River dune based roughness uncertainty for the Dutch Rhine branches

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ABSTRACT: This work aims to establish discharge-dependent main channel roughness scenarios due to dune dynamics for the four largest Dutch river Rhine branches. Roughness predictions were made using three roughness predictors with dune measurements as input. Although a large scatter in the roughness predictions was observed, roughness scenarios were established for all branches. These scenarios indicate a bandwidth of expected roughness values. As expected from literature, increasing main channel roughness is observed with increasing discharge. The large spreading in main channel roughness is expected to significantly affect local water levels in the river system.

1. INTRODUCTION

Hydraulic models are widely used to predict water levels in river systems (Warmink et al. 2013). These hydraulic models are an interpretation of the physical river system. Any model representation goes hand in hand with model uncertainties. For river systems the most important sources of uncertainty are the upstream discharge and the main channel roughness (Warmink et al. 2013, Bozzi et al. 2015). Under the new Dutch probabilistic flood risk approach it is required to explicitly account for these uncertainties in the design and assessment of flood protection systems (Ministerie van Infrastructuur & Milieu, 2016).

In hydraulic modelling the main channel roughness is widely used as a calibration parameter, thereby marginalizing the connection with actual physical behaviour of river dunes. However, this connection is required for accurate uncertainty assessment. Physically, it is expected that dunes grow in height for an increasing discharge and slowly decrease in size for the falling stage of a discharge wave (Julien et al. 2002). This general discharge-dependent behaviour is observed in various large rivers, e.g. the Mississippi river (Julien et al. 1995) and the Upper Rhine (Julien et al. 2002, Warmink et al. 2013). Observations have shown that dunes in some rivers do not show this consistent behaviour, e.g. the river Waal (Frings & Kleinhans, 2008). At the same time a large spread in dune heights for the same hydraulic conditions is often observed. These uncertain dune dynamics strongly affect the predictions of main channel roughness.

This study aims to quantitatively estimate the uncertainty range in main channel roughness due to the presence of river dunes for a range of hydraulic conditions. This uncertainty is expressed in roughness scenarios for various river branches. The purpose of these scenarios is using them in a system analysis of a bifurcating river system. Predictions for hydraulic roughness due to river dunes are carried out for 7 locations in the three branches in the Dutch river Rhine after the river has bifurcated (Fig. 1).

The outline of this paper is as follows. In section 2, the domain is characterized, the available data sources are shown, the roughness predictors are introduced and the method to construct roughness scenarios is described. In section 3 the results are shown

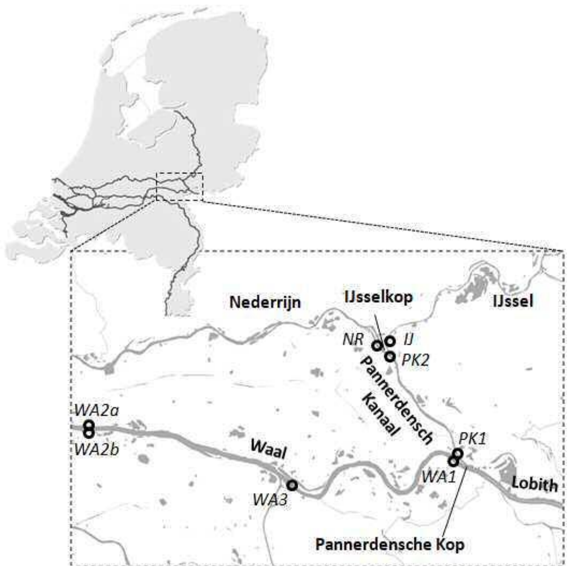

Figure 1. Area of interest. The circles indicate the locations at which dune measurements are available (Table 2). Locations WA2a and WA2b are the northern and southern half of the local main channel.

if the data is implemented in the roughness predictors. From these data points roughness scenarios for every branch are set up. The final two sections are a discussion and a conclusion, respectively.

