Human interventions in a bifurcating river system: Numerical investigation and uncertainty assessment

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Abstract
In bifurcating rivers, an intervention aimed at flood risk reduction may trigger a change in discharge distribution and thus influence water levels throughout the entire river system. This article aims at assessing the impact of interventions on system-wide water levels, explicitly accounting for a range of discharges and model parameter uncertainty. An idealized 1D model with dimensions of the bifurcating Dutch Rhine River is used. The results show that an unwanted increase in water levels downstream of the intervention occurs due to an increased discharge if a single intervention is implemented in a distributary. This effect can be counteracted by implementing a second intervention that balances the hydraulic effect of the first intervention at the bifurcation. However, unwanted water level increases still occur at other discharges. Furthermore, while interventions may reduce local water-level uncertainty, it appears that uncertainty in discharge distribution is not reduced. This implies that flooding probabilities cannot be reduced throughout the entire river system by the implementation of interventions in upstream reaches. Concluding, for intervention design in a bifurcating river, it is important to consider the entire river system and explicitly account for a range of discharge conditions to avoid unwanted water level increases throughout the river system.

KEYWORDS
bifurcating river, flood risk management, hydraulic modeling, impact analysis, Rhine River, river intervention, uncertainty

1 | INTRODUCTION

Worldwide, investments are made to reduce flood risks in river systems, which could otherwise increase as a result of more frequent extreme hydrological events related to climate change, and due to increasing socio-economic value in flood-prone areas (Winsemius et al., 2016). Traditionally, flood risk reduction strategies focused on increasing the height and strength of flood protection systems (Silva et al., 2004). The Netherlands largely abandoned this strategy in the recently completed “Room for the River” program, which instead aims to...
reduce flood risk by creating more conveyance capacity in the river (Asselman & Klijn, 2016; Deltaprogramma Rivieren, 2014). Such strategies are also becoming more popular in other countries (Dierauer et al., 2012; Guida et al., 2015; Zevenbergen et al., 2013).

Creating more space in the river lowers water levels and flow velocities (Silva et al., 2004), thereby reducing flooding probabilities as well as the expected consequences if a flood occurs (Asselman & Klijn, 2016; Klijn et al., 2018). Both of these aspects are considered in the new Dutch flood risk framework (Kok et al., 2017) for which the norms are set in the Dutch Water Act. Under this new framework, the system is designed based on minimizing the expected annual costs that are associated with flood risk, calculated as the product of flooding probabilities and its associated potential losses during occurrences of floods. This approach takes into account various failure mechanisms that can lead to flooding at a range of discharge conditions. Examples are dike breaching at medium-high discharges, and dike overtopping at extremely high discharges. That way, optimal flood protection is not related to a single reference discharge, but rather to a range of discharges where flood probabilities, failure mechanisms and the associated impacts are considered.

The downside of the Dutch flood risk framework is that it is mathematically demanding to explicitly calculate the net annual flood risk for all potential interventions. For that reason, the Netherlands has also defined simpler flood management rules that are meant to guide the design of acceptable river interventions (Rijkswaterstaat, 2019). The rationale behind these rules is that interventions are not allowed to increase the flood risk at any location in the river system. Under the first rule, interventions may not induce water level increases greater than 1 mm for a reference upstream discharge of 16,000 m$^3$/s. Under the second rule, the intervention is not allowed to affect the discharge distribution at either of the bifurcation points in the Rhine by more than 5 m$^3$/s. Again, this relates to the reference discharge level of 16,000 m$^3$/s. These imposed regulations are very strict and practically mean that no significant solitary interventions can be taken in the vicinity of the bifurcation points in the river Rhine.

An argument that solidifies these strict rules is that Deltares (2018) showed that a change in the discharge distribution over the distributaries would require high costs of dike reinforcements in places where flood risk goes up, which almost always significantly outweighs the economic savings that are achieved by reduced costs in places where flood risk goes down. However, this “lock-in situation” and conservative strategy is also problematic, because changes may still occur in the river system naturally. Interventions may still be needed to restore or counteract such trends, which are typical for rivers in a lock-in situation (Di Baldassarre et al., 2018; Warmink et al., 2017). It is, therefore, important to look beyond the “lock-in” and the imposed strict design rules for river interventions, and also to improve our ability to anticipate the impacts that interventions near the bifurcation points may have. Moreover, even within the existing strict regulation rules, there is the possibility to consider combinations of interventions around the bifurcation points that compensate or counteract each other’s effect. That way, strict regulation rules are respected while other benefits could be achieved.

