Water Level Uncertainties Due to Uncertain Bedform Dynamics in the Dutch Rhine System

Matthijs R. A. Gensen, Jord J. Warmink and Suzanne J. M. H. Hulscher

Abstract Quantitative estimations of water level uncertainties are essential for the design and assessment of flood protection systems. This work aims to quantify the water level uncertainties in the bifurcating Dutch river Rhine system as a result of main channel roughness uncertainty. An one-dimensional hydraulic model of the Rhine branches is used to estimate the water levels in the system for several roughness scenarios. Model results show that the roughness effect has a large influence on the modelled water levels. However, for the larger Waal branch, the changing discharge distribution counteracts the roughness effect, thereby decreasing the range of possible water levels. For the smaller Nederrijn and IJssel branch it is possible that the discharge in the respective branch increases even though the branch has a high roughness. Thereby, for these branches the discharge distribution effect increases the range in modelled water levels. The large and varying effects on water levels by roughness uncertainty and changing discharge distributions in a bifurcating river system indicate the importance to consider the system as a whole instead of as separate branches in the design and assessment of river engineering works.

Keywords River bifurcation · Uncertainty · Hydraulic modelling · Rhine · Bedforms

1 Introduction

In a river delta the river system consists of multiple bifurcating river branches, creating a complex and dynamically active system. These systems experience a large risk of flooding with the threat coming from both the seaward and landward side. In a bifurcating river, local changes in the system can cause changes in water levels of the entire system due to a varying discharge distribution over downstream branches. These system effects, via a changing discharge distribution, may have an important influence on the future planning of river engineering works.

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In several countries around the world, e.g. the UK, the USA and the Netherlands, probabilistic approaches are incorporated in flood risk practice. Under a probabilistic approach, flood protection systems are not designed and assessed on the basis of exceedance probabilities, but instead on the basis of probabilities of flooding. As a consequence, it is important to take into account the full probability distribution of all water levels. Furthermore, in a probabilistic framework, uncertainties play an important role as uncertainties influence the probability of flooding. Therefore, there is an increasing need to include the influence of uncertainties in river management.

The most important sources of uncertainty in river water levels are the upstream discharge and the main channel roughness due to large-scale river bedforms (Gensen 2018; Warmink et al. 2013). In the bifurcating river system uncertainties in water levels may strongly affect the distribution of discharge over branches. Such interaction is one of the most complex factors if performing an uncertainty analysis (Merz et al. 2015). This study aims to quantify the system effects, caused by the presence of a river bifurcation, on the uncertainty in river water levels for a range of discharges. It is investigated how uncertain river bedform characteristics in the bifurcating river affect the water levels throughout the system.

2 Study Area: Dutch River Rhine System

The study area consists of the upper reaches of the Dutch Rhine branches (Fig. 1). Near Lobith the Upper Rhine enters the Netherlands. At the Pannerdensche Kop the river splits into the river Waal and the Pannerdensch Kanaal. The division of discharge at this bifurcation point is approximately 2/3 to the river Waal and 1/3 to the Pannerdensch Kanaal. The ten-kilometer long Pannerdensch Kanaal bifurcates into the river Nederrijn (further downstream called river Lek) and the river IJssel.

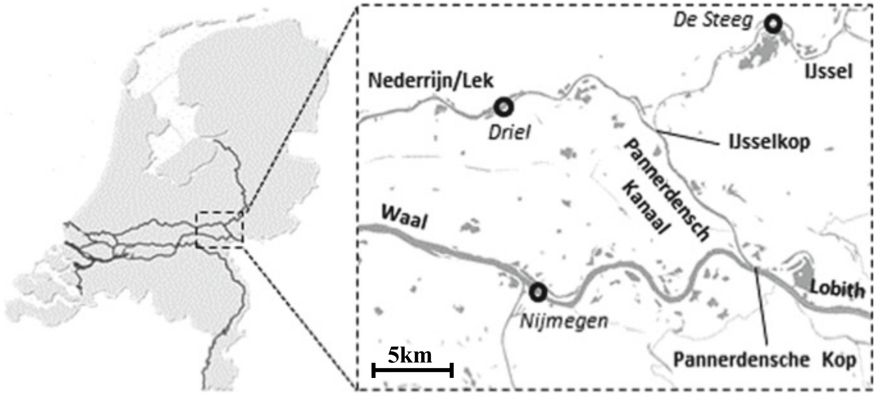

Fig. 1 The area of interest. The circles indicate the representative locations for the branches at which water levels are determined

