Robust river systems: on assessing the sensitivity of embanked rivers to discharge uncertainties, exemplified for the Netherlands' main rivers

Klijn, Frans; Asselman, Nathalie; Mosselman, Erik

DOI
10.1111/jfr3.12511

Publication date
2018

Document Version
Final published version

Published in
Journal of Flood Risk Management

Received: 26 April 2018 | Revised: 4 October 2018 | Accepted: 26 October 2018

DOI: 10.1111/jfr3.12511

CIWEM Chartered Institution of Water and Environmental Management WILEY Journal of Flood Risk Management

ORIGINAL ARTICLE

Robust river systems: On assessing the sensitivity of embanked rivers to discharge uncertainties, exemplified for the Netherlands' main rivers

Frans Klijn[1,2] | Nathalie Asselman[2] | Erik Mosselman[2,3]

[1]Delft University of Technology, Department of Technology, Policy and Management, Delft, The Netherlands

[2]Deltares, Delft, The Netherlands

[3]Delft University of Technology, Department of Civil Engineering and Geosciences, Delft, The Netherlands

Correspondence
Frans Klijn, Delft University of Technology, Department of Technology, Policy and Management, Jaffalaan 5,NL 2628 BX Delft, The Netherlands.
Email: f.klijn@tudelft.nl

There is increasing attention for the robustness of systems, in view of more frequent and more extreme weather events. Calls to increase a system's robustness are usually motivated by the resulting reduced sensitivity to extreme events and uncertainties about their probability of occurrence. The concept has been elaborated for flood risk systems, but recently questions have arisen about whether subsystems, such as flood defences or rivers, should and could also be assessed on their robustness. Against the background of a recent debate in the Netherlands about whether to raise the embankments again or to make more room for the rivers in anticipation of increasing extreme river discharges into the future, we propose to define the robustness of embanked alluvial rivers by their sensitivity to uncertainties in flood discharge, expressed by the relationship between discharge and flood water level. We assess the Rhine River branches and Meuse River in the Netherlands and show how their planform, as defined by the location of the embankments and the presence of obstacles in the floodplains, causes remarkable differences in robustness per river and per river stretch. We finally discuss what this might entail for policy planning.

KEYWORDS

conveyance capacity, flood hazard, Meuse River, Rhine River, robustness, room for rivers, stage–discharge relationship, the Netherlands

1 | INTRODUCTION

Worldwide, rivers have been regulated and embanked in order to maximise their societal functions and to reduce the risks they pose to society. And in order to reduce flood risks, large parts of the alluvial plains are reclaimed and protected from flooding by extensive flood defence systems. Especially lowland rivers, running through wide alluvial plains or in deltas, are often fully embanked and constrained into narrow active floodplains along a trained main channel. Examples are the Donau, the Elbe, the Po, the Great Ouse (UK), or the Mississippi River. The Rhine and Meuse Rivers are sometimes qualified as perhaps the most heavily modified large rivers in the world.

The flipside of regulating and straightjacketing rivers has already been recognised for many decades (Jansen, Van Bendegom, Van den Berg, De Vries, & Zanen, 1979). Especially in alluvial rivers any human interference inevitably triggers natural feedback processes that govern river behaviour. Disturbance of the delicate balance between erosion and deposition results in changes in morphology. Unregulated braided or meandering rivers tend to react primarily by horizontal erosion of the riverbanks and changes in the planform, whereas rivers with fixed channels tend to react by vertical erosion and deepening of the river bed, or, in contrast, by deposition and shallowing. Especially in embanked alluvial rivers with fixed channels we see scouring of the channel and deposition on the floodplains at the cost of the river's discharge capacity. It makes the management of alluvial rivers a constant balancing act.

In this balancing act, the focus has long been on the relatively frequent conditions related to normal discharges. Recently, however, in response to the many flood disasters of the last decades (Jongman, Ward, & Aerts, 2012; Samuels et al., 2010) and in view of the possible effects of climate change on the discharge regime of the rivers, attention for extreme discharges is growing. In that context, the question has arisen how much straightjacketing of our rivers is acceptable, and which balance we should seek between higher embankments and giving our rivers more room. In the UK a Space for Water policy has been defined (Johnson & Priest, 2008) and the Netherlands has just completed the implementation of a 2.4 billion euro Room for the Rivers programme (Klijn, de Bruin, de Hoog, Jansen, & Sijmons, 2013; Mosselman, 2006; Sijmons, Feddes, Luiten, Feddes, & Nolden, 2017) in the wake of a policy transition that already began in the 1990s (Van Heezik, 2008). About 30 measures have been implemented along the Rhine River branches in response to increased design flood discharges, and a similar programme is being carried out along the Meuse River. It is, however, expected that climate change may cause the river discharges to increase even further (Sperna Weiland, Beersma, Hegnauer, & Bouaziz, 2015), but it is uncertain to what extent and how fast. As it has also been assessed that the flood protection standards in the Netherlands were outdated and needed revision (Van der Most, Tánczos, De Bruijn, & Wagenaar, 2014) and that the flood defences are currently not as strong as expected, the Netherlands now face the huge challenge of adapting to already changed geo-physical and socio-economic circumstances as well as to continuously changing conditions into the future. This challenge is tackled by the so-called Delta Programme (Van Alphen, 2016).