The aim of this study is to assess the impact of river interventions on system-wide water levels in a bifurcating river system, with particular focus on the Rhine River in the Netherlands. A range of discharge conditions and uncertainties in the main channel and floodplain roughness are considered to determine the impact throughout the system. For this purpose, an idealized modeling approach is taken such that the effect of the interventions can be quantified.

## 2 | METHODOLOGY

### 2.1 | Study area: Dutch Rhine branches

The river Rhine in the Netherlands bifurcates into three main distributaries: the river Waal, river Nederrijn and river IJssel (Figure 1). The Rhine River enters the Netherlands at Lobith after which it reaches the first bifurcation point, the Pannerdensche Kop, after approximately 5 km. The river Waal is the largest distributary and conveys approximately two-third of the Lobith discharge. The other one-third of the discharge is carried by the Pannerdensch Kanaal, which again bifurcates after 11 km at the IJsselkop bifurcation. At the IJsselkop, the discharge distributes in a fraction of approximately two-third and one-third over the Nederrijn and IJssel rivers, respectively. The yearly average discharge of the Rhine at Lobith is approximately 2200 m$^3$/s. The bank-full discharges of all Rhine distributaries correspond to a Lobith discharge of around 5000 m$^3$/s. All branches are compound channels, with wide floodplains conveying significant discharge when the bank-full discharge is exceeded. The hinterland is protected by dikes, which are dimensioned to keep out water until discharges of 16,000 m$^3$/s, generally associated with a return period of 1250 years (Klijn et al., 2018). More recent studies show that this discharge level is more likely associated with lower return periods, perhaps exceeding 10,000 years (Sperna Weiland et al., 2015). The maximum discharge that can reach Lobith is estimated at 18,000 m$^3$/s (Bomers et al., 2019).
2.2 Model schematization and configurations

A one-dimensional, idealized network model of the Rhine branches is set up in the SOBEK modeling environment (Deltares, 2020). SOBEK numerically solves the 1D Saint-Venant equations on a staggered grid. The dimensions of the river network are assigned by cross-sections, which are divided into different sections to create a compound cross-section. The governing equations are solved for each of these sections separately, such that average flow velocities can differ within the cross-section, and that each of these sections is assigned its own hydraulic roughness. Computational grid points are spaced 250 m apart and the maximum time step is set to 10 min, which is similar to other 1D-model studies of the Rhine branches (e.g., Berends et al., 2018).

The schematized river network is based on the dimensions of the Rhine branches (Figure 2a). The three distributaries, the Waal, the Nederrijn, and the IJssel have respective lengths of 93 km, 107 km, and 113 km. A uniform bed slope of $10^{-4}$ is assigned for each branch, averaging the actual bed slope of the Rhine branches which varies between $0.9*10^{-4}$ and $1.2*10^{-4}$ (Reeze et al., 2017). Every branch is assigned a uniform compound cross-section with of which the dimensions are based on the average geometries of Rhine branches. In every branch, the floodplain base level is located 8 m above that of the main channel, which is the approximate water depth at which the banks that demarcate the main channel and floodplains are exceeded. Both the main channel and the floodplain roughness are defined by probability distributions of Manning roughness values (Figure 2b, see Section 2.3). The upstream boundary of the model is a steady discharge $Q_{Lobith}$, which can be varied between runs. Each distributary has a characteristic stage-discharge relationship at its downstream boundary, which is located far away from the bifurcation points, chosen such that under mean roughness values the flow will be uniform along the entire branch.

In a bifurcating river system, changes in water levels downstream of the bifurcation create a feedback mechanism through the discharge distribution. If the water level goes down in one branch, then that branch will draw more discharge from the bifurcation, which, in turn, will increase the water level in that branch. This interaction between the water levels of downstream branches and discharge distribution at bifurcation points is known to affect the uncertainty of water levels compared to a single-branch river (Gensen et al., 2020; Straatsma et al., 2013). To single out effects that are caused by changing discharge distributions, an alternative “branch configuration” of the model is included in the analysis where only the Waal branch is modeled, such that the effects of the feedback mechanism at the bifurcation are absent. The model configuration with feedback at the bifurcation points is referred to as the “system configuration” (Table 1). For the branch configuration, the upstream boundary is located at the bifurcation point. The inflow discharge is steady and is equal to the discharge that is diverted into the Waal branch in the system configuration without any intervention under mean roughness conditions.

Typical “Room for the River” type interventions, which enlarge the conveyance capacity of the floodplains, are studied. A dike setback widens the floodplains and a floodplain excavation deepens a floodplain, thereby both reducing the water levels for given discharges. First, a single intervention (a dike setback) is implemented in the Waal branch. As the Waal is the largest branch, it is expected that an intervention along this branch give the largest change in discharge distribution (Gensen et al., 2020). The dike is set back by 500 m over a length of 10 km (Figure 2a). The upstream end is located at 6 km downstream from the bifurcation. This is close enough to the bifurcation to have a large impact on the discharge distribution, but it is far enough from the bifurcation to achieve a reduction of water levels in the Waal branch upstream of the intervention. The transition
between the cross-section with the dike setback and the original cross-section is smoothed out over 1 km both upstream and downstream to avoid abrupt changes in channel geometry. The hydraulic roughness of the widened section is equal to the roughness of the floodplains in the original Waal branch.

To compensate for the discharge shift at the bifurcation point due to the dike setback in the Waal river, a second intervention is considered over the entire length of the Pannerdensch Kanaal (11 km). Three combinations of compensating interventions are assessed (Table 1): (1) two dike setbacks, (2) a dike setback in the Waal combined with a floodplain excavation in the Pannerdensch Kanaal, and (3) a floodplain excavation in the Waal at the same location as the original dike setback combined with a dike setback in the Pannerdensch Kanaal. The dimensions of the compensating interventions (Table 1) are chosen such that the discharge distribution is exactly restored to that of the system without interventions at a reference discharge of $Q_{Lobith} = 16,000 \text{ m}^3/\text{s}$. Considering combinations of interventions, and using model settings with and without feedback at the bifurcation point, seven model configurations will be considered (Table 1).

### Table 1: Model configurations

| Configuration                  | Intervention Waal       | Intervention Pannerdensch Kanaal | Results in Section: |
|-------------------------------|-------------------------|---------------------------------|---------------------|
| System, no intervention       | None                    | None                            | 3.1                 |
| Branch, no intervention       | None                    | –                               | 3.1                 |
| System, single intervention   | 500 m Dike setback      | –                               | 3.2                 |
| Branch, single intervention   | 500 m Dike setback      | –                               | 3.2                 |
| Compensating system 1         | 500 m Dike setback      | 120 m Dike setback              | 3.3                 |
| Compensating system 2         | 500 m dike setback      | 0.39 m Floodplain excavation    | 3.4                 |
| Compensating system 3         | 1.46 m Floodplain excavation | 120 m Dike setback             | 3.4                 |

#### 2.3 Monte Carlo simulation of uncertain intervention impact

The effects of river interventions on water levels using model simulations are inherently uncertain (Berends et al., 2019). The uncertainty in the water levels is accounted for by setting the main channel roughness and floodplain roughness as stochastic parameters, both being major sources of uncertainty in hydraulic modeling (Bozzi et al., 2015; Pappenberger et al., 2008; Warmink et al., 2013). A rather simple approach is adopted in which the main channel roughness and floodplain roughness are normally distributed (Figure 2b). The mean values of the Manning’s roughness for the main channel and floodplain are 0.03 and 0.05 m$^{1/2}$/s and the standard deviations are 0.002 and 0.005 m$^{1/2}$/s, respectively. The roughness of the main channel roughly represents a riverbed covered with dunes (Julien et al., 2002), while the roughness of the floodplains roughly represents floodplains covered with bushes as vegetation (Chow, 1959). The roughness distributions are the same for every branch of the river system, and the roughness is assumed independent between the branches. While correlation is expected (e.g., Straatsma & Huthoff, 2011), the degree of
correlation is difficult to determine. The significance of the assumption is addressed in Section 4.1.

A Monte Carlo Simulation (MCS) is run 2000 times for every model configuration and for 18 discharge conditions, giving a total of 36,000 runs per model configuration. The upstream discharge is varied from 1000 m$^3$/s to 18,000 m$^3$/s in steps of 1000 m$^3$/s. A set of 2000 quasi-random samples is established using Sobol sequencing. One sample consists of eight roughness values, being a main channel and floodplain roughness for each of the four branches. Sobol sequences ensure good coverage of the parameter domain and reproducibility (Saltelli et al., 2010). The same set of 2000 samples is used as input for every model configuration and for every discharge condition to allow direct comparison. Figure 3 shows that 2000 samples are sufficient to ensure convergence of the 90% confidence intervals (CIs) of calculated water levels.

The intervention impact is quantified by two parameters: (1) mean effect on water levels at location “x,” $\Delta h_x$, and (2) relative uncertainty of the effect on water levels, $RU_{90x}$. Often the results are shown for the reference discharge $QLobith = 16,000$ m$^3$/s, which is the discharge for which the dikes along the Rhine branches are currently designed.

First, the mean effect on water levels $\Delta h_x$ is quantified by determining the mean of the set of 2000 water level differences (Equation 1). This set is obtained by subtracting the water levels in the configuration without interventions (system or branch) from the modeled water levels in the configuration with interventions. This subtraction is done for every roughness sample and for every location “x” separately.

Mean effect at location “x” $\Delta h_x$: $\bar{\Delta h}_x = \frac{h_{s,x} \text{ with intervention} - h_{s,x} \text{no intervention}}{s}$ (1)

where, $h$ is the water level, $x$ is any location in the river system, and $s$ is the sample number.

Second, from the set of 2000 water level differences, the 90% CI is quantified by using the 5th percentile and 95th percentile water level differences. Subsequently, this 90% CI is divided by the mean change in water levels to obtain the relative uncertainty (Equation (2)). Relative uncertainty is a metric introduced by Berends et al. (2019) that enables comparison between different types of interventions.

Relative uncertainty at location “x”: $RU_{90x} = \frac{90\%CI \Delta h_x}{\Delta h_x}$ (2)

3 | RESULTS

3.1 | Branch and system configurations without interventions

Figure 4 shows the results of the branch and system configurations without applying any interventions. These configurations are comparable to Gensen et al. (2020), extended here by including floodplain roughness uncertainty. The results show that mean water levels and the shape of the water depth-discharge relationship are the same between the branch and system configuration (Figure 4a). The depth-discharge relationship is steep below bank-full discharge (~5000 m$^3$/s) and flattens above bank-full discharge as the floodplains start conveying discharge. Note that the CI for the system model configuration is narrower than for the branch model configuration. This is the result of the feedback mechanism at the bifurcation which counteracts the highest perturbations in flow parameters and thereby distributes the uncertainty over downstream branches, as was also shown in Gensen et al. (2020).

Figure 4b shows the nearly normally distributed water depth in the two configurations for $QLobith = 16,000$ m$^3$/s. Both distributions have a slight
skewness with a heavier left tail. As already pointed out for Figure 4a, the 90% CI in the system configuration is narrower than that of the branch. The 90% CI in the branch configuration is 0.95 m, which is in the same order of magnitude as Warmink et al. (2013) (95% CI = 0.68 m), who used a 2D model and considered the same Waal branch under the reference discharge of 16,000 m³/s and used uncertain main channel and floodplain roughness as well. This shows that the idealized 1D model reproduces results of more complex and more realistic model studies reasonably well.

Figure 4c shows that the 90% CI in the system configuration is narrower than in the branch configuration along the largest part of the Waal branch. In the branch configuration, the width of the 90% CI reduces to 0 m in downstream direction, as the downstream model boundary fixes the water level if the discharge is invariant. In the system configuration, water-level-uncertainty is still present (0.54 m) at the downstream boundary as the branch discharge varies.

Figure 4d,e show the width of the 90% CI as function of discharge and location along the Waal branch in the branch and system configuration, respectively. In general, the CI widens with increasing discharge. A sharp decrease in water-level-uncertainty is observed around and just above bank-full discharge (about 5000 m³/s) as the conveyance capacity suddenly increases.

### 3.2 Impact of a single intervention

Figure 5 shows the results for a single intervention, a dike setback, in the Waal branch for both the system configuration and the branch configuration. In both configurations, the impact is generated over the length of the intervention with a maximum water-level-reduction at
the upstream end of the intervention at kilometer 6. These are \( \Delta h_{x=6} = -0.14 \text{ m} \) and \( \Delta h_{x=6} = -0.24 \text{ m} \) in the system and branch configuration, respectively. Toward the bifurcation point at kilometer 0, the impact reduces following a backwater curve. The feedback mechanism at the bifurcation in the system configuration reduces the water-level-lowering effect of the intervention, and it creates an increase in water levels of about 9 cm downstream of the intervention location. This downstream water level rise is caused by an average increase in discharge towards the Waal branch of 164 m\(^3\)/s, which is a result of the feedback mechanism.

The relative uncertainty (RU90), that is, the ratio of 90% CI to the mean effect, at the location of most reduction at kilometer 6 is approximately 25%. A value of 20% for a dike setback was found by Berends et al. (2019), who used a more detailed 2D model for the Waal branch and used a more comprehensive approach with respect to the uncertainty sources. Again, this shows that the idealized model used in this study can realistically represent the effect of a river intervention and its uncertainty. The uncertainty is lower in the system configuration than in the branch configuration, see Figure 5. This result supports the finding of Berends et al. (2019) that the uncertainty related to the effect of the intervention generally scales linearly with the effect itself. Also, the relative uncertainty in the increase of downstream water levels in the system configuration remains relatively constant at 25% along the entire length of the river.

### 3.3 Impact of two compensating interventions of the same type

Figure 6 shows that the implementation of a compensating intervention of the same type (a dike setback) in the opposing branch removes unwanted water level increases throughout the river system that are caused by a single intervention. The mean effect on Waal water levels is equal in the branch and system configuration. This implies that the two dike setbacks result in the same mean discharge distribution as in the pre-intervention situation for \( Q_{\text{Lobith}} = 16,000 \text{ m}^3/\text{s} \), which is where they were designed for. For other discharges than 16,000 m\(^3\)/s, the two compensating interventions do not have exactly equal effect, causing a small change in the discharge distribution in comparison to the situation without interventions. Still, the resulting water level increases throughout the system are very small, with a maximum of 0.8 cm in the Waal and 0.2 cm in the IJssel (see Figure 7 in Section 3.4).

The relative uncertainty appears to be strongly affected by the presence of the bifurcation. First, upstream of the intervention, the uncertainty is narrower for the compensating interventions (green shaded area in Figure 6) than for the single intervention in the branch configuration (blue shaded area in Figure 6). This gives a relative uncertainty of 18%, while this was 25% in the system configuration with a single intervention. The uncertainties related to the two interventions partly cancel out at the bifurcation. Illustratively, to reach a large water-level-reduction, the floodplain roughness needs to be low in both of the branches. As the hydraulic roughness values of the branches are assumed to be independent, the probability of having such large water-level-reduction is therefore smaller than in the branch configuration. If the branches experience
unequal roughness conditions, the discharge distribution would change, thereby invoking the feedback mechanism at the bifurcation and balancing out the impacts of the two interventions. This change in discharge induces the uncertainties as observed downstream of the interventions.

3.4 Impact of compensating interventions of different types as function of discharge

Unwanted water level increases occur downstream of one of the compensating interventions if the compensating interventions are not of the same type (Figure 7 and Table 2). Figure 7 shows the impact on water levels 30 km into the Waal branch (left panel) and 30 km into the IJssel branch (right panel) of different combinations of interventions. At these locations, water level differences are governed by the changes in discharge distribution that are induced by the interventions. Therefore, an increase in water levels at this location in the Waal branch is always accompanied by a decrease in water levels in the IJssel branch and vice versa.

A system configuration with a single intervention in the Waal branch shows a steadily increasing impact on water levels with increasing discharge (Figure 7), causing increasing Waal water levels and decreasing IJssel water levels. The reduction of discharge towards the
Pannerdensch Kanaal is attributed to both downstream branches (IJssel and Nederrijn), resulting in water level decreases here that are in the same order as the water level increase in the Waal. For two compensating dike setbacks, very little mean effects occur ($\Delta h_{\text{Waal30}} \sim 0$ and $\Delta h_{\text{IJssel30}} \sim 0$), as observed in Section 3.3. Still, an uncertainty in downstream water levels is present that increases with increasing discharge.

The compensation configurations which have different types of interventions still do not lead to mean effects at either location for $Q_{\text{Lobith}} = 16,000 \text{ m}^3/\text{s}$, as the interventions were designed to compensate for this discharge. Whether water levels increase or decrease at a location, depends on both the discharge and the intervention type attributed to a branch. A floodplain excavation is more effective at reducing water levels for discharges below the bank-full discharge and the design discharge of $16,000 \text{ m}^3/\text{s}$. Additionally, around bank-full discharge the effect is very uncertain (high RU90) as the floodplain excavation changes the bank-full height. Oppositely, a dike setback is more effective at reducing water levels for discharges over $16,000 \text{ m}^3/\text{s}$. If one of the interventions is more effective, it will draw discharge toward the branch with that intervention, resulting in water level increases along that branch. In principal, the impact thus mirrors between the two compensating configurations which have different types of interventions (yellow vs. purple in Figure 7).

The magnitude of mean effect and related uncertainty is different between the two compensating configurations that have unequal intervention types. Generally, the impact (both mean effect and uncertainty) is larger in the IJssel branch as it is more sensitive to discharge than the Waal branch. Therefore, if the floodplain excavation is implemented in the Pannerdensch Kanaal (yellow in Figure 7), a large increase in water levels is observed in the IJssel for medium-high discharges, while it is accompanied by a smaller water level decrease in the Waal.

| Configuration | $\Delta h_x$ and (90% CI of $\Delta h_x$) for $Q_{\text{Lobith}} = 6000 \text{ m}^3/\text{s}$ | $\Delta h_x$ and (90% CI of $\Delta h_x$) for $Q_{\text{Lobith}} = 18,000 \text{ m}^3/\text{s}$ |
|---------------|------------------------------------------------------------------|------------------------------------------------------------------|
|               | $x = \text{Waal km 30}$                                         | $x = \text{IJssel kilometer 30}$                                 |
| DS            | $+1.5 \text{ cm (1.4 cm)}$                                       | $-3.4 \text{ cm (2.7 cm)}$                                       |
| DS DS         | $+1.0 \text{ cm (0.5 cm)}$                                       | $-1.0 \text{ cm (2.7 cm)}$                                       |
| DS FE         | $-4.7 \text{ cm (2.6 cm)}$                                       | $+11.0 \text{ cm (5.9 cm)}$                                      |
| FE DS         | $-6.4 \text{ cm (2.0 cm)}$                                       | $-13.3 \text{ cm (7.4 cm)}$                                      |

### 4. DISCUSSION

#### 4.1 Water-level-uncertainty and flood water levels in a bifurcating river

This study has shown that water levels can be reduced locally by the implementation of a “Room for the River” type intervention. However, as shown, this is generally accompanied by an unwanted water-level-increase elsewhere in the river system. Alternatively, interventions could be aimed at reducing water-level-uncertainty, which also results in lower flooding probabilities as the highest water levels in the water-level-distribution (e.g., 95th percentile water levels) contribute most to this probability (Kok et al., 2017). A “Room for the River” type intervention is able to reduce water-level-uncertainty upstream of its location, thus also reducing water-level-uncertainty at the bifurcation (Table 3). On top of the mean effect of the intervention, this further reduces the flooding probabilities at these locations. In the enlarged cross-section, water levels are less sensitive to discharge (also considered by Klijn et al., 2018) and to roughness parameters, effectively flattening the depth-discharge relationship.

In a bifurcating river system, the uncertainty in discharge distribution is an important driver of water-level-uncertainty in the downstream reaches of the river system (Van Vuren et al., 2005). In the upper reaches, water-level-uncertainty and discharge distribution interact through the feedback mechanism. For downstream reaches, the discharge distribution does affect water-level-uncertainty, but water-level-uncertainty does not influence the discharge distribution. Consequently, reducing discharge-distribution-uncertainty lowers the downstream water-level-uncertainty and thus flooding probabilities. However, it appears that an intervention in cross-sectional geometry in an upstream reach does not necessarily reduce, and even possibly increases, the uncertainty in discharge distribution, even though water-
level-uncertainty is reduced at the bifurcation (Table 3). This is explained by the shape of the depth-discharge relationship in the intervened situation, which is flatter in comparison to the original situation. This means that a smaller perturbation in water levels is needed to trigger a certain change in discharge distribution compared to the original situation.

Potentially, water-level-uncertainty and thus flooding probabilities throughout the entire system could be lowered by reducing the uncertainty in underlying parameter uncertainty in the vicinity of bifurcation points. In this study, uncertainty in roughness parameters was assessed. Several strategies can be pursued at reducing these uncertainties. For main channel roughness, potential flattening of bed forms for very high discharges is poorly understood (Naqshband et al., 2017), but it may trigger a large change in discharge distribution (Gensen et al., 2020). Preventing such flattening from occurring, for example, through changing the sediment composition, therefore reduces flooding probabilities in downstream reaches. For floodplain roughness, a reduction in uncertainty can be achieved by eliminating errors in the classification of vegetation (Straatsma et al., 2013). Alternatively, stricter vegetation maintenance strategies can be implemented near the bifurcations (Makaske et al., 2011).

### 4.2 Sensitivity to roughness distributions

A simplified roughness-modeling approach was applied to study the effect of model parameter uncertainty on intervention impact. It was shown that this idealized approach could represent more realistic modeling studies, as the ones performed by Warmink et al. (2013) and Berends et al. (2019). More realistic roughness distributions could improve the accuracy of the results, but the feedback mechanism between water levels and discharge would still have a similar qualitative effect on the uncertainty of intervention impact. If the roughness of the branches would be more uncertain than what was considered in this study, water-level-uncertainty and uncertainty of the impact would increase as well.

In this study, it is assumed that the roughness is constant along a branch. Some variability can be expected based on the local characteristics of the main channels and the floodplains. Such variability can affect the water-level-uncertainty along the branches (Warmink et al., 2013). However, as the roughness conditions are the same in both the pre-intervention and the post-intervention models, the impact of incorporating variability of the roughness along a branch are expected to be rather small (equivalent to Berends et al., 2019).

Furthermore, the roughness between the branches was assumed independent. In reality, a certain degree of dependence can be expected (e.g., Straatsma & Huthoff, 2011). Figure 8 shows that even if the roughness would be fully correlated between the branches, uncertainty intervals would only be marginally different. The two extremes of full correlation and fully independent roughness show the maximum bandwidth of possible results. For the single intervention in the system configuration (red), the water-level-reduction achieved by the intervention is slightly more certain, while the downstream uncertainty is unaffected. In this configuration, the uncertainty is governed by the partitioning of flow over the main channel and floodplains, which in turn is determined by the local roughness conditions. The uncertainty related to the impact of the intervention is more affected by the assumption of independence for the compensating interventions configuration. If the roughness between the branches is fully correlated, the uncertainties of the two interventions do not cancel each other out anymore through the feedback mechanism at the bifurcations.

| System configuration | At bifurcation; Waal kilometer 0 | Waal kilometer 30 | IJssel kilometer 30 |
|----------------------|---------------------------------|-----------------|-------------------|
|                      | 90% CI water levels | 90% CI discharge distribution | 90% CI water levels | 95th percentile water depth | 90% CI water levels | 95th percentile water depth |
| Waal                 | Pan. Kan.             | 0.57 m 948 m$^3$/s | 0.52 m 13.41 m | 0.67 m 11.91 m |
| – –                  | 0.57 m 948 m$^3$/s | 0.53 m 13.51 m | 0.67 m 11.82 m |
| DS –                 | 0.55 m 949 m$^3$/s | 0.52 m 13.41 m | 0.67 m 11.91 m |
| DS DS                | 0.56 m 937 m$^3$/s | 0.53 m 13.41 m | 0.66 m 11.90 m |
| DS FE                | 0.56 m 957 m$^3$/s | 0.51 m 13.40 m | 0.68 m 11.91 m |
| FE DS                | 0.56 m 947 m$^3$/s | 0.52 m 13.41 m | 0.67 m 11.91 m |
bifurcation. Therefore, almost no downstream effect is expected in case of fully correlated roughness.

4.3 Uncertainty analysis of intervention impact

In this study, an idealized 1D network model was applied that allowed the analysis of intervention impact for a large number of roughness conditions and discharges. In practice, more realistic and 2D model simulations are used for the design and assessment of river interventions, which have a much higher computational demand. In the early design phases, it is practically unfeasible to go through multiple iterations of combined intervention using such advanced models and at the same time to consider a range of discharge conditions as well as model parameter uncertainty.

Another constraint to a more practical assessment of discharge and model parameter uncertainty is that the full bifurcating system should be considered. This study has shown that the feedback mechanism between water levels and discharge distribution affects the impact of interventions and their uncertainties. Using the branch configuration with a stochastic discharge distribution to perform an uncertainty analysis could also provide similar results, while significantly reducing the computational demand. However, because the impacts on discharge distribution and impacts on water levels are linked together, it is essential to consider the feedback mechanism. This is illustrated by the results in Section 3.4, where the downstream water level differences are entirely determined by the changes in discharge distribution. Therefore, to obtain accurate results in an uncertainty analysis of intervention impact in a bifurcation river system, a model that considers all branches is always recommended.

This study has isolated and quantified the order of magnitudes of interactions that occur between water levels, impacts of interventions, and discharge distribution. To perform the same analysis in a realistic river system, a reduction of computational demand is needed. Berends et al. (2018) showed that this can be achieved by using the correlation in model results from pre-intervention and post-intervention models in a single-branch model to estimate the uncertainties. This strategy can also be applied for a bifurcating river system, once a sufficiently accurate estimate of the water-level-uncertainties in the reference situation is obtained. However, this would also require quantification of correlations between the roughness of the branches, which is not readily available.

This study has shown that the changes in water levels and discharge distributions that are caused by an intervention depend on upstream discharge. For instance, water level increases can occur for discharges that compensating intervention was not designed for. As such, water level increases should be avoided as much as possible to prevent increases in flooding probabilities, it is recommended to consider a few discharge conditions in the design of interventions. Some of these conditions could be the bank-full discharge, a medium-high discharge (e.g., 12,000 m$^3$/s, the highest recorded discharge), and the maximum attainable discharge of the Rhine system.
5 | CONCLUSIONS

In this study, the influence of river interventions on system-wide water levels in a bifurcating river system was assessed. It was shown that it is essential to consider the entire river system for accurate estimations of mean effects of interventions and their uncertainties.

For a single water-level-lowering intervention in a bifurcating river system, a high water level increase downstream of the intervention is observed due to an increase in discharge towards the branch. A compensating intervention in the opposing branch can offset the increase in discharge towards the branch, such that only for specific discharge and roughness conditions no water level increases are observed. For all other discharge and roughness conditions, water level increases occur either downstream of the intervention or in the other branches of the system of which the magnitude of these water level increases depends on the types of interventions.

Flooding probabilities along downstream reaches can be lowered by reducing water-level-uncertainty at those locations, for which uncertainty in discharge distribution is an important source. However, discharge distribution uncertainty cannot be reduced by interventions in river geometry without triggering a mean shift in the discharge distribution. This means that water-level-uncertainty throughout the system and therefore the extremes of the water-level-distribution remain unaffected. Potentially, reducing underlying model parameter uncertainty can result in lower flooding probabilities. This may for instance be achieved by more accurate predictions of the main channel and floodplain roughness. For future research, we recommend to assess the sensitivity of the results to the locations and the size of the interventions. It is expected that the effect of the feedback mechanism and the resulting amount of downstream water level increase will become larger with increasing size of the intervention and if the intervention will be implemented closer to the bifurcation.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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