Table 1 General characteristics of the Dutch Rhine branches

Branch	Discharge [m^3/s]	Water depth [m]	Flow velocity [m/s]	Observed dune heights [m]
Waal	500–11,000	1.5–17	0.7–2.0	0–2.5
Pannerdensch Kanaal	50–6000	1.5–17	0.3–1.5	0–1.2
IJssel	50–2700	1.5–13	0.5–2.0	0–1.5
Nederrijn	0–3400	1.5–13	0–1.5	0–1.2

The discharge distribution is approximately 2/3 and 1/3 towards the Nederrijn and IJssel, respectively. General characteristics of the upper reaches of these branches are given in Table 1. The maximum recorded discharge at Lobith occurred in 1995 and is approximately 12,000 m^3/s. The branches all have a relatively low bed gradient, which is approximately 0.1 m/km. Generally, the branches have wide floodplains, conveying approximately 1/3 of the total discharge at extremely high discharges (Warmink et al. 2013).

3 Methods: Hydrodynamic Model and Roughness Scenarios

In the Netherlands, the Directorate-General for Public Works and Water Management (Dutch: Rijkswaterstaat) uses a Sobek model (Deltares 2015) of the Rhine branches for operational purposes. Sobek is a modelling environment which numerically solves the one-dimensional Saint-Venant equations. A schematization of the Rhine branches in the Sobek environment allows the computation of water levels. In this study the most recent schematization is applied: the 2016 version (*Rijn-j16_5_v1*). The river engineering works which have been executed in the years before, are implemented in this model.

The river is schematized with cross-sections with a longitudinal spacing of approximately 500 m. The cross-sections consist of a flow profile and a storage area. The upstream boundary of the model is a static discharge boundary placed at Lobith (see Fig. 1). Downstream water level boundaries, corresponding to the constant upstream discharge, lie several tens of kilometers away from the area of interest in this study. The model is run with static discharges ranging from 5000 to 18,000 m^3/s to estimate the for varying upstream conditions.

For every branch a discharge-roughness relationship defines the main channel roughness for the entire branch (Fig. 2). To define these scenarios, data of bedform characteristics derived from bed level measurements in the Rhine branches in various studies (Frings and Kleinhans 2008; Wilbers and Ten Brinke 2003; Sieben 2008) was used. These bedform characteristics were translated into roughness predictions, expressed in Nikuradse roughness height, using the predictors of Van Rijn (1993)

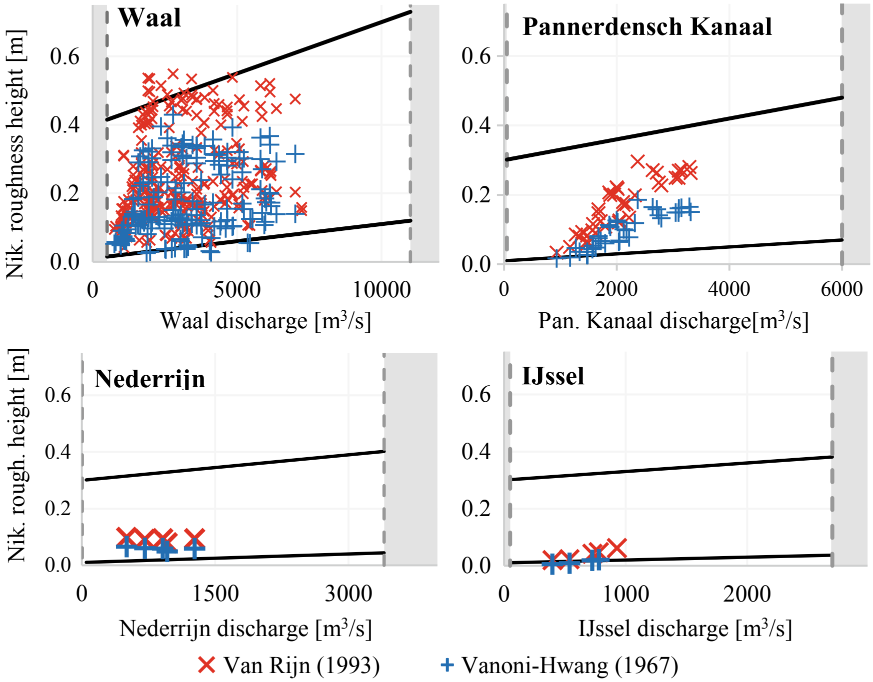

Fig. 2 Predicted roughness values using the Van Rijn (1993) and Vanoni and Hwang (1967) roughness predictors. The black lines show the defined roughness scenarios

and Vanoni and Hwang (1967). For each branch a linear higher limit and a linear lower limit of the discharge-dependent roughness was visually defined based on the roughness predictions (black lines in Fig. 2). These lines represent extreme scenarios of possible low and high roughness for each branch. Further details on the roughness limit lines are found in Gensen et al. (subm.). Finally, the combination of a higher limit or a lower limit per branch for all branches leads to 16 roughness scenarios. The defined roughness scenarios serve as input for the one-dimensional hydrodynamic Sobek model.

