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A Stochastic Model Approach for Optimisation of Lowland River Restoration Works

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ABSTRACT: Over the course of centuries, river systems have been heavily trained for the purpose of safe discharge of water, sediment and ice, and improves navigation. Traditionally, dikes are used to be reinforced and heightened to protect countries from ever higher flood levels. Other types of solutions than technical engineering solutions, such as measures to increase the flood conveyance capacity (e.g., lowering of groynes and floodplains, setting back dikes) become more popular. These solutions may however increase the river bed dynamics and thus impact negatively navigation, maintenance dredging and flood safety. A variety of numerical models are available to predict the impact of river restoration works on river processes. Often little attention is paid to the assessment of uncertainties. In this paper, we show how we can make uncertainty explicit using a stochastic approach. This approach helps identifying uncertainty sources and assessing their contribution to the overall uncertainty in river processes. The approach gives engineers a better understanding of system behaviour and enables them to intervene with the river system, so as to avoid undesired situations. We illustrate the merits of this stochastic approach for optimising lowland river restoration works in the Rhine in the Netherlands.

KEY WORDS: river restoration, flood protection, dredging, navigation, stochastic approach, Room for the River program.

0 INTRODUCTION

For centuries river engineers in the Netherlands have focused on regulating the Dutch rivers (e.g., the Rhine). When making designs of regulation works, the engineers had to reconcile a number of functions, such as protection against floods and provision of safe and efficient navigation, floodplain agriculture, ecology and recreation.

In the 19th and early 20th centuries, the Rhine was heavily trained for the purpose of safe discharge of water, sediment and ice, and improved navigability. The river training consisted of (1) the construction of levees and dikes, (2) bend cut-offs straightening the river at various points, (3) the construction of groynes systematically fixing and narrowing the main channel, (4) dredging navigation channels and (5) the removal of islands and sandbanks. This resulted in the 'present-day' appearance of the river (Fig. 1): a fixed planform, with non-permeable groynes, a single main channel intensively used for navigation, low levees ('summer dikes') that protect floodplains from frequent flooding, silted up flat floodplains used as meadows and high dikes acting as a main flood defence. These dikes protect the densely populated low-lying polders in the Netherlands.

The flood events in 1993 and 1995 nearly led to disastrous flooding, but raised the awareness that intervention was needed to improve the flood protection level. Through the enactment of the Delta Plan Major Rivers (RWS, 1995), the government decided to accelerate dike reinforcements. The government also initiated the implementation of spatial river works in the Dutch rivers. Instead of raising dikes, 34 river intervention projects along the Dutch Rhine were selected in order to provide a better protection against flooding for hundreds of thousands of people. The projects were realised within the so-called Room for the River (RfR) program. The main idea of this program is to not continue increasing the height of the dikes, but to give the river more room for its function as water discharger. Only when other measures are not possible, dikes are reinforced and heightened (van Stokkom, 2005; Silva et al., 2001). Besides the RfR program also other large scale projects in the Dutch rivers have started in the last decades to restore nature in the floodplains, and to secure the quality of water bodies (European Water Framework Directive, or WFD program). Typical RfR and WFD measures are: lowering of floodplains, groyne lowering, longitudinal dams, side channels, oxbow lakes, free banks and reconnecting lakes (see Fig. 1).

Sustainable development of river systems has become an internationally important issue. As a consequence, river restoration based on RfR and WFD design principles is not totally unique for the Netherlands. Examples can be found elsewhere in the world. Recently master plans were developed in China for the Wei and Qing rivers, including the implementation of secondary channels and extra water storage. In Romania the potential of the Room for the River approach has been evaluated in integrated spatial plans for the Danube River (Groot and Termes, 2009). Other examples are Room for the River for the

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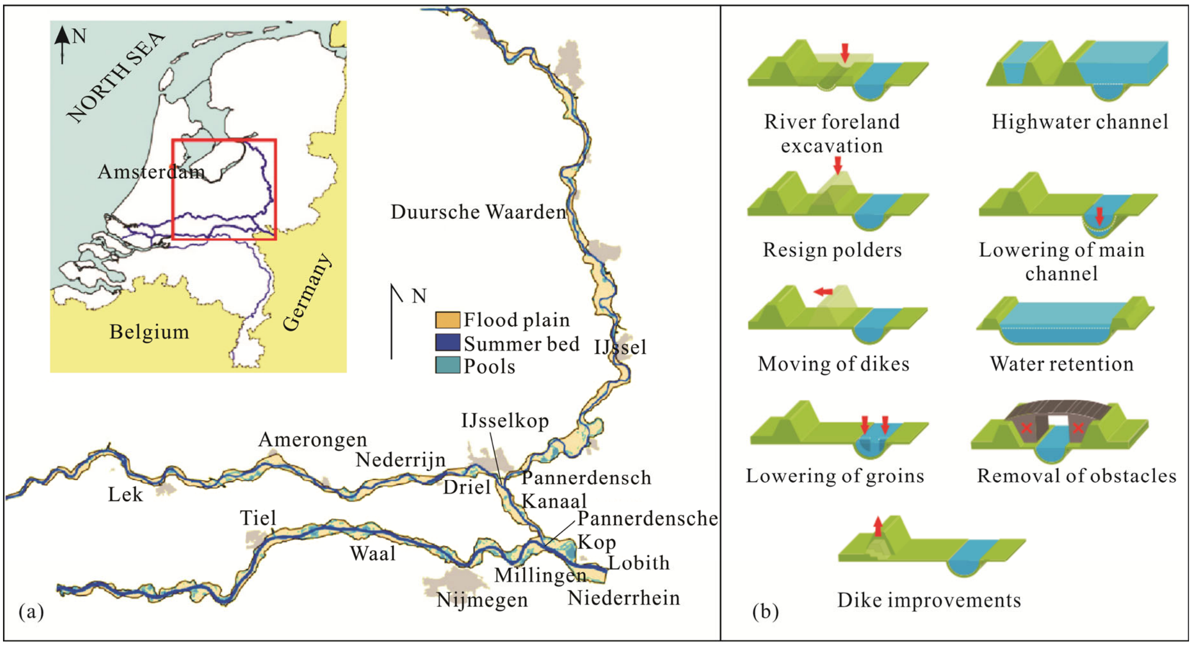

Figure 1. The Rhine branches in the Netherlands and typical measures proposed in the Room for the River program.

Cauca River in Colombia (De Groot, 2015) and Room for the River in Germany (Barneveld et al., 2010). RfR and WFD restoration works often turn out to affect flow and sediment transport fields, thus increase the river bed dynamics (van Vuren, 2005). This may induce negative impacts on a number of functions the river has to reconcile. Morphological changes can induce for instance dike instability and flood safety problems, navigation problems, problems with the water distribution over different river branches and instability of hydraulic structures. They may also influence the groundwater level, which may on its turn affect other functions, such as ecology and agriculture.

A variety of rather sophisticated models are available to predict the impact of river restoration works on river processes. However, river systems are of a dynamic nature and the underlying hydrodynamic and morphodynamic processes are not completely understood. Uncertainty in the description of the physical processes in numerical models that are commonly used in engineering practice, along with the inability to accurately quantify model inputs and parameters in these models, leads to uncertainty in hydrodynamic and morphodynamic predictions. This uncertainty can partially be reduced by a more detailed and advanced physical model description. Part of the uncertainty however, will always be there, and this emphasizes the importance of dealing with uncertainty in a responsible manner. For this reason, quantifying uncertainty in hydrodynamic and morphodynamic predictions is necessary in order to understand the impact of river restoration works on the physical behaviour of river systems.