2. METHODOLOGY

2.1 Domain description

The domain for this study consists of the four largest Dutch Rhine branches shown in Figure 1. Just after entering the Netherlands at Lobith, the Rhine splits into the Waal and the six kilometer long Pannerdensch Kanaal. Subsequently, the Pannerdensch Kanaal splits into the Nederrijn and IJssel. General characteristics of these Rhine branches are shown in Table 1.

Table 1: General characteristics of the Dutch Rhine branches

Branch	Discharge [m^3/s]	Water depth [m]	Mean flow velocity [m/s]	D50 [mm]
Waal	500-11000	1.5-17	0.7-2.0	0.5-2.0
Pan.Kan.	50-6000	1.5-17	0.3-1.5	2.0-9.0
IJssel	50-2700	1.5-13	0.5-2.0	1.0-9.0
Ned.Rijn	0-3400	1.5-13	0-1.5	0.5-5.0

Table 2: Available dune measurements of Wilbers & Ten Brinke (2003; WB03), Sieben et al. (2008; SI08) and Frings & Kleinhans (2008; FK08). The locations are shown in Figure 1.

Source	# data points	Location	Period
WB03	38	WA1	1997-1998
WB03	84	WA2a	1989-1998
WB03	49	WA2b	1994-1998
WB03	31	PK1	1997-1998
SI08	94	WA3	2002-2003
FK08	5	PK2	Jan. 2004
FK08	5	IJ	Jan. 2004
FK08	5	NR	Jan. 2004

2.2 Available data

In several studies the elevation of the river bed of the Dutch Rhine branches has been measured, from which dune characteristics were deduced (Table 2). Additionally, corresponding data on discharges, water levels, flow velocities in the main channel and grain characteristics are available. The amount of available data differs significantly between the branches. Dunes in the river Waal have been measured multiple times, for different hydraulic conditions and at different locations. However, for the rivers IJssel and Nederrijn dune characteristics are only available for a short period in 2004 during low discharge and at one location per branch.

2.3 Roughness predictors

The dune characteristics are translated into main channel roughness values using the formulation of Van Rijn (1993). This method is widely used due to its good match with both flume data as well as data from rivers. To account for uncertainty in the choice of roughness predictor the predictors of Wright & Parker (2004) and Vanoni & Hwang (1967) are added. Along with Van Rijn's predictor these predictors perform well for a section of the Upper Rhine between Lobith and Pannerdensche Kop (Warmink et al. 2013). While the Van Rijn predictor uses only dune characteristics, the Vanoni & Hwang predictor additionally uses water depths and flow velocities. The Wright & Parker predictor is only based on water level and flow velocity data along with general grain characteristics. For location WA3 only the Van Rijn predictor is applied as water depth and flow velocity data is not available for this location.

The Nikuradse roughness height was selected as roughness parameter, because in a conversion to a different roughness parameter the water depth is required, which cannot be obtained objectively for all hydraulic conditions as it would always require the use of a hydraulic model for extreme conditions.

2.4 Roughness scenarios

For each branch an upper and a lower roughness scenario is defined for the range of discharges (Table 1). The two scenarios per branch present the realistic bandwidth of main channel roughness values. Therefore, they be used as input for hydraulic modelling in which the propagation of uncertainties to water levels can be determined.

The scenarios are defined based on dune theory as well as a visual inspection of the data. Wherever unrealistic roughness values are predicted by a predictor, which is the case for the Wright & Parker predictor, these values are discarded from the analysis. Linear functions of discharge versus roughness height are chosen as a first order estimate of the discharge-dependency. Hysteresis is expected to cause non-linear effects which are not taken into account in this analysis.

As theory predicts increasing dune heights and associated roughness for an increasing discharge the roughness scenarios are defined with a positive slope. The slopes are based on the average trend in the data of the river Waal as for this branch sufficient data is available. For the other branches the slopes of the scenarios are assumed equal to that of the Waal as for these branches insufficient data is available to independently estimate a slope. It is thus assumed that the discharge-dependent behaviour of the dunes is similar.