4 Results

The results are shown for three representative locations in the branches: Nijmegenhaven for the Waal, De Steeg for the IJssel and Driel for the Nederrijn (see Fig. 1). Figure 3 displays the modelled water levels at the three locations as a result of the 16 roughness scenarios as a function of upstream Lobith discharge. It shows the average water levels and bandwidth of water levels conditional on the roughness in

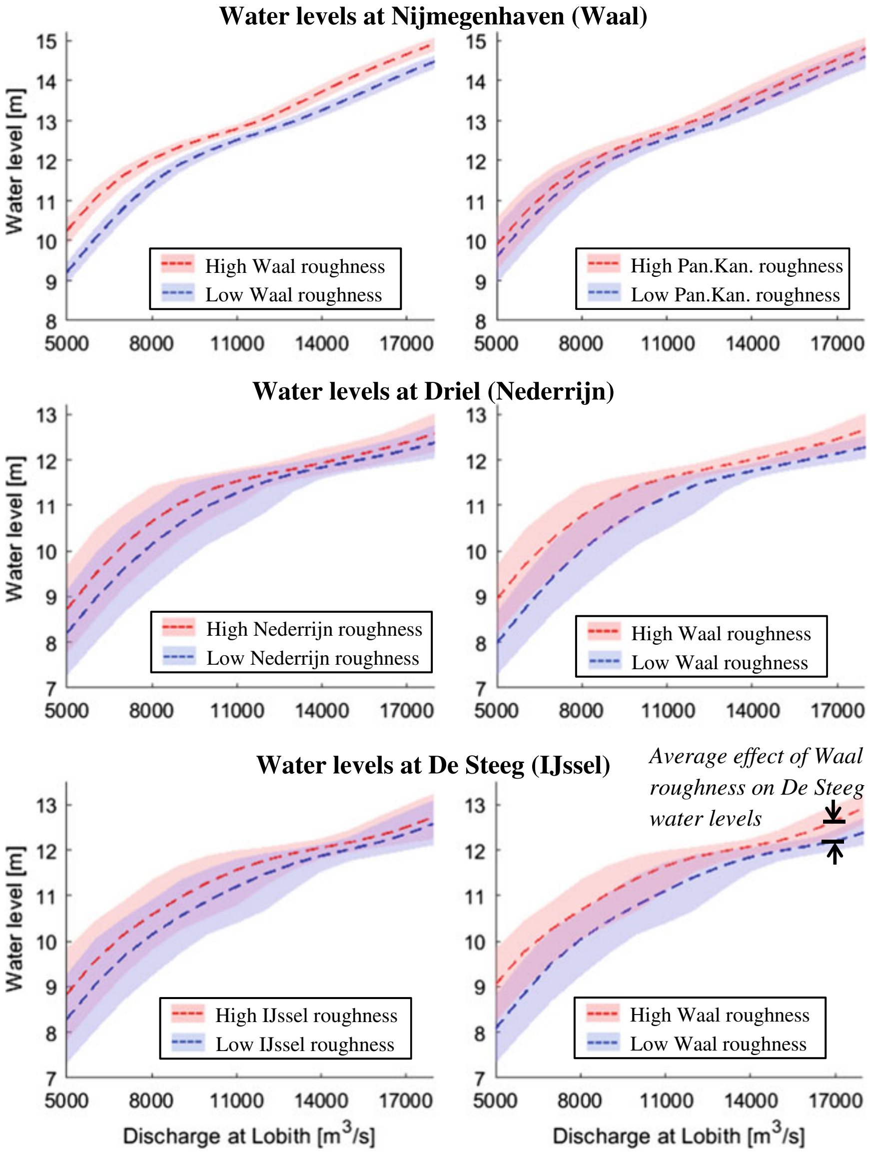

Fig. 3 Water levels at the three representative locations (see Fig. 1) as a function of upstream Lobith discharge for the 16 roughness scenarios. The dashed lines give the average of the 8 scenarios with either a high or a low roughness in the signified branch. The shaded area shows the range in possible water levels given a high or low roughness in the signified branches. The black arrows in the lower right figure illustrate the average water level effect of a change in roughness in the signified branch on the water levels at the location. Values of this average effect for all combinations of branches and locations are given in Table 2