Van Vuren (2005) therefore proposed a stochastic model approach. In this paper, we evaluate whether: “the stochastic model approach is essential for proper anticipation on flood and maintenance aspects, as it enables river engineers to (1) quantify uncertainties in morphodynamic responses induced by river restoration works (expressing ranges of possible future states via the ensemble dimension, which contain all possible states that could have occurred or may occur), (2) get insight into the likelihood of deterministic morphodynamic predictions, (3) indicate river locations with a large bed level variability that have a higher potential to cause negative impacts on navigation, maintenance dredging and flood safety and (4) interfere with the river system, so as to avoid undesired situations”. We will try to evaluate this and illustrate the potential of this stochastic approach in river management practice. For the purpose of illustration, various RfR restoration works meant to improve the protection against flooding in the Netherlands are evaluated. Focal point is the suitability of the stochastic model approach for the impact assessment of the new river restoration works on the river’s morphology, navigability and maintenance requirements. We illustrate how this approach can help the river engineers optimising their designs for lowland river restoration works, and finding means to counterbalance morphodynamic impacts more effectively. Lessons learnt from this will be useful for optimising RfR restoration works in the Netherlands, but also for similar type of river intervention works elsewhere in the world.

This paper is organised as follows. Section 1 starts with an introduction of the Rhine system in the Netherlands, the typical RfR intervention works and the cases considered in this paper. Section 2 presents with a description of the stochastic model approach. Section 3 presents the results, a discussion follows in Section 4 and final conclusions are given in Section 5.

1 THE RHINE IN THE NETHERLANDS AND RFR INTERVENTION WORKS

The Rhine is a large river in western Europe, with a total length of 1 320 km. It originates in the Alps in Switzerland as a snowmelt-fed mountain river and eventually debouches as a rain- and snowmelt-fed lowland river in the North Sea in the Netherlands. In the 19th and early 20th centuries, the Rhine was heavily trained for the purpose of safe discharge of water, sediment and ice, and to achieve good navigability conditions.

In the Netherlands the Rhine consists of six main branches: Niederrhein, Waal, Pannerdensch Kanaal, IJssel, Lower-Rhine and Lek (see Fig. 1). Two bifurcation points connect the different branches: the Pannerdensche Kop and the IJsselkop. At the Pannerdensche Kop bifurcation approximately 66% of the Rhine discharge is directed to the Waal. The remaining 34% flows into the Pannerdensch Kanaal, and at the IJsselkop bifurcation two thirds of this is directed into the Lower-Rhine and one third into the IJssel. Under low and intermediate flow conditions, the distribution is controlled by a weir in the Lower-Rhine.

Geometry and bed slope vary between the different Rhine branches. All branches have a cross-section in which different zones can be distinguished: the main channel bed, the groyne section, the flow-conveying floodplains and the storage area. Even within a branch differences in geometry exist. Wide and narrow floodplains are located alternately at the left and the right side of the river, variation exist in levee height and vegetation cover, storage and conveyance capacity of floodplains and radius of curvature.

Within the framework of Room for the River various re-landscaping projects are currently taking place in the Dutch Rhine, meant to increase the river's flood conveyance capacity and to enable nature restoration. They consist of a variety of measures, such as lowering groynes, floodplain lowering, implementation of secondary channels, removing obstacles and setting back dikes, as indicated in Fig. 1.

The start of the preparation phase of the RfR program dates back to the mid-nineties of the previous century. A large number of advisory and research projects has ultimately resulted in 34 river restoration projects along the Dutch Rhine branches. These restoration works are currently under construction. Each of these RfR restoration works has two main objectives, namely (1) increasing the river's flood conveyance capacity (flood protection), and (2) improving the spatial quality by means of nature development. These two objectives have received most attention in the design phase.

RfR appears to have a negative influence on navigability. RfR restoration works inevitably influence the flow and sediment transport fields. Depending on the flow stage, a larger part of the discharge will be diverted from the main channel towards the flood plains. Downstream of the project locations, this discharge will flow back into the main channel. This yields larger local gradients in the flow velocity, hence in larger local gradients in sediment transport. Due to these gradients, erosion and accretion waves are initiated, which propagate downstream through the river system. This increased river bed dynamics may negatively influence the river's navigability and lead to extra maintenance costs. The intended dredging operations will hamper navigation, which may have significant economic consequences and reduce navigation safety.

Since, the Rhine provides a natural access to the European hinterland, it is economically very important to inland water transport in the Netherlands (Leenaers and Donkers, 2010). Therefore, minimizing these negative side effects is of great importance. The fact that already in the present situation navigability problems encountered stresses this importance even more. Yet, in the design phase of the RfR program the potential impact of the restoration works on inland navigation has received little attention (Havinga and van Adrichem, 2013; van Vuren and Havinga, 2012).

In this paper, we investigated the impact of a number of RfR-measures on morphological response statistics using the Rhine model in a MCS-setting (as described in Section 2). Two case studies are considered: (A) lowering floodplains and summer level removal along the Waal, and (B) re-design alternatives of the Rhine by combining a number of RfR-measures.

Case A is hypothetical case, as it consists of only one type of RfR-measure. As a result, the impact of this measure can be assessed in a transparent way and locations where river improvement measures locally increase the bed level variability can be identified. It turned out to be essential not to remove summer levees, in order to avoid a strong morphological response in the main channel, resulting in a large bed variability and uncertainty. Floodplain lowering with removal of the summer levees should only be done at locations where there is a small variation in the morphological response.

Case B is a more realistic case, as it consists of RfR schemes composed of a combination of different types of RfR measures. The major aim is to get insight into the extent to which these river improvement measures affect the morphology and enhance the bed level variability, relative to a reference situation with traditional dike reinforcement. This information about the ensemble dimension containing all possible states that may occur, can help to design the final RfR scheme.

2 STOCHASTIC MODEL APPROACH

2.1 Stochastic Methods

River engineers commonly use a variety of tools to determine the hydrodynamic and morphological responses to engineering works. Numerical models appear to be effective tools to provide insight into the physical system behaviour. In the last century a variety of numerical models have been developed, ranging from 1-dimensional (1D) to more sophisticated 2D and 3D models (Wang and Wu, 2004). Predictability of these models is restricted by the various uncertainty sources involved, such as uncertainties introduced during the modelling process (choice of model concept and specification of boundary conditions, initial conditions and model parameters), and others due to the lack of understanding of the physical processes. Identifying the uncertainty sources and assessing their contribution to the overall uncertainty in hydrodynamic and morphodynamic predictions is necessary in order to understand the river's system behaviour (before and after river restoration works). This calls for a stochastic method that enables us to indicate ranges of possible future states, their probability of occurrence and the estimation of undesired effects.

There is a number of stochastic methods available to cope with the uncertainty of large complex system behaviour, such as Monte Carlo simulation (MCS) (Hammersly and Handscomb, 1964), first-order reliability method (FORM) (Morgan and Henrion, 1990), numerical integration (Ouypornprasert, 1988) and stochastic differential equations (Kloeden et al., 1994; Jazwinsy, 1970). The applicability of these methods to river morphology depends on how well the methods deal with the strong non-linearity and complexity of river morphodynamics. Since existing deterministic numerical morphodynamic models are able to deal with this nonlinearity and complexity, stochastic methods that make use of such models are preferred (Gardner and O'Neill, 1983).

Monte Carlo simulation (MCS) with crude sampling appears to be a robust and suitable method to quantify uncertainties involved in morphodynamic predictions (van der Klis, 2003). The principle of MCS is to run a deterministic model repeatedly, each time with a different set of statistically equivalent model inputs. Van der Klis (2003), Chang et al. (1993) and Maurer et al. (1997) successfully applied the MCS-approach to numerical morphodynamic models. They used a highly simplified schematization to describe the complex river system. The complex physical processes and phenomena were described through the use of simplified mathematical expressions, such as empirical formulae or one-dimensional morphodynamic models of a straight prismatic channel.

