simulated dune heights during the design discharge show that USPB starts to develop during day 6 (Fig 3). This suggests that USPB can indeed develop in the IJssel just upstream of Kampen. The second most probable location (river Waal near Tiel) did not show development of USPB.

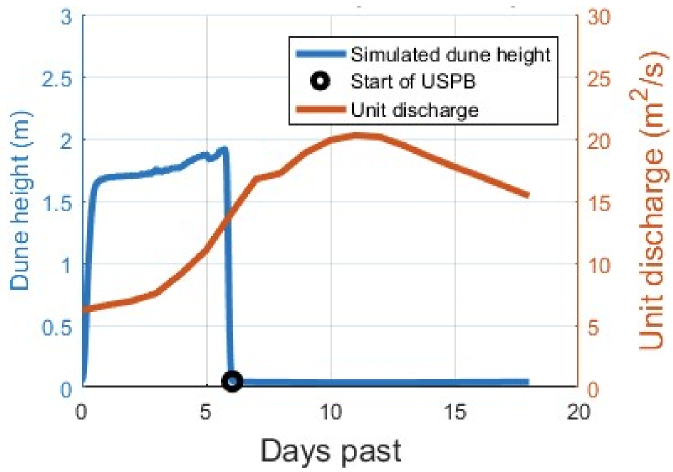

Figure 3: Dune height evolution during the design unit discharge wave at the IJssel near Kampen

4. Discussion

The model predicts USPB where the USPB-index does not. This difference may be caused by the model application on river scale and by the uncertain roughness in the WAQUA-simulation. The model on the river scale is applied on the central part of the river while the dashed line in Fig. 2 is based upon width-averaged observations. The width-averaged conditions required to develop USPB are higher than the conditions required in the central part of the river. The WAQUA-simulation uses the bed roughness to calibrate; this means the expected depth-discharge relation determines the bed roughness. Hence, the bed is simulated as dunes, while in the model of Van Duin et al. (2017) the bed is dynamic allowing it to become a plane bed, resulting in other flow conditions.

The IJssel upstream of Kampen is the only assessed location found where USPB can develop according to the model of Van Duin et al. (2017) and the most likely location according to the USPB-index. A detailed analysis showed that the small grain size at this location (D_{50} = 0.25 mm) is the main reason for USPB to develop. Therefore, USPB in the Dutch rivers is probably most likely when small grain sizes are present.

5. Conclusion

According to the model-analysis performed in this study, the IJssel near Kampen may develop USPB under a design discharge wave. The dune evolution model of Van Duin et al. (2017) is applied upon a river scale and is shown to be able to predict dune heights and realistic hydrodynamic conditions. Also the exploratory analysis with the newly developed USPB-index indicated that this location is the most likely to develop USPB. Potentially, this USPB may lead to a self-regulation in rivers decreasing water levels at extreme discharges which may occur due to climate changes.

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