one of the branches. Tables 2 and 3 summarize the average effects of the roughness per branch on the water levels (indicated in the lower right panel of Fig. 3) and discharges, respectively, for every location. This average effect is defined as the difference between the average water levels at the location or the average discharge in a branch for the 8 scenarios with a high roughness in the signified branch and the 8 scenarios with a low roughness in the signified branch, for an upstream discharge of 17,000 m^3/s, which is the design discharge of the Dutch Rhine system.

Figure 3 and Table 2 show that, on average, high local roughness values result in high local water levels (e.g. +0.47 m at Nijmegenhaven in the Waal). This value is affected by two mechanisms. Firstly, a high roughness will result in a high water level. The two roughness limit lines in a branch result in two possible (local) stage-discharge relationships, in which a high roughness clearly gives high water levels. Secondly, a high water level in a downstream branch of a river bifurcation, will

Table 2 The difference between the average water level over the 8 scenarios with a high roughness in a branch and the average water level over the 8 scenarios with a low roughness in a branch for an upstream discharge at Lobith of 17,000 m^3/s (design discharge). In Fig. 3 this value is illustrated for the effect of Waal roughness on the water levels at De Steeg (0.45 m). The values in this table can be interpreted as the average effect of the roughness in a branch on the water levels at a certain location

Discharge at Lobith: 17,000 m^3/s		Average effect on the water level at:		
		Nijmegenhaven (Waal)	Driel (Nederrijn)	De Steeg (IJssel)
High versus low roughness of:	Waal	+0.47 m	+0.31 m	+0.45 m
	Pan. Kanaal	+0.21 m	−0.13 m	−0.18 m
	Nederrijn	+0.07 m	+0.17 m	+0.25 m
	IJssel	+0.08 m	+0.23 m	+0.15 m

Table 3 The difference between the average discharge in a branch over the 8 scenarios with a high roughness in the signified branch and the average discharge in a branch over the 8 scenarios with a low roughness in the signified branch for an upstream discharge at Lobith of 17,000 m^3/s. The values in this table can be interpreted as the average effect of the roughness on the discharge in a certain branch. For the Pannerdensch Kanaal, the change in discharge is naturally opposite to that of the Waal branch

Discharge at Lobith: 17,000 m^3/s		Average effect on the discharge in branch:		
		Waal	Nederrijn	IJssel
High versus low roughness of:	Waal	−932 m^3/s (−8.9%)	+354 m^3/s (+9.6%)	+578 m^3/s (+20.1%)
	Pan. Kanaal	+391 m^3/s (+3.8%)	−156 m^3/s (−4.2%)	−235 m^3/s (−8.2%)
	Nederrijn	+126 m^3/s (+1.2%)	−441 m^3/s (−11.9%)	+316 m^3/s (+11.0%)
	IJssel	+148 m^3/s (+1.4%)	+261 m^3/s (+7.1%)	−409 m^3/s (−14.2%)

change the discharge distribution with a lower amount of discharge for the branch with a high water level (see Table 3, e.g. 937 m^3/s less discharge to the Waal). This in turn will result in a lower water level, thereby counteracting the effect of roughness alone. Table 2 shows that on-average the balance the two counteracting mechanism has a positive balance for every branch (+0.47 m at Nijmegenhaven, +0.17 m at Driel and +0.15 m at De Steeg).

Figure 2 and Tables 2 and 3 show that for the IJssel and Nederrijn, the influence of the Waal roughness on the water levels in these branches is very large. This is caused by the third mechanism: through changes in the discharge distribution, the water levels in a branch are affected by changes in roughness in another branch. For example, a change from low to high roughness in the Waal branch causes, on-average, an increase in discharge towards the IJssel of 578 m^3/s (Table 3), which causes an average increase in water levels of 0.45 m (Table 2). For the IJssel and Nederrijn branches, the average effect of the Waal roughness is larger than the average effect of their own roughness. Thereby, it is also possible that discharges in these branches increase due to a high Waal roughness, even though their own roughness is high as well.