Monte Carlo simulation (MCS) is utilized in this paper to quantify the uncertainty in the morphological impact of river restoration works that are currently undertaken within the framework of the RfR program in the Netherlands. We used a morphodynamic model of the river Rhine in the Netherlands that is more detailed than the models used by van der Klis (2003), Chang et al. (1993) and Maurer et al. (1997). A description of the morphodynamic Rhine model and the Monte Carlo simulation is provided below.

2.2 Morphodynamic Rhine Model

In principle, river morphology concerns a 3D problem, where a mobile bed is in constant interaction with complex turbulent flow patterns. However, fully 3D models are hardly available for river morphology and most problems do not need to be tackled by means of a 'complete' 3D description. In river engineering practice, 1D and quasi-3D morphodynamic models are commonly used that focus on the dominating processes in particular river settings. A 1D model does not discriminate between the left and the right side of a river, and produces a width-averaged representation of the morphodynamic behaviour in a river system. If more detailed bed responses are desired a quasi-3D model may be used which describes multi-dimensional phenomena, such as time dependent 2D river bed deformations.

Running complex morphodynamic models in an MCS-setting is rather time-consuming. The computational effort that is required for a single deterministic simulation with a 1D model is in the order of hours. For a quasi-3D model this is in the order of days. Given that the computational effort per individual simulation differs considerably between 1D and multi-dimensional models, preference is given to the use of a less time-consuming 1D model approach. By doing so, we neglect the 2D phenomena such as the asymmetry of river cross-sections and the cross-sectional profile evolution. With the 1D approach we expect to produce generic knowledge on the potential of a stochastic model approach in river management practice that also applies to multi-dimensional model approaches.

We make use of a morphodynamic Rhine model (Jesse and Kroekenstoel, 2001), which is based on the 1D morphodynamic simulation package SOBEK of the Institute for Inland Water Management and Wastewater Management (RIZA) and WL|Delft Hydraulics. With this model, we make unsteady flow simulations, each covering a period of 100 years, with a morphological time step of 10 days and a grid size of 500 m. At each spatial grid point (so every 500 m) a cross-sectional profile is defined, distinguishing between the main channel, the groyne section and the flow-conveying floodplain and the storage area. At each spatial grid point information on the hydraulic roughness of the main channel, hydraulic roughness of the floodplain and the grain size of the bed material (uniform bed material) has been specified.

The model was calibrated on the basis of hydraulic and bathymetric data and data on sediment transport rates in the period 1987–1997. The hydraulic roughness, the grain size, the nodal-point relation (describing sediment distribution at bifurcations), the sediment transport formula and the parameters in the sediment transport formula were used as tuning parameters in the calibration process of the model. Calibration focused on the reproduction of (1) morphodynamic phenomena (yearly cross-section averaged bed level changes, bed level slopes, propagation velocity of bed disturbances), (2) sediment transport rates, (3) dredging volumes, and (4) distribution of discharge and sediment at bifurcation points (Pannerdensche Kop and IJsselkop, see Fig. 1).

The model is composed of three modules: a flow, a sediment transport and a bed topography module. A quasi-steady approach is used, meaning that, given the bed topography, the flow module iterates until the flow pattern reaches a steady state solution, after which the sediment transport rates are computed and the bed levels are updated on the basis of the sediment balance. The model solves the 1D cross-sectionally integrated shallow-water equations, while retaining a distinction between the main channel, the groyne section, the flow-conveying floodplains and the storage area. The bed load sediment transport formula of Meyer-Peter and Müller (1948) is incorporated. The morphologically active part of the cross-section is restricted to the main channel and is indicated by the transport width. Lateral sediment transport from the main channel into the floodplains or vice versa is neglected. All sediment transport and all morphological changes therefore occur in the main channel. Since the Rhine model describes the main channel as a single thread, the computed changes in the main channel are cross-sectionally averaged.

The Rhine model consists of a network of nodes and branches. It includes the six main branches of the Rhine and the bifurcation points Pannerdensche Kop and IJssel Kop (see Fig. 1). At each spatial grid point a new cross-sectional profile is defined, on the basis of bathymetric soundings and topographical and digital elevation maps. The model has an upstream boundary (at the downstream point of the Niederrhein) and four downstream boundaries (at the downstream end of the Waal, the Lek and two sub-branches at the downstream end of the IJssel). The following hydraulic boundary conditions are imposed: (1) a discharge hydrograph at the upstream boundary and (2) rating curves (discharge-water level relationships) at the downstream boundaries. The morphological condition is that at any point in time the incoming sediment transport rate equals the local transport capacity at the boundary. Furthermore, initial conditions are given for each of the three dependent variables (discharge, water level and bed level in the main channel).

2.3 Monte Carlo Simulation

The morphodynamic Rhine model involves various types of uncertainties, including those in the model schematisations and in the specification of the model input (for example boundary conditions, initial conditions) and the model parameters. Van der Klis (2003), van Vuren (2005) and Huthoff et al. (2010) have shown that the discharge hydrograph is one of the most important sources of uncertainty in morphological predictions. Out of the various sources of uncertainty involved, we therefore only consider the uncertainty in the discharge hydrograph imposed at the upstream boundary.

MCS gives accurate results, as long as the sample size is large enough and the description of the input uncertainty is adequate. In the case of the Rhine model, a sample size of 500 turns out to be large enough to have sufficiently converged output statistics (van Vuren, 2005). This means that 500 model runs are made, for each of which a new discharge time series is synthesised (van Vuren, 2005). On the basis of the set of outputs of all model runs, the morphological response statistics could be analysed in terms of expected value, variance, 5% and 95% percentile values and confidence intervals.

Bootstrap resampling (Efron, 1982) is applied to construct a new time series by resampling from the original discharge dataset. We randomly select short discharge time series of one-year duration from a 100-year historical record of discharges taken near Lobith, where the Rhine enters the Netherlands. The one-year discharge time series are subsequently arranged at random to construct new time series of *N*-years duration. This way of resampling, preserves the seasonal dependency of the discharge (dry season with low discharges in summer, high-water season with floods in winter), the correlation of discharges in successive periods and the statistical properties of mean, maximum and minimum discharges, see also van Vuren (2005). In this way, we have constructed 500 discharge time series of 100 years duration. Outcomes of the MCS using time series of 100 years duration provide insight into the physical system behaviour and the uncertainty (e.g., temporal evolution of bed level response at a certain location, and longitudinal profile evolution of river reaches in response to training works).

3 RESULTS

3.1 Case A: Lowering Floodplains along the Waal

3.1.1 Case description

This case focuses on the morphodynamic impact induced by large-scale floodplain lowering along the Waal River (see Fig. 2). Three cases are considered (1) reference situation with traditional dike reinforcements showing the further evolution of the system without any additional human intervention; (2) situation with floodplain lowering by 1.5 m over a distance of 45 km (river section 885–930 km) with summer levees kept as they are; and (3) as case 2, but with the summer levees removed.

The morphological response to large-scale floodplain lowering depends on the following factors.

(1) Lowering the floodplains: Depending on the flow stage, lowering the floodplains will influence the discharge distribution between the floodplains and the main channel: a greater part of the discharge will be conveyed through the floodplains and may lead to morphological consequences. This inevitably has morphological consequences. It seems likely to assume that the morphological response will increase in magnitude as the floodplains are lowered more.