One of the key dilemmas in the Delta Programme concerns the question of how to respond to these changing conditions, and more specifically whether to reinforce and raise the embankments, or to increase the conveyance capacity of the rivers by providing more room. Enhancing the conveyance capacity of rivers has been shown to both reduce the flooding probability and the consequences of flooding (Asselman & Klijn, 2016; Klijn, Asselman, & Wagenaar, 2018), but reinforcing the embankments is much cheaper and in many cases appears more easily accepted by local societies. Against that background, all advantages and disadvantages of making room for the rivers are currently being reconsidered. A relatively new argument in the debate relates to the notion that making more room for rivers, in particular by widening the floodplains, may reduce the sensitivity of the flood levels to deviations from the expected discharge regime. This would imply that rivers with wide floodplains are more robust discharge systems and consequently less hazardous from a flood risk perspective.

In this paper, we especially address the benefit of making more room for the rivers by its influence on the relationship between river discharge and flood level, implying that rivers with widened floodplains are less sensitive to uncertainties about future river discharges. This makes the river system more robust, which may be regarded a benefit of making room for rivers beyond the mere reduction of flood probabilities and consequences, which it also achieves. The objective of this paper is therefore to propose a measure for the assessment of the robustness of embanked alluvial rivers in view of uncertainties about extreme flood discharges and to demonstrate its applicability by testing it on the two largest rivers in the Netherlands.

2 | ON THE CONCEPT OF ROBUSTNESS

The concept of robustness in relation to flood risk management is of relatively recent date (Mens, 2015; Mens & Klijn, 2015; Mens, Klijn, de Bruijn, & van Beek, 2011; Mens, Schielen, & Klijn, 2015). It can, however, be considered the logical successor of the resilience a concept describing a system's behaviour under stress, which has been used for several decades already (c.f. Holling, 1973). There has been ample scholarly debate about how we should interpret resilience as a property or characteristic of systems in general (c.f. Folke, 2006; Folke et al., 2010; The Royal Society, 2014), and as a property of flood risk systems in particular (De Bruijn, 2005; De Bruijn, Buurman, Mens, Dahm, & Klijn, 2017). Resilience has also been used as guiding principle for the design of flood risk management strategies (De Bruijn, Klijn, McGahey, Mens, & Wolfert, 2008; FLOODsite, 2009; Klijn, Van Buuren, & Van Rooij, 2004; Vis, Klijn, De Bruijn, & Van Buuren, 2003).

Mens (2015), however, recognised that flood risk management strategies in practice usually apply a combination of two distinct principles, namely resistance and resilience, and that the combination of both determines a strategy's effectiveness. Flood defence to reduce the probability of flooding would primarily classify as resistance, whereas spatial planning, warning and evacuation as well as insurance schemes would rather reduce the consequences of flooding and enhance a society's recovery capacity and hence classify as resilience. The term robustness was then proposed to cover both and defined as being a function of resistance and resilience. Thus, robustness would provide us with a more complete concept to indicate whether a system can cope with external stress. This conceptualization applies if we limit our interpretation of resilience to the behaviour of a response system as “gradual/proportional response and recovery”. If resilience is, in contrast, understood in a much broader sense, comprising even adaptation and transformation into the future (c.f. Folke et al., 2010; The Royal Society, 2014), there is no merit in distinguishing between resistance and resilience either, nor in considering robustness as a new concept (c.f. De Bruijn et al., 2017). We therefore do not support this very broad interpretation, but instead follow Mens (2015).

If we then define robustness as the ability to cope with extreme events, robustness can be understood as the inverse of vulnerability (or sensitivity); a robust system is the opposite of a vulnerable system. This explains the positive reception of this concept by policy makers, both politicians and public authorities. Nobody is against robustness.

Robustness, like resilience, only becomes a meaningful concept when we specify which system we focus on, and which stressor. After all, a system may be robust against floods, but perhaps it is not against air pollution, or it may be able to cope well with extreme weather, but without being able to cope with economic crises. Both De Bruijn (2005) and Mens (2015) investigated the resilience and robustness of comprehensive flood