The size of the bandwidths in Fig. 3 also gives an indication on the balance of the three mechanisms. It is observed that for the Waal branch, all scenarios with a high Waal roughness result in higher water levels compared to the scenarios with a low Waal roughness (the red-shaded and blue-shaded areas do not overlap). This indicates that a low Waal roughness will always result in a below-average water level and thereby an above-average discharge. The range of possible water levels is thereby reduced, compared to the situation in which the discharge distribution would not adapt. Simultaneously, as the Waal branch draws more discharge, the other branches see both a reduction in water levels and discharge. This causes a large range in possible water levels in the IJssel and Nederrijn branch, as observed in Fig. 3.

5 Discussion

In this paper the changes in the water levels resulting from uncertainty in river bedforms in a bifurcating river system are quantified. River bedform variation is implemented by means of roughness scenarios, capturing an extreme range in main channel roughness uncertainty. The defined roughness scenarios should be considered as very extreme. For less extreme roughness scenarios, the bandwidths in water levels on the branches will be smaller. However, these extreme scenarios have shown the potential effects of roughness uncertainty in a river system. It is observed that changes in roughness and subsequent changes in discharge distributions can have varying, possibly opposite, effects on the water levels, due to the feedback mechanisms. It is expected that for less extreme roughness scenarios these water level variations will still be found and can largely be explained by the effects found for the extreme scenarios.

This study has applied an one-dimensional model to obtain the understanding of the propagation of uncertainties in a bifurcating river system as well as to obtain a first quantitative estimation. In future work it may be necessary to apply a two-dimensional model to attain more accurate uncertainty predictions. Furthermore, a two-dimensional model allows the inclusion of the regulation structures at the bifurcation points of the river Rhine and allows the inclusion of the uncertain effects of river engineering works (Berends et al. 2018) on the discharge distribution.

6 Conclusions

In this study, the effect of uncertain river bedforms on the water levels in the bifurcating river Rhine system was estimated. In the presented case study the presence of river bifurcations showed to have a strong influence on the possible water level variation given the roughness uncertainty. The feedback mechanisms between downstream water levels and discharge distributions can cause both an increase and a decrease in bandwidths in possible water levels. For the larger Waal branch, the effect of a high roughness on the water levels is partly compensated by a reduction in the local discharge. Thereby, the maximum bandwidth in possible water levels is decreased. For the smaller Nederrijn and IJssel branches, scenarios exist in which the discharge in the branch increases even though the branch has a high roughness. Therefore, the discharge distribution effect causes a wider range of possible water levels.

The observed differences in roughness effects and discharge distribution effects on the water levels affect the probabilities of water levels along the branches. Therefore, it is important to regard the branches as an interconnected system in which varying discharge distributions may cause an increasing or decreasing uncertainty in water levels. This impacts river management and future planning and assessment of river engineering works.

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References

Berends KD, Warmink JJ, Hulscher SJMH (2018) Efficient uncertainty quantification for impact analysis of human interventions in rivers. Environ Model Softw 107:50–58

Deltares (2015). SOBEK 3, D-Flow 1D. User manual. Version 3.4.0

Frings RM, Kleinhans MG (2008) Complex variations in sediment transport at three large river bifurcations during discharge waves in the river Rhine. Sedimentoligy 55(5):1145–1171

Gensen MRA, Warmink JJ, Hulscher SJMH (subm.) River dune based roughness uncertainty for the Dutch Rhine branches. Marine and River Dune Dynamics 2019, Bremen, Germany

Gensen MRA (2018) Large-scale uncertainties in river water levels: literature report. University of Twente, Enschede. CE&M research report 2018-001/WEM-001

Merz B, Vorogushyn S, Lall U, Viglione A, Blöschl G (2015) Charting unknown waters—on the role of surprise in flood risk assessment and management. Water Resour Res 51:6399–6416

Sieben J (2008) Taal van de rivierbodem. Rijkswaterstaat

Van Rijn LC (1993) Principles of sediment transport in rivers estuaries and coastal areas. Aqua publications, Blokzijl, Netherlands

Vanoni VA, Hwang LS (1967) Relation between bedforms and friction in streams. J Hydraul Div 93:121–144

Warmink JJ, Booij MJ, Van der Klis H, Hulscher SJMH (2013) Quantification of uncertainty in design water levels due to uncertain bed form roughness in the Dutch river Waal. Hydrol Process 27(11):1646–1663

Wilbers AWE, Ten Brinke WBM (2003) The response of sub-aqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. Sedimentology 50(6):1013–1034