(2) Rate of accretion in the floodplains: This may increase, due to the increased lateral sediment transport into the floodplains caused by changes in the discharge distribution, and due to the increased trapping efficiency of the lowered floodplains. Therefore, floodplain lowering is not a self-sustaining measure. Without any countermeasures, the situation of the past is likely to be restored in the long run.

(3) Nature development and (re-)landscaping in the floodplains: Nature development is another function of the floodplains. Nature development is incorporated in the (re-)landscaping programs, which tend to replace the traditional agricultural land in the floodplains by various types of more natural vegetation. This entails an increased hydraulic roughness, which usually increases as the vegetation grows, thus counteracting the water level lowering effect (Baptist, 2005).

In this case study, it is assumed that the floodplains are lowered instantaneously, after which their level is maintained. Also, the extra sediment transport into the floodplains is neglected. These assumptions are justified, as a maintenance program will be defined to maintain the river restoration works in correspondence with their designs. Nature development and (re-)landscaping of floodplains (other than floodplain lowering) is not incorporated in the analysis. The type of vegetation in the floodplains is assumed to be the same before and after lowering. In this way we are able to assess the individual impact induced by floodplain lowering only.

The stochastic nature of the morphological evolution in the main channel of the Waal is analysed on the basis of 500 model runs, each covering a period of 100 years. Each run is driven by one of the discharge time series synthesised by Bootstrap resampling (see Section 2.2) and results in a computed bed topography, reflecting one possible future state. A varying discharge, in combination with non-uniformities in the river geometry (width variation and man-made structures), leads to a specific morphological response. Each non-uniformity in the river geometry acts as a generator of new bed level waves, each of which travels downstream. Given the uncertainty in the discharge hydrograph, this may lead to large uncertainties in the morphological prediction.

3.1.2 Morphological response statistics

The results in Fig. 3 show the morphological response statistics in the main channel in the Waal section between the Pannerdensche Kop (886 km) and Tiel (915 km) at the end of the simulation period. Figures 3a and 3b present the morphological response statistics (the mean bed level changes, the 95%-percentile value, 5% percentile value) and the size of the 90% confidence interval of the bed level changes for (1) reference situation, (2) situation with floodplain lowering, and

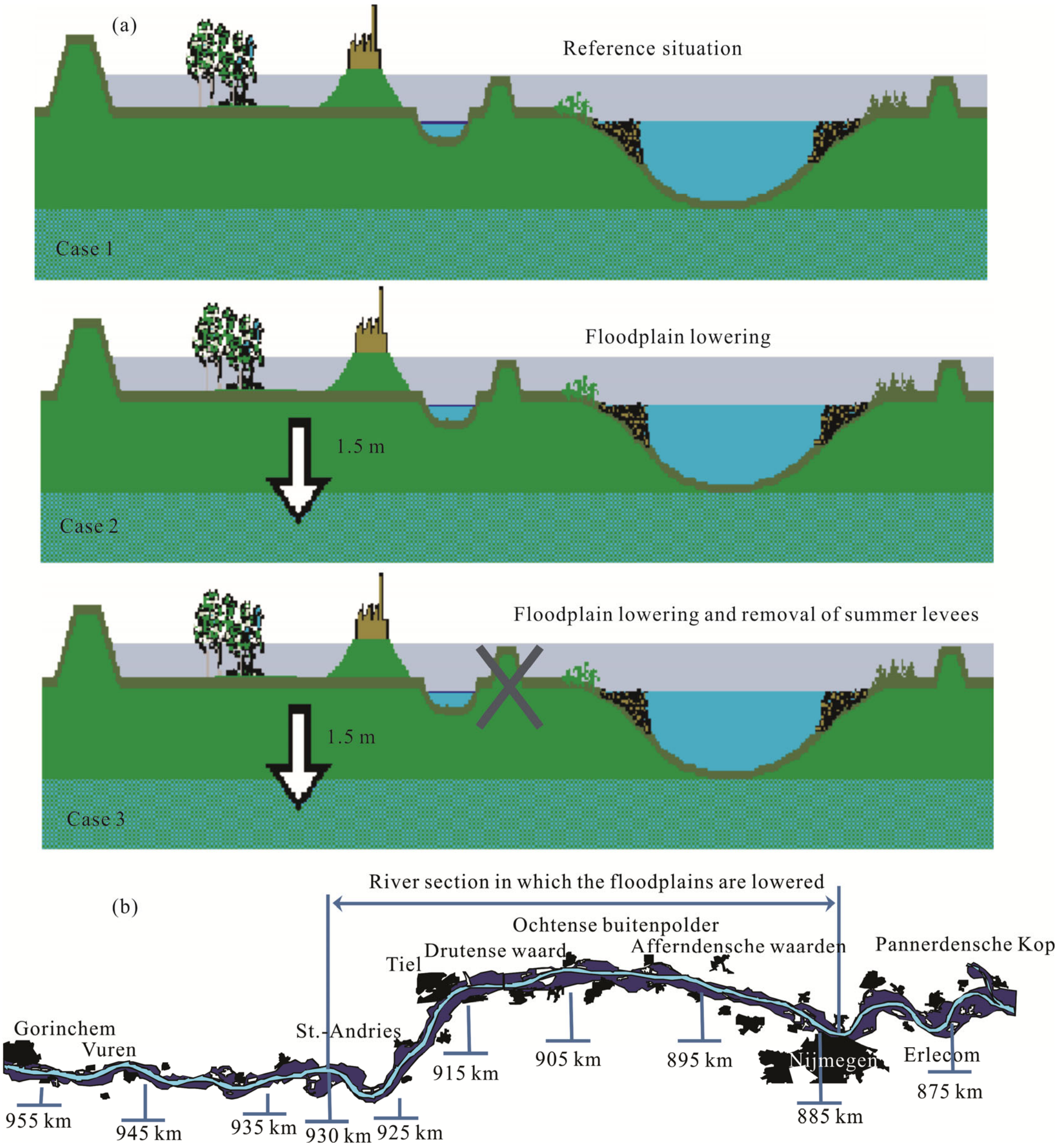

Figure 2. River section in which the floodplains are lowered with 1.5 m.

(3) situation with floodplain lowering and removal of summer levees. Figures 3c and 3d show the difference in the morphological response statistics and the size of the 90% confidence interval from the reference situation. Note that the lines of the response statistics and the confidence interval in Fig. 3 represent the envelopes of all realisations and cannot be considered as individual realisations.

As can be seen, the bed level of the main channel gradually decreases over the simulation period. Also, the river is slowly tilting around a hinge point somewhere downstream (results not shown here) (Fig. 3a). Figure 3a shows that the morphodynamic responses of the floodplain measures are small compared to the reference response and to the uncertainty in the outcomes. Figure 3b presents the 90% confidence interval, indicating that with a probability of 90% the bed level changes are within this range. The size of the confidence band is an indication for the variation of the response. At locations with strong geometrical non-uniformities, a peak in the confidence interval of the bed level is observed (see Fig. 3b).