For the Pannerdensch Kanaal the intercept of the upper scenario is changed to represent the observed roughness values. Subsequently, this upper scenario for the Pannerdensch Kanaal is also used for the IJssel and Nedderijn as for these branches too little data is available and the characteristics are more similar to that of the Pannerdensch Kanaal than to the Waal (Table 1).

3. 3 RESULTS

Figure 2 shows the defined roughness scenarios along with the roughness predictions for the available dune data using the three roughness predictors.

It is observed that the dunes are higher in the Waal river compared to the other branches, which also leads to higher main channel roughness values. This is likely caused by the relatively coarse-grained river beds of the Pannerdensch Kanaal, IJssel and Nederrijn.

It is also observed that the Wright & Parker formulation predicts significantly different roughness heights compared to the other two predictors. It predicts unrealistically high and unrealistically low roughness values for the fine-grained and coarse-grained branches respectively.

4. 4 DISCUSSION

Using the roughness predictors of Van Rijn (1993), Vanoni & Hwang (1967) and Wright & Parker (2004) roughness scenarios were defined using dune and hydraulic data from the Dutch Rhine branches. Even though little data was available for the IJssel and Nederrijn branches, roughness scenarios for these branches were defined using information from the other branches.

The results indicate a discharge-dependent main channel roughness, which is consistent with literature (Julien et al. 2002, Naqshband et al. 2014). However, this discharge-dependency is not as large as for the upper Rhine (Warmink et al. 2013).

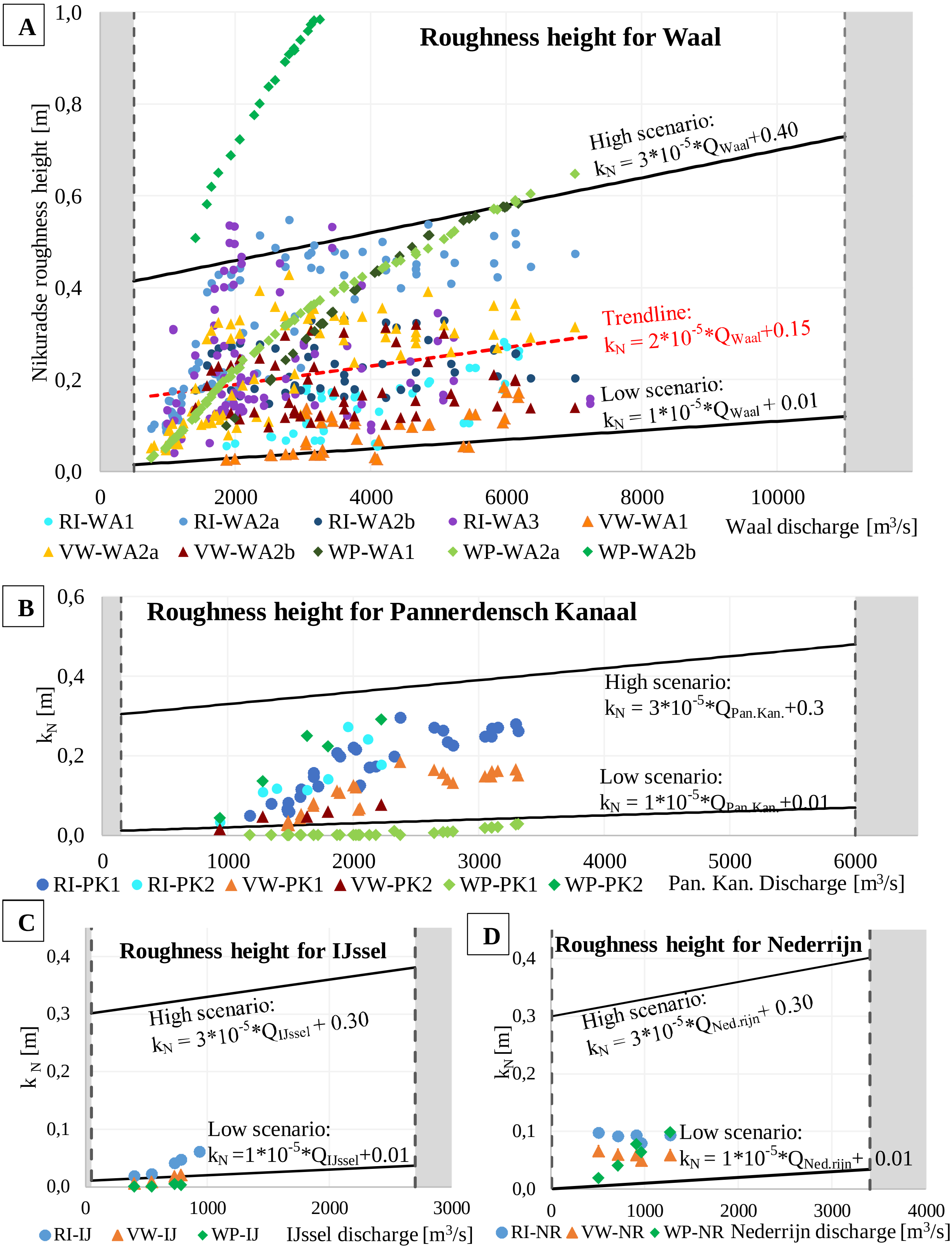

Figure 2: Nikuradse roughness heights calculated with the Van Rijn (RI), Wright & Parker (WP) and Vanoni & Hwang (VW) roughness predictors for the available data in the respective branches: (A) Waal, (B) Pannerdensch Kanaal, (C) IJssel, (D) Nederrijn. The black lines indicate the visually constructed roughness scenarios constructed. For the IJssel and Nederrijn branch the roughness scenarios are similar to those of the Pannerdensch Kanaal. The red dotted line in plot (A) shows the linear trend through the RI and VW data. The Wright & Parker predictor is discarded from the analysis wherever it gives unrealistic roughness values.

This inconsistency was also observed by Frings & Kleinhans (2008). In cases where the flow strength is large enough during very high discharges, upper stage plane bed (USPB) may develop. It is not known whether this will occur in any of the Dutch Rhine branches (Hulscher et al. 2017). If it is able to develop at high discharges, grain roughness may be an indication of the roughness values. With 90th percentile grain sizes in the order of 10 mm (Frings & Kleinhans, 2008), the grain roughness is in the order of 0.03 m (k_N = 3*D90. Van Rijn, 1993). For the smaller IJssel and Nederrijn branches, the lower scenario is in the same order of magnitude and may be an estimate for the roughness under the influence of upper stage plain bed.

Furthermore, a large spreading in dune heights and subsequent roughness predictions is observed. This demonstrates the large uncertainty involved with main channel roughness. Partly this uncertainty is caused by inaccuracies in the methods to deduce dune characteristics from longitudinal river profiles.

In this paper the roughness scenarios have been defined under the assumption of similar dune dynamics on the various branches. The stronger discharge-dependency of main channel roughness for the Pannerdensch Kanaal is an indication that differences between the dune dynamics for the branches exist. Such variations in dune dynamics in the considered branches have also been found by Frings & Kleinhans (2008). It is therefore possible that the assumption of similar dune dynamics in the branches is not fully valid.

The roughness scenarios serve as input for a sensitivity analysis in the bifurcating river system. It is expected that the wide ranges of main channel roughness values expressed in the roughness scenarios cause a large spread in modelled water levels for the analysed river branches.

5. CONCLUSIONS

This abstract has presented roughness predictions and extreme scenarios for the Dutch Rhine branches. The results showed that the dune dynamics and its resulting main channel roughness are not significantly discharge-dependent for the analysed branches, with the exception of the Pannerdensch Kanaal. The uncertainty in main channel roughness is large, which is indicated by the large spread in the roughness predictions.

Future work should aim at improving the roughness scenarios by including more dune data, especially for the IJssel and Nederrijn branches. Subsequently, the roughness scenarios can be used to estimate the effect of the main channel roughness on the water levels in the river Rhine system.

6. ACKNOWLEDGEMENTS

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