Effects of a river intervention on water levels in a bifurcating river system

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ABSTRACT: In bifurcating river systems, river interventions affect the water levels in all of the downstream branches. An accurate impact quantification is therefore important. However, the hydraulic models used to estimate these impacts are inherently uncertain. This study assesses the impact of a dike set-back and its uncertainty in a bifurcating river system using a 1D network model. The results show that the presence of the river bifurcation strongly decreases the maximum water level reduction and the uncertainty of it. Generally, the uncertainty of the impact scales with the impact itself. However, in a bifurcating river system, the hydraulic roughness parameters that cause the uncertainty in the impact, also have an own influence on the discharge distribution. These interactions all affect the uncertainty of the impact in a bifurcating river system. The knowledge on these interactions can aid in the decision process for the future design of interventions near bifurcations.

1 INTRODUCTION

River flooding is a major natural hazard. In deltaic rivers with multiple branches the risks of flooding are particularly high. To decrease flood risk, investments in river interventions are increasing. An accurate estimate of what the impact of a river intervention is, is essential information in the decision process (Rijke et al. 2012). How cost-effective an intervention is at reducing flood risks is one of the most important factors in deciding which intervention is implemented (Rijke et al. 2012).

Hydraulic models are increasingly being used to assess the impact of an intervention on river water levels at design conditions. Most often these conditions have never occurred or at least never been observed in the current river system (Klijn et al. 2018). Therefore, model input parameters at these conditions are uncertain, leading to uncertain predictions of river water levels at design conditions. Consequently, the impact analysis of river interventions is also prone to uncertainties. Uncertainty in the impact of a river intervention can influence the decision process (Berends et al. 2019).

In a deltaic area, a river splits into multiple downstream branches. How much discharge every downstream branch receives is essential in the hydraulic modelling of these river systems (Schielen et al. 2018, Bomers et al. 2019). This discharge distribution is controlled by the water levels in the downstream branches, which in turn is determined by geometry, hydraulic roughness and discharge (Edmonds 2012, Wang et al. 1995). The discharge distribution is thereby also affected by uncertainties in these parameters. The feedback mechanism between water levels and the discharge distribution provides self-regulation of downstream water levels (Gensen et al., 2020). This self-regulation reduces water level uncertainties; e.g. a higher than expected water level in a downstream branch is partly counteracted by a reduction in discharge towards this branch. This reduction in water level uncertainties affects the probabilities of water levels and thereby the flood risk.

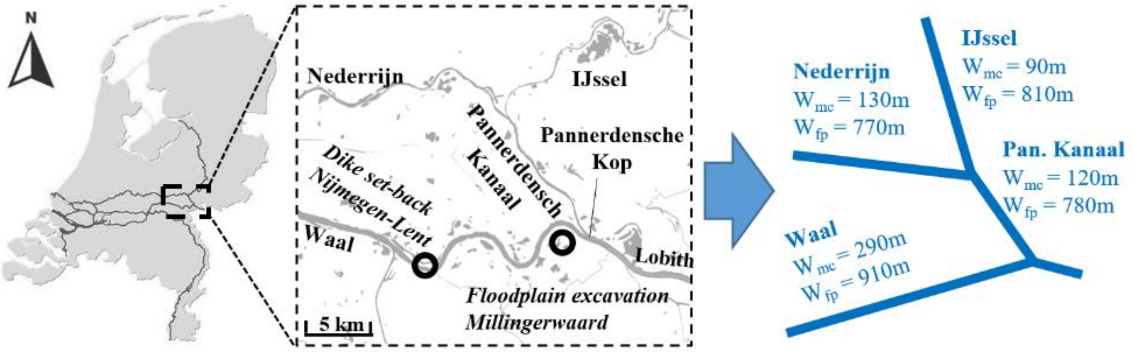

Figure 1. Left: the study area in the Netherlands: the four primary Rhine branches. Indicated with the two circles are two water level reducing river interventions implemented during the Room for the River program. Right: the 1D network schematization of the branches. In this schematization every branch has a uniform compound cross-section with typical main channel width (W_{mc}) and floodplain width (W_{fp}).

Berends et al. (2019) performed impact analyses on various types of river interventions aimed at water level reduction in the river Waal in the Netherlands. Some of the intervention types that were assessed, are: floodplain excavation, dike relocation, side channels and floodplain smoothing. The results showed that not only the expected water level reduction (i.e. the deterministic impact if all model parameters are set to their mean value) varies between interventions, but also the uncertainty of the water level reduction. Generally, a higher water level reduction leads to a larger uncertainty. For example, a deeper floodplain excavation has a bandwidth of water level reductions than a floodplain excavation with a smaller elevation change. Furthermore, the water level reduction impact for some intervention types is inherently more uncertain than for others. For example, a side channel attains a fairly certain amount of water level reduction, while floodplain smoothing by vegetation removal has a fairly uncertain amount of water level reduction (Berends et al. 2019).

If an intervention is implemented in the vicinity of a river bifurcation, it can change the discharge distribution (Glock et al. 2019). In the Dutch Room for the River program 39 projects were executed, all aimed at reducing flood water levels. Some of these projects were built close to the first major bifurcation of the Rhine river in The Netherlands (Fig. 1), e.g. the floodplain excavation at the Millingerwaard and the large-scale dike set-back at Nijmegen-Lent. An increase in discharge towards the Waal would occur due to the reductions in water levels induced by the interventions unless the change in water level at the bifurcation is compensated for in the other branch. This compensation could be achieved by a different setting of the (passive) regulation structure at the bifurcation if it has enough regulating margin (Schielen et al. 2018). For the given examples this was indeed the case. However, one could imagine that for interventions having a larger water level reduction, the regulation structure would not have sufficient regulating margin. In that case, compensation could also be achieved by a compensating intervention in the opposing branch (Schielen et al. 2018). The compensating intervention should then be designed such that at the intended discharge it would have an equal water level impact at the bifurcation as the other intervention, thereby keeping the original discharge distribution intact.

In this study, the impact on water levels and the associated uncertainty of a river intervention in a bifurcating river system are assessed. The impact is the change in water levels along the downstream branches. As a river intervention close to a river bifurcation can change water levels in all downstream branches, the uncertainty of its impact also influences system-wide water levels. The uncertain input parameters, the impact of an intervention and its uncertainty and how the discharge distribution affect each other, will aid in the future design of interventions (and potentially compensating interventions).

2 STUDY AREA AND MODEL SET-UP

In The Netherlands, the river Rhine splits into three main distributaries: the Waal, Nederrijn and IJssel (Fig. 1) The first bifurcation is 5 kilometre downstream from Lobith, the town at which the river Rhine enters The Netherlands. At this bifurcation point, the Pannerdensche Kop, the Rhine

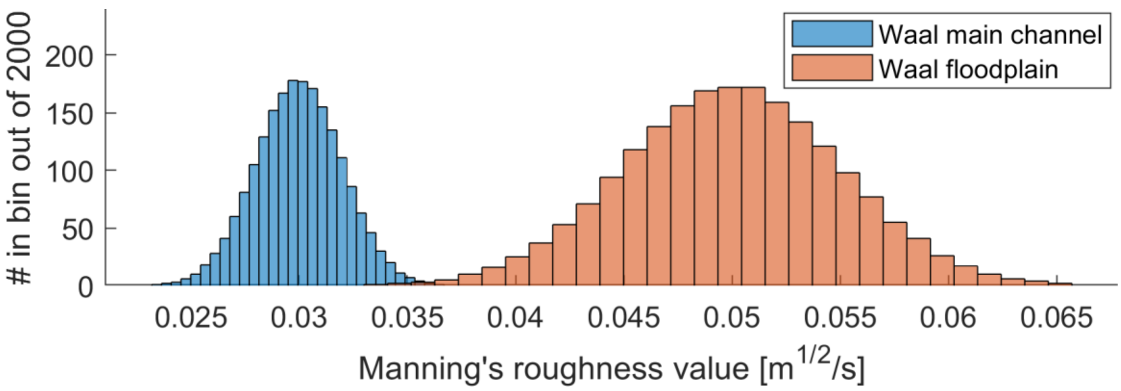

Figure 2. Values of Manning's roughness for the main channel and floodplain of the Waal in the set of 2000 Sobol samples.

splits into the Waal and the Pannerdensch Kanaal. The second bifurcation lies at the end of the six kilometer long Pannerdensch Kanaal, at which it splits into the Nederrijn and the IJssel. Roughly, the discharge distribution over the distributaries is 2/3, 2/9 and 1/9 towards the Waal, Nederrijn and IJssel respectively. The yearly average discharge at Lobith is approximately 2,200 m^3/s. Before 2017, the design discharge was 16,000 m^3/s, while the maximum attainable discharge at Lobith is approximately 18,000 m^3/s (Bomers et al. 2019).

An idealised one-dimensional network model of the Rhine branches in the Netherlands is set up (Fig. 1). The schematization consists of 4 uniform branches, representing the 4 Dutch Rhine branches. The bed slope of every branch is set to 10^{-4}. Every branch has a typical compound cross-section with a main channel and a floodplain. The dimensions of the cross-section are set such that stage-discharge relationships and discharge distributions give realistic values. The upstream boundary conditions is a steady discharge at Lobith. At the end of every distributary a stage-discharge relationship controls the outflow. The downstream boundaries are far enough away to not influence the water levels in the area of interest (~100 km to the bifurcation point). The roughness of the main channel and the floodplain are set as stochastic variables (Fig. 2), as those are generally among the most uncertain parameters (Warmink et al. 2011). For the purpose of this study, the roughness values between the different branches are assumed independent.

3 METHODOLOGY

Four different configurations of the model are used to assess the influence of a river bifurcation on the impact of river interventions. The first two configurations are the reference models, one in which the discharge distributions are not allowed to vary ("Ref – fixed Q") and one in which the discharge distribution is free ("Ref – free Q"). The other two configurations are the intervention models, again one with a fixed discharge distribution ("Int – fixed Q") and one with a free discharge distribution ("Int – free Q"). It is noted that the fixed discharge distribution is a hypothetical configuration, as it is not possible to fix the discharge distribution without an active control structure. This configuration is applied as it helps showing the influence of a free discharge distribution.

The studied intervention is a dike set-back; a typical conveyance capacity increasing intervention generally giving a large water level reduction. The intervention is implemented in the Waal branch, having an upstream end with distance X towards the bifurcation point. This distance X is varied between 1 and 51 kilometres. Over a length of 10 kilometres from the upstream end the floodplain is widened with 500 meters. The widened area has the same roughness as elsewhere in the Waal branch.

A quasi-random Monte Carlo Simulation (MCS) with 2000 Sobol samples is run for every configuration (the two reference models and the two intervention models). Every sample consists of 8 independent roughness values, for every branch a value for the main channel and the floodplain. Figure 3 shows a histogram of the 2000 main channel and 2000 floodplain roughness values for the Waal branch. The Sobol sequence ensures that the individual samples are equal for every MCS.

The impact of an intervention, i.e. the changes in water levels in the entire river system is quantified by subtracting the water levels in the reference model from the water levels in the intervention model. This is done per sample, so that between the reference model and the intervention model the roughness values are equal. This gives a set of 2000 impacts, i.e. changes in water levels in the entire system. From this set a mean impact and the 90% confidence interval of the impact at every location in the system is determined. Finally, the 'relative uncertainty', as introduced by Berends et al. (2019) is determined for every location 'x' in the system (Eq. 1). This metric relates the impact of an intervention to its uncertainty.

$$U_r\ (x) = \frac{Width\ 90\%\ confidence\ interval\ of\ the\ change\ in\ water\ level\ at\ location\ x}{Change\ in\ water\ level\ at\ location\ x} \quad (1)$$

The impact of an intervention and its uncertainty with both a fixed and a free discharge distribution is determined for two cases: 1) example case and 2) variations in location of the intervention. Firstly, the example case is an intervention with its upstream end six kilometres from the bifurcation point for an upstream Lobith discharge of 16,000 m^3/s. This example case will demonstrate what the differences in impacts and uncertainties are for a fixed and free discharge distribution. This information then serves as a base for the subsequent case. Secondly, the location of the intervention along the Waal branch is varied. It is expected that the location of the intervention is irrelevant for the impact with a fixed discharge distribution as the flow parameters are the same along the branch. However, the distance towards the bifurcation point is important for a free discharge distribution as the influence on the discharge distribution weakens gets weaker if the disturbance is moved further away from the bifurcation point..

4 RESULTS

In this section the results are presented for the example case (4.1) and for the case of variations in intervention location (4.2). All results presented here are related to an intervention in the Waal branch, a dike set-back of 500 meters over a length of 10 kilometres, for an upstream discharge of 16,000 m^3/s.

4.1 *Example case*

Clear differences in impact and the uncertainty of the impact are observed between fixing the discharge distribution versus not fixing the discharge distribution (Fig. 3). For a fixed discharge distribution, a typical impact is found: a water level reduction generated over the length of the

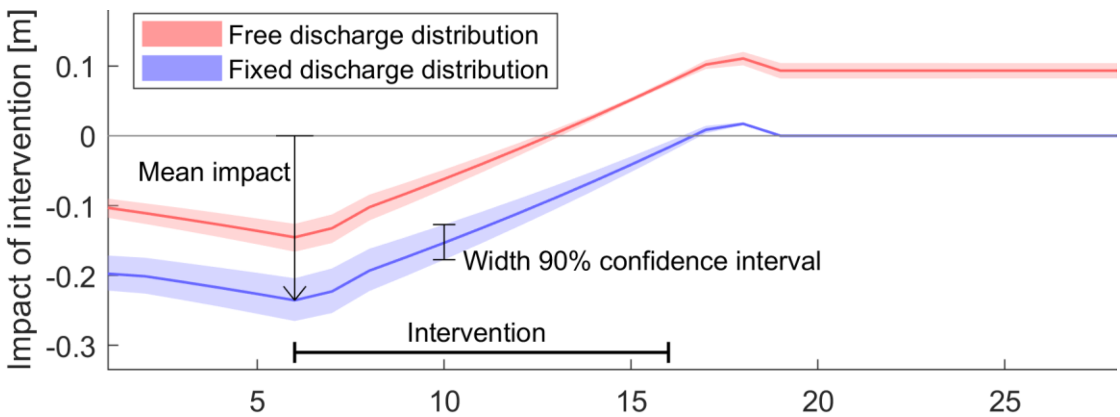

Figure 3. Impact and its uncertainty of an intervention with an upstream end six kilometres into the Waal for an upstream discharge of 16,000 m^3/s. The shaded areas are the 90% confidence intervals while the continuous lines are the mean impacts. If the discharge distribution is free, the water level reducing effect of an intervention is smaller and a clear downstream increase in water levels occurs.

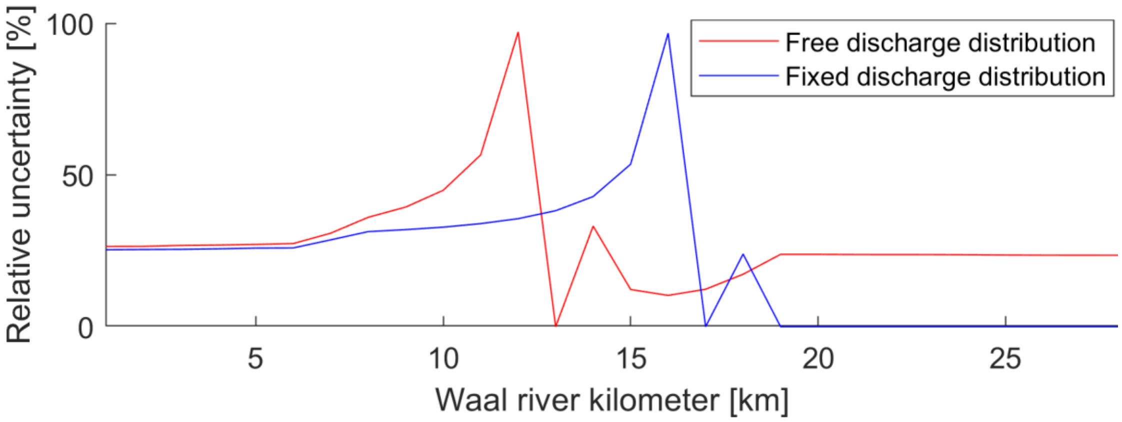

Figure 4. Relative uncertainty of the impact of the intervention in the example case with both a free and a fixed discharge distribution. Having a fixed or free discharge distribution does not influence the relative uncertainty upstream of the intervention. The free discharge distribution has a relative uncertainty downstream that is more or less equal to the relative uncertainty upstream.

intervention with a maximum water level reduction at the upstream end. The impact follows a backwater shape upstream of the intervention. Downstream of the intervention, no change in water levels occur as no changes in stage-discharge relationships and no changes in discharge occur here. As expected, for a free discharge distribution the maximum water level reduction induced by the intervention decreases. This is due to self-regulation of the water levels via an increase in discharge towards the Waal branch, i.e. a disturbance that reduces the water level is counteracted by an increase in discharge. Downstream of the intervention, the water levels are higher than in the reference situation due to the larger Waal discharge. The water levels in the other branches of the system decrease due to a decrease in discharge there (not shown here).

The uncertainty in the impact generally scales with the impact itself, as also found by Berends et al. (2019). This is observed upstream of the intervention, where the width of the 90% reduces in upstream direction. Also, the larger impact under a fixed discharge distribution is accompanied with larger uncertainties. The scaling of the uncertainty of the impact with the impact itself, is reflected in a fairly constant value of the 'relative uncertainty' as function of location (Fig. 4), with a major exception within the area of the intervention. The peaks in relative uncertainty are related to the locations of zero impact, where the uncertainty does not reduce to zero. The constant relative uncertainty is explained by similar lengths of the backwater curve in upstream direction (Berends et al. 2019).

Fixing and letting free the discharge distribution does not significantly influence the relative uncertainty upstream of the intervention (Fig. 4). This indicates that the uncertainty in impact close to the intervention is mainly related to the intervention itself and not related to changes in discharge distribution. Downstream of the intervention, the configuration with a fixed discharge distribution has no relative uncertainty as there is no impact, while in the configuration with a free discharge distribution the water level increase is relatively more or less as uncertain as the water level reduction upstream of the intervention.

4.2 *Influence of varying the location of the intervention*

The location of the intervention has a significant influence on the impact and its uncertainty if the discharge distribution is let free (Fig. 5). In contrast, the location has no influence on the maximum attainable water level reduction if the discharge distribution is fixed. The latter is explained by the uniformity of the branch, signifying that the change in stage-discharge relationship at the intervention is the same for every location of the intervention. Evidently, for a free discharge distribution the influence of the discharge distribution becomes smaller the further away from the bifurcation the intervention is implemented. Thereby, both the maximum water level reduction as

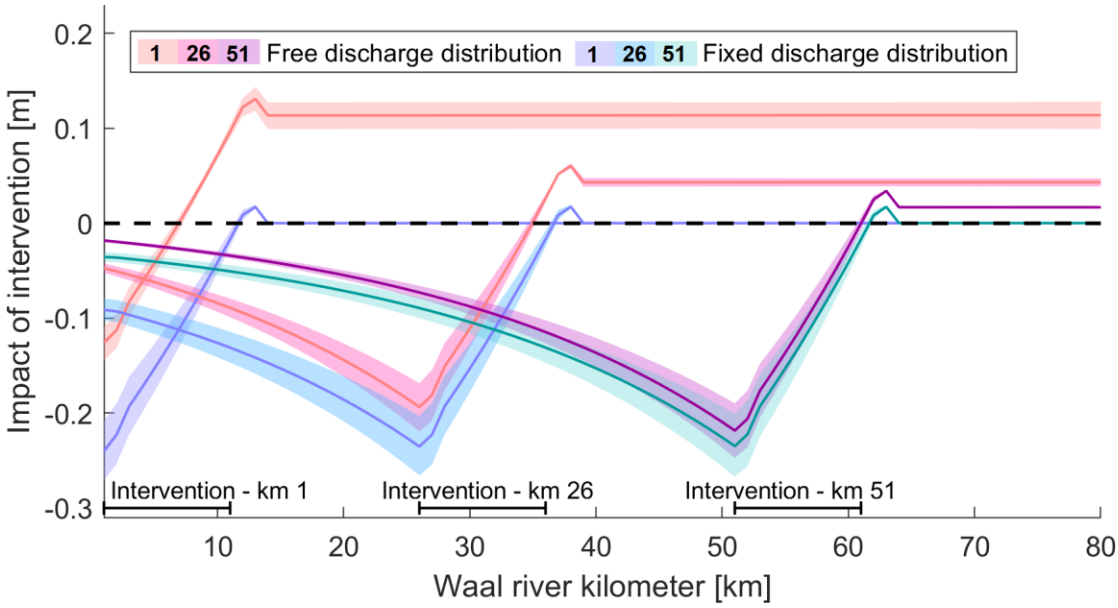

Figure 5. Impacts of interventions with upstream ends at kilometres 1, 26 and 51. Again, the red tones indicate the configuration with free discharge distributions and the blue tones the configuration with fixed discharge distributions.

the uncertainty in the maximum water level reduction increase the further downstream the intervention is. In contrast, the water level increase downstream of the intervention and the water level reduction in the other branches become smaller as the intervention is further downstream.

At first sight, the uncertainty in impact again seems to scale along with the impact. On closer inspection however, the relative uncertainty of the water level reduction near the bifurcation point is smaller the further away the intervention is from the bifurcation point (Fig. 5). This is indicated by the relatively faster narrowing of the 90% confidence interval of the intervention at 66 kilometres in Figure 5. It means that the uncertainty of the impact reduces faster than the impact itself. Additionally, the relative uncertainty of the water level increase downstream of the intervention and the water level reduction in the other branches have a similar value as the value at the bifurcation point, also becoming more certain as the intervention is further away from the bifurcation point. These results suggest the presence of some self-regulation in the uncertainty of the impact.

The origin of the non-constancy of the relative uncertainty in a configuration with a free discharge distribution, evidently has to lie in the impact on the discharge distribution at the bifurcation. A three-way feedback mechanism exists between impact of an intervention, roughness parameters and discharge distribution. The discharge distribution is both a function of the water level impact of the intervention (a higher impact gives a larger increase in Waal discharge compared to the reference situation) and a function of the roughness values (a lower roughness in the Waal, gives a higher Waal discharge). However, also the impact of the intervention itself depends on the roughness values. A high impact is obtained if the main channel roughness is high and the floodplain roughness is low, causing a larger portion of the discharge to flow in the floodplain.

To illustrate these dependencies, the 2000 samples are scattered for two of the interventions in Fig. 5, showing the maximum water level reduction in the Waal branch versus discharge distribution at the primary bifurcation point (Fig. 6). It appears that for the intervention close to the bifurcation point a positive correlation is found between maximum water level reduction and fraction of discharge towards the Waal, while this correlation is negative for an intervention further away. Close to the bifurcation point it generally holds that “the higher the impact, the larger the increase in discharge”. For the intervention further away, this apparently is more often not the case. The explanation should be found in the underlying roughness parameters that facilitate either a high or a low impact. A high main channel roughness in the Waal, which causes a higher impact, would itself induce a lower Waal discharge. As the high impact intervention is far away, it is

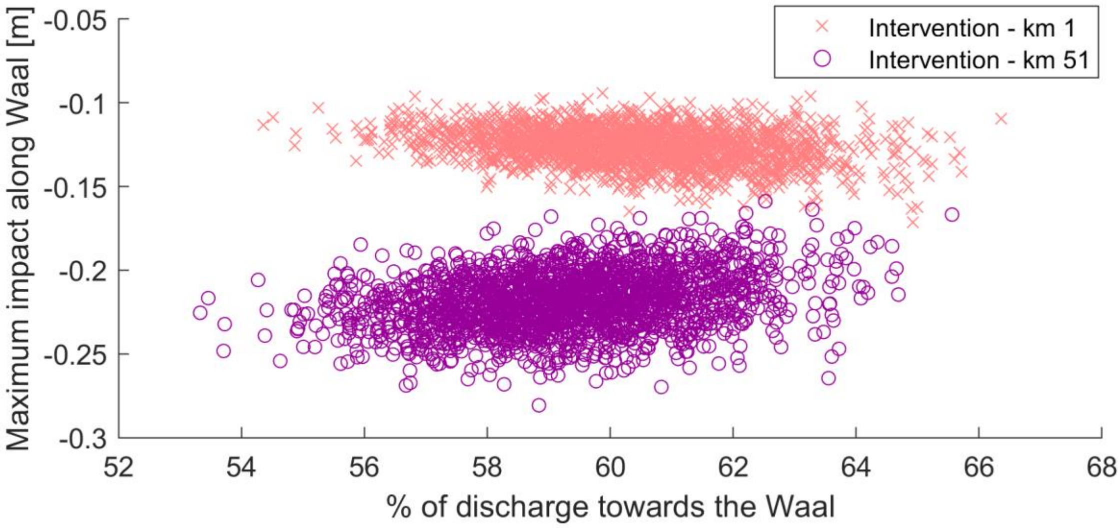

Figure 6. Scatter plot of percentage of discharge towards the Waal versus the maximum change in water level anywhere along the Waal for an intervention at kilometer 1 (crosses) and for an intervention at kilometer 51 (circles). The maximum water level change occurs right at the upstream end of the intervention, i.e. at km 1 and km 51 respectively.

mostly the high main channel roughness now that determines the discharge distribution. So, following this reasoning, a high impact can therefore be accompanied by a relatively low discharge.

It is noted that this reversed correlation (i.e. a lower impact with a higher discharge) is strongly dependent on the underlying roughness distributions. Using the same reasoning, it is found that with only an uncertain roughness of the floodplain, it would hold that higher impacts are found with higher discharges; a low floodplain roughness gives a high impact while it also gives a high discharge. It is thus the balance between the uncertainty in the main channel roughness and the uncertainty in the floodplain roughness that determines if the impact of an intervention and the discharge distribution are positively or negatively correlated.

5 DISCUSSION AND CONCLUSION

In this study, it was showed that the presence of a river bifurcation strongly affects the impact of an intervention as well as its uncertainty. Generally, both the water level reduction caused by a river intervention as well as its uncertainty, are smaller as the discharge distribution adapts to the disturbance. The location of the intervention influences the uncertainty of the impact of an intervention. Consequently, as the intervention is implemented further away from the bifurcation, the influence of the discharge distribution diminishes. This leads to a higher water level reduction and a larger uncertainty of that water level reduction. Additionally, while the relative uncertainty of an intervention appears to be fairly constant along a branch with a fixed discharge distribution (Berends et al. 2019), a free discharge distribution affects the relative uncertainty both upstream and downstream of the intervention.

A one-dimensional idealised model with uniform branches was used to simulate the changes in water levels caused by an intervention. This allowed an isolation of the mechanism that induces the impact and its uncertainties. In reality, the impact of an intervention and its uncertainty is much more dependent on the location of the intervention, the spatially-varying local conditions and other sources of uncertainty (Berends et al. 2018). For example, a dike set-back of 500 meters in a narrow bottleneck of the river will give a larger water level reduction than the same dike set-back of 500 meters in a wider section of the same river and the length of backwater curves varies with river geometry. However, the impact of an intervention in the vicinity of the bifurcation point and its uncertainty will still be prone to the mechanisms as shown in this paper. Generally, the water level reducing effect and the uncertainty of it still diminish if accounting for the changes in discharge distribution. How relatively uncertain the impact of an intervention is, and if it is larger or smaller due to the presence of the river bifurcation depends on all uncertain parameters and the three-way feedback mechanism between the uncertain parameters, the impact of an intervention and the discharge distribution.

This study has shown that in a bifurcating river system both the impact and its uncertainty (absolute and relative) are affected by a variable discharge distribution. Water level statistics used in flood risk analyses are a function of both water levels and uncertainties in water levels. Therefore, in quantifying the effect of an intervention on flood risk, the effect of a changing discharge distribution cannot be ignored.

Currently, large-scale interventions in the vicinity of a river bifurcation are generally avoided, due to the (uncertain) changes in discharge distribution they would induce. A simultaneous intervention in the opposing branch of the river bifurcation can mitigate the changes in discharge distribution. This is also current practice in the Dutch Rhine branches. Using the approach as presented here, it is possible to aid in the design of such sets of interventions. Possibly, combined interventions can be designed such that they have a compensating effect on the discharge distribution for a range of conditions, despite inherent uncertainties. Better insights in conditions and characteristics for effective compensating interventions could open up the way for safe implementations of large-scale interventions closer to river bifurcations.

6 ACKNOWLEDGEMENTS

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