Examples of locations where changes in river geometry cause a wide range of bed level changes are: (1) The bottom protection structures at 873–876 km near Erlecom and at 882–885 km near Nijmegen. These structures are designed for navigation purposes that prevent the riverbed from scouring. In the model the structures are schematized as fixed bed layers imposing a lower bound on the bottom. The fixed layers result in a relatively stable bed and hence a small 90% confidence interval. At both locations, the results after 100 years show that the fixed layers have become an obstacle in the river bed and that it causes a dip in the confidence interval. Clearly, both are due to a lack of erosion. Note that the fixed layers not only prevent erosion, they also yield extra scour and bed level variability immediately downstream (indicated by a peak in the confidence interval). (2) Locations with a large variation in the floodplain width in the floodplains at 898–901 km (Hiensche Waarden and Affendensche Waarden), at 902–906 km (Ochtense Buitenpolder) and at 906–913 km (Willemspolder and Drutense Waard). At these locations an increase in the size of the confidence

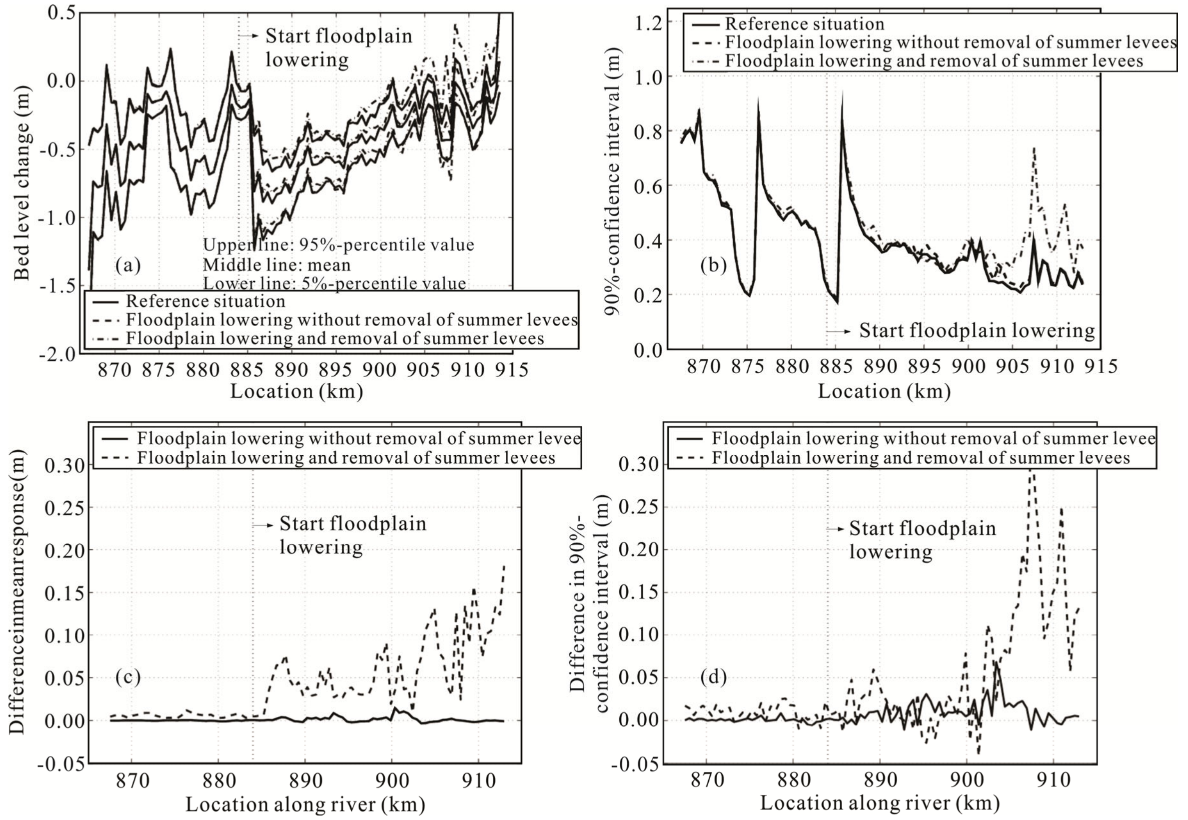

Figure 3. Spatial variation of the statistical properties of the cross-sectionally averaged bed level response in the Waal in December of the 100th year. (a) Morphological response statistics; (b) 90%-confidence interval; (c) difference in mean morphological response from the reference situation; (d) difference in 90%-confidence interval from the reference situation.

interval is noticed. For example, there is a large open water area between 906 and 908 km in the floodplain ‘Willemspolder’, followed by a sudden width-reduction just beyond 908 km. In overbank flow conditions, an increase in flood-conveying width leads to sedimentation in the main channel, a decrease to erosion. At the transition, this results in an increase in bed level variability, hence a larger confidence interval. (3) The Pannerdensche Kop bifurcation at 867 km: The actual discharge distribution and the sediment distribution at this point depend on the local morphological situation, which is strongly variable, as indicated by the large confidence interval.

Lowering floodplains and maintaining summer levees results in a similar response as in the reference situation (solid line in Figs. 3c and 3d). The summer levees keep the flooding frequency of the floodplains from increasing. Occasionally, when the water level exceeds the crest level of the levees, flooding occurs and the degree of floodplain lowering will have an effect on the morphological response. Due to the low frequency of occurrence of this situation, it has little effect on the total morphological response.

Lowering the floodplains combined with removal of the summer levees has a much stronger effect on the morphological response (dashed line in Figs. 3c and 3d). It leads to more frequent and more extensive flooding of the floodplains, whence the impact is more pronounced. With respect to the reference situation, sedimentation takes place in the main channel of the lowered reach. Not only does the mean bed level increase at the location of the floodplain lowering, also the size of the confidence band increases and has more pronounced peaks, indicating that the bed level response exhibits a larger uncertainty. The latter is especially noticed for the river sections with large geometrical non-uniformities (see examples (1)–(3) mentioned above).

The temporal variation of the response statistics provides information about when and how often the bed exceeds a particular level. The temporal variation of the response statistics for the reference situation and the situation with floodplain lowering and summer levee removal is analysed for two locations: one with a large geometrical non-uniformity (a large change in floodplain width) and the other in a uniform river section (no change in floodplain width). Figure 4 shows the impact of floodplain lowering combined with summer levee removal on the temporal variation of the response statistics at these two locations.

The figure shows that the seasonal fluctuation of the morphological response statistics is more pronounced at locations with large geometrical non-uniformities, such as 907.4 km (Fig. 4a). The largest confidence interval is found right after the period with the highest flood probability. The bed level variability in periods of high water is much larger than in periods of low water. The impact of floodplain lowering combined with summer levee removal on the temporal variation of the response statistics at location 907.4 km is significant: the confidence interval increases with approximately 80%. Apparently, the temporal response statistics at more or less uniform river sections, like 895.3 km (Fig. 4b), are less influenced by the intervention.

Especially at the location with the non-uniformity in geometry (907.4 km), the temporal variation in morphological response statistics is significant. An interesting aspect is the asymmetry in the seasonal variation of the 95%-percentile and the 5%-percentile. The 95% percentile has a larger amplitude than the 5% percentile. The highest 90% confidence level is found in the high-water period, the lowest one in the low-water period. This temporal variation can be explained from the gradients in sediment transport and reflects the seasonal variation of the river discharge.

At this location (the transition from a narrow to a wide cross section) the current velocity will decrease at discharges above bankfull, which induces sedimentation in the main channel. The 95%-percentile strongly oscillates, while the 5%-percentile is more or less constant. This can be explained by the fact that at discharges above bankfull bed waves are initiated in the main channel. These bed waves migrate downstream and (partly) decay at discharges lower than bankfull. At low flow, the river stays within the main channel and does not respond to variations in the floodplain width. Therefore, the seasonal variation in the 5%-percentile is limited.

At location (895.3 km), a uniform river section, the seasonal signature is less evident. The uncertainty in the bed level change at this location is affected by the bed waves that have been generated at other locations in the river and propagate downstream.

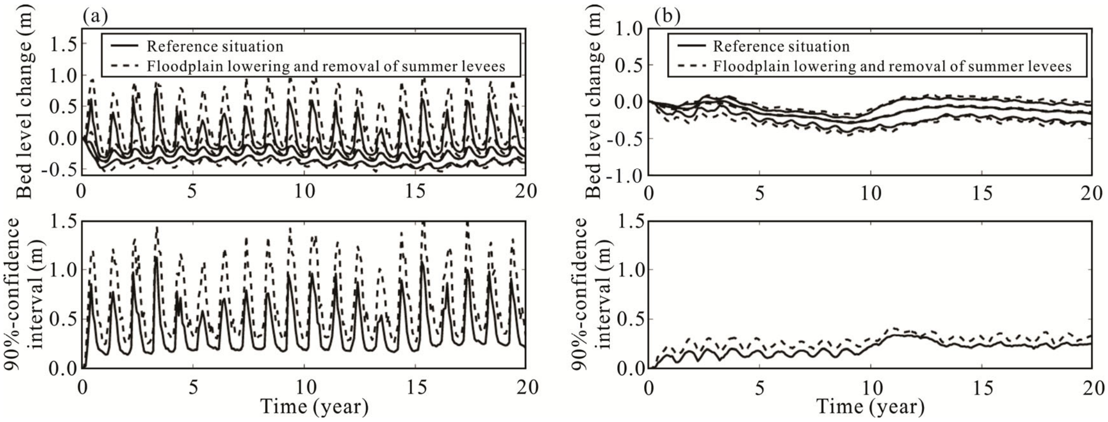

Figure 4. Temporal variation of the statistical properties of the cross-sectionally averaged bed level response at two locations in the Waal. (a) Location 907.4 km; (b) location 895.3 km.

3.1.3 Importance of stochastic modelling

It is demonstrated that discharge variability has important impacts on the resulting bed levels. The stochastic approach helps to express ranges of possible future states via the ensemble dimension of the morphodynamic responses and to get insight into the likelihood of morphodynamic predictions. Already in the reference case, various non-uniformities in the river in combination with an uncertain river discharge lead to an uncertain morphological response. At locations with large discontinuities a local increase in bed level variability is observed, since the width of the confidence band is significantly larger there. In addition, the seasonal variation of the response statistics increases at these locations. If floodplains are lowered and the summer levees are maintained, the response is similar to the reference situation, because of the infrequent flooding of these floodplains. If floodplains are lowered and the summer levees removed, the morphological response is much stronger, due to the more frequent flooding of the floodplains. Not only does the mean bed level increase at the location of floodplain lowering, also the size of the confidence band increases and has more pronounced peaks.

3.2 Case B: Re-design of the Rhine by Combining RfR-Measures

3.2.1 Case description

Using only one type of measure for the entire river, e.g., floodplain lowering over a distance of 45 km, as considered in the previous section, will not be the optimal solution for each of the individual river sections. As mentioned above, at some locations the impact of a certain measure is more pronounced than at others. Next, more realistic alternatives have been defined that include different types of RfR-measures. Some RfR-measures appear to be only of use in upstream parts of the river (lowering of groynes, floodplain lowering; also see Silva et al., 2001), whereas others are more effective downstream, such as dredging of the main channel. At urban bottlenecks, where urbanisation at either side of the river leaves no room for floodplains, the local flood conveyance capacity is low and floods create high water levels. Such bottlenecks can either be removed, e.g., by dike set-back, or by-passed via so-called green rivers inland of the main dikes.

Different sets of river improvement measures have been explored for each river section in the RfR-study. In principle, a large number of possible alternatives for the re-design of the Rhine could be defined by combining RfR-measures. Here, we consider two design alternatives that were compiled early in the process, each enabling a safe discharge of 16.000 m^3/s through the Rhine system (RfR, 2005).

Re-design alternative 1 is also known as the low-budget variant. In order to stay within the available budget of 1.9 billion Euro, a selection is made of mostly dike strengthening and some cost-effective RfR-measures, like lowering groynes and deepening the main channel by means of dredging. Costly measures, such as large-scale floodplain lowering in combination with nature development, are avoided as much as possible. Re-design alternative 1 consists of 50 km dike strengthening, 66 km groyne lowering, 26 km main channel deepening, 4 cases of dike set-back, 3 cases of obstacle removal and 11 floodplain (re-)landscaping projects.

Re-design alternative 2 emphasises the RfR-philosophy. Dike strengthening is avoided as long as spatial measures are applicable. Nature development and landscaping of floodplains play an important role in this alternative. The estimated costs of this alternative, some 3 billion Euro, exceed the available budget by far. Re-design alternative 2 consists of 6 km dike strengthening, 64 km groyne lowering, 26 km main channel deepening, 5 cases of dike set-back, 4 cases of obstacle removal and 29 floodplain (re-)landscaping projects.

3.2.2 Morphological response statistics

The upper panels in Fig. 5 shows the morphological response statistics in the main channel of the Waal for the two re-design alternatives, along with results for the reference situation. The lower panels in Fig. 5 show the deviation of the stochastic morphodynamic response from the reference situation.

Figure 5 shows that the impact of the proposed measures of Re-design alternative 1 on the morphology turns out to be limited: there is no significant change in the morphological response statistics. Negative influence on navigation and maintenance dredging will therefore also be limited.

Re-design alternative 2, which mostly consists of floodplain (re-)landscaping plans including floodplain excavation and nature development, has a more pronounced impact on the morphology of the Waal than Re-design alternative 1. This can be explained from the type of RfR-measures, which lead to more frequent and extensive floodplain inundations. In the Waal near Nijmegen (884–890 km), dike set-back is combined with floodplain lowering, the construction of a secondary channel in the floodplains and nature development. This induces local accretion of the river bed and a large confidence interval of the morphological response. The same (but even more pronounced) is the case for the river section 924–958 km where various floodplain (re-)landscaping plans are proposed. The morphological response induced by these measures is much stronger, due to more frequent flooding of floodplains. Not only is the mean bed level higher, also the confidence interval is larger and has more pronounced peaks than in the section near Nijmegen (880 km).

3.2.3 Importance of stochastic modelling

The stochastic approach provides insight into the morphological response to different sets of RfR-measures and the

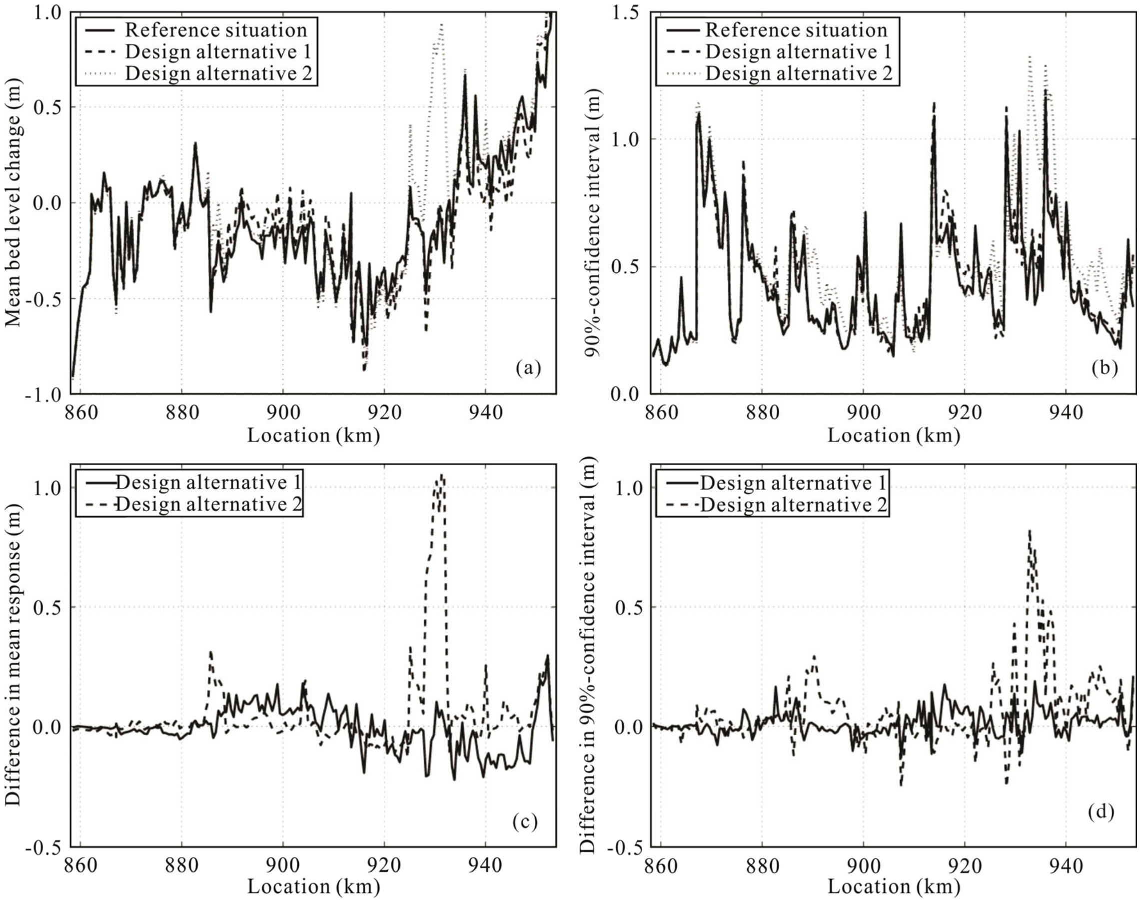

Figure 5. Spatial variation of the statistical properties of the cross-sectionally averaged bed level response in the Waal after 15 years in the high-water season. (a) Mean morphological response; (b) 90%-confidence interval; (c) difference in mean morphological response from the reference situation; (d) difference in 90%-confidence interval from the reference situation.

uncertainty involved. It shows that some locations are more susceptible to the RfR-design alternatives than others. At some locations, the RfR-measures locally enhance the bed level variability, and so lead to a significant increase of the uncertainty range in the predicted morphological response. Apart from this, the mean morphological state may locally respond to the RfR-measures by the formation of accretion and erosion patterns.

Design alternative 2, which mostly consists of floodplain (re-)landscaping plans including floodplain excavation and nature development, has a more pronounced impact on the morphology of the Waal than Design alternative 1. This can be explained by the type of RfR-measures in Design alternative 2 that have a stronger impact on the frequency and the extent of floodplain inundation.

The question is whether the inclusion of uncertainty considerations leads to conclusions—and associated paths of action—that would remain hidden if uncertainties were not considered. For instance, one single deterministic model run will most probably also show that Design alternative 2 induces sedimentation in the main channel of the Waal. The added value of stochastic approach is that it enables to quantify the uncertainty in this morphological response and provides information about likelihood of undesired possible states (e.g., states that cause large negative impacts on navigation or maintenance dredging efforts). The merits of a stochastic approach become even more apparent when statistically assessing, e.g., the river's navigability and maintenance dredging efforts for different design alternatives, using the morphological response statistics. Insight into the statistics of navigability and maintenance dredging requirements helps making proper river management decisions. In this particular case, one may choose to base the final river restoration scheme on traditional dike reinforcement or on RfR-principles. If the latter is chosen, one should be aware of the fact that these works increase river bed dynamics. There are countermeasures to mitigate this effect: Case A shows the importance of maintaining summer levees; some additional recommendations for counterbalancing morphodynamic impacts are given in the discussion. Insight into the statistics of maintenance dredging requirements of the final RfR scheme (mean, 5%- and 95%-percentile values, maximum and minimum dredging volumes) also helps the river manager in drawing up performance-contracts with dredging companies.

4 DISCUSSION

The examples in the previous section showed that a stochastic approach can be useful to assess the impacts of engineering works. It provides insight into the morphological response to different sets of RfR measures and the uncertainty involved. It gives insight into the range of possible morphological responses to different design alternatives, and into their probability of occurrence. Not only does the stochastic approach show that a range of morphodynamic states can occur, it also shows that at some locations the impact of engineering measures is more pronounced than at others. This goes for the mean response, as well as for the variability, and also for the seasonal variation.

Knowledge on the spatial and temporal variation of morphological response statistics is of importance to the allocation and design of future river improvement schemes. At some locations, the RfR measures locally increase the bed level variability, and so lead to a significant increase of the uncertainty range in the predicted morphological response. Apart from this, the mean morphological state may locally respond to the RfR measures by the formation of accretion and erosion patterns. This tells us that some locations are more susceptible to the proposed RfR measures than others. These locations also have a higher potential to develop into nautical bottlenecks, involving an increase of maintenance dredging costs.

Despite the fact that a re-design of the Rhine, consisting mostly of floodplain (re-)landscaping including floodplain excavation and nature development (viz. Re-design alternative 2 in the previous section), is bound to have a more pronounced impact on the morphology (sedimentation in the main channel and an increased uncertainty in the local bed response), this type of measures have formed the basis of the final RfR scheme to improve flood protection. Figure 6 gives an overview of the RfR restoration plans that are currently under construction in the Dutch Waal branch. It consists of a large number of floodplain (re-)landscaping plans, groyne lowering and the construction of longitudinal dams. Dike strengthening is limited as much as possible.

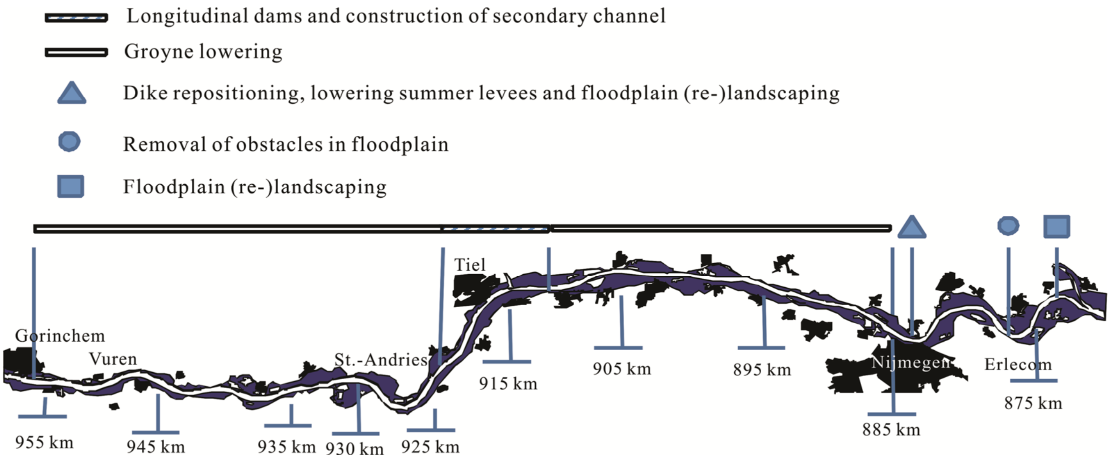

Figure 6. Overview of the RfR restoration plans that are currently under construction in the Rhine in the Netherlands.

We investigated the impact of the final RfR restoration scheme that are currently under construction on morphology, navigation and maintenance dredging. As already expected from the results in Section 3, the final RfR restoration plans induce in general an increase of the mean bed level, as well as an increase of the size of the confidence interval with more pronounced peaks. Some locations tend to develop into nautical bottlenecks and negatively affect navigation or maintenance dredging efforts. We quantified the impact on dredging if navigability is maintained. Figure 7 shows the statistical characteristics of the amount of maintenance dredging for the situation before and after implementing the RfR restoration scheme.

Apparently, the stochastic predictions indicate that there is a large uncertainty involved in the prediction of dredging volumes. The impact on dredging following from individual model runs varies between the minimum and the maximum volumes in Fig. 7. The RfR restoration projects will increase the average maintenance dredging volumes by about 20%. The uncertainty in the amount of maintenance dredging is also expected to increase.

This indicates that implementation of the various re-landscaping projects within the framework of Room for the River will exert an additional stress on the system. Van Vuren and Havinga (2012) expect that the RfR restoration plans will entail € 4 million extra costs for dredging per year for the Waal River. The required dredging operations will hamper inland navigation. If many dredging vessels are needed to maintain the navigation channel, this will hinder inland navigation with significant economic consequences and less safe inland navigation. The hindrance of navigation traffic induced by the large number of dredging vessels and the inevitable navigable depth reduction (despite dredging) will result in extra transport costs, estimated to be about € 15 million per year (van Vuren and Havinga, 2012).

This brings us to the question ‘Could we have done better in the design of the river restoration plans such that impacts on navigation and maintenance dredging would have been less?’. An easy answer would be that if we had chosen for a design that leaves the RfR philosophy and consists mostly of dike strengthening combined with large-scale groyne lowering, the impact on morphology, navigation and maintenance dredging would have been much smaller. This was shown by case B in Section 3. But considering the fact that the restoration plans do follow the RfR philosophy, we believe that more could have been done to counterbalance the morphodynamic impacts more effectively.

Firstly, considering that already in the present situation navigation problems are encountered, strict design criteria for inland navigation should have been posed next to the safety and environmental quality targets set by the RfR program. For each individual RfR project targets were set. Per project an extra amount of maintenance dredging was allowed. Accordingly, the impact of each RfR project on navigation was assessed individually to realise this target. The resulting dredging volume due to the combination of all RfR works was not considered and is now expected to rise significantly. Therefore, we recommend for restoration programs of navigable rivers elsewhere or in the future to set design criteria for inland navigation per river branch or sub-section.

Additionally, if all RfR works would have been considered jointly and an integral assessment would have been made, the urgency to limit the negative effects on navigation would have been more evident in an earlier stage. In the optimization process only the floodplain area of individual RfR plans was considered. Possibilities to mitigate the morphological effects by means of measures in the adjacent low water bed or groyne section (such as adaptation of groynes, guide bunds, longitudinal dams, inlet structures near side channels, floating screens, bottom vanes, sediment extruder, sills) were poorly considered. We recommend an integral assessment of future river restoration plans to counterbalance the system response to RfR-type re-landscaping.

Finally, we believe that a different lay-out of the river system, using structural measures could help dealing with the inheritance of the RfR restoration scheme, especially its negative effect on navigability and maintenance dredging. Structural measures in the lay-out of the river system could prevent the accretion and erosion patterns that cause these effects. Also they can be used to relocate sedimentation to places where it will not hamper navigation and where the sediment without causing too much hindrance may settle. Such structural measures can be divided in two main categories. The first one consists of well-known measures like local river training works such as groyne adaptations and longitudinal dams, beside new developments in groyne design (shape, permeability). The second category is not yet well-known in regulated rivers, as

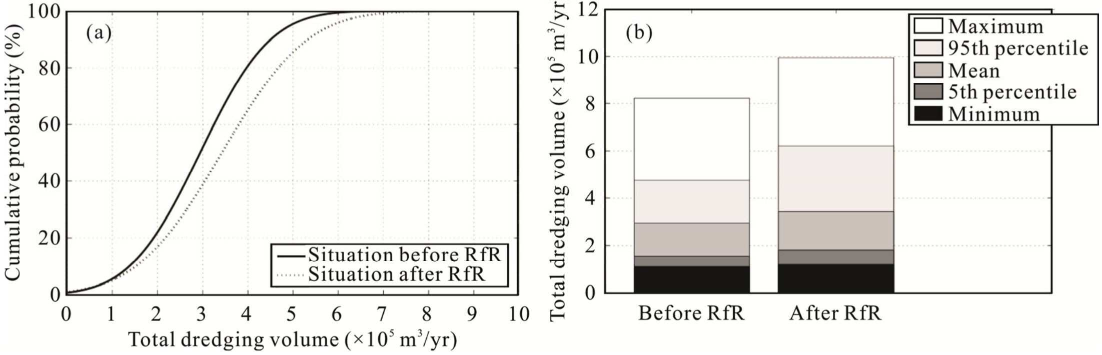

Figure 7. Statistical properties of dredging volumes in the Waal for the situation before and after implementing the RfR restoration scheme. (a) Cumulative probability distribution of maintenance dredging; (b) statistical characteristics of the amount of maintenance dredging.

the measures originate from irrigation schemes: inlet structures near side channels, floating screens, bottom vanes, sediment extruder and sills. Research is recommended to study the (cost-) effectiveness of structural measures to improve the navigability of the Rhine system and reduce the amount of maintenance dredging.

In morphologically dynamic river systems like the Rhine, morphology may also affect flood levels and thus cause flood safety problems. This paper mainly focuses on the impact of river restoration (to improve flood protection) on river bed dynamics and its negative effects on navigability and maintenance dredging. We recommend investigating the impact of morphological responses on flood levels and flood safety problems.

5 CONCLUSIONS AND RECOMMENDATIONS

The potential of a stochastic model approach is demonstrated in the paper. The paper shows how to analyse the stochastic nature of lowland river morphology and the impact of interventions to improve the flood protection level of a river system. The conclusion can be drawn that a stochastic model approach is useful in river engineering and maintenance practice. Application of the approach provides insight into the range of possible morphological responses to different design alternatives, as well into their probability of occurrence.

At some locations the impact of engineering measures turns out to be more pronounced than at others. This goes for the mean response, as well as for the variability, and also for the seasonal variation. Knowledge on the morphological response statistics is of importance to the design of river restoration schemes. For example, the case study in this paper leads to the conclusion that, in order to avoid a strong morphological response with a large bed variability and uncertainty, the summer levees should be maintained when lowering the floodplain of the Rhine. Floodplain lowering with removal of the summer levees should only be done at locations where there is a small variation in the morphological response. In this way, the stochastic approach enables the river engineer to optimise the design of river restoration schemes. It tells where summer levees should be maintained when taking measures to increase the flood conveyance capacity, so as to avoid undesired situations for navigation, maintenance dredging and flood safety. It is therefore recommended to test design alternatives for river restoration schemes to improve flood protection using the stochastic method described in this paper. The stochastic method will provide information about which design alternative yields the largest impacts on morphology, navigation and maintenance dredging (mean response, but also differences in uncertainty indicated in response statistics).

If the potential of structural measures to mitigate the impact of river restoration schemes for improved flood protection on morphology, navigation and maintenance is better understood, we can start making a new design for the lay-out of the river system. This should result in a lay-out of a largely self-sustaining river system that keeps itself navigable. Preferably, the reduction of dredging amounts should be achieved by structural measures with maintenance dredging as a closing entry. Flexibility to anticipate and regulate uncertainties in this self-sustaining strategy is important. The stochastic approach as used in the present paper can assist a river manager to decide where and how to interfere with the system, in order to avoid an increase in bed dynamics and the ensuing extra maintenance dredging. Information about the spatial and temporal variation of morphological response statistics in the present and future situation can be useful to decide where to locate structural measures in order to achieve maximum self-sustainance. Insight into the statistics of maintenance dredging requirements of the final river restoration schemes (mean, 5%- and 95%-percentile values, maximum and minimum dredging volumes) can help the river manager in drawing up performance-contracts with dredging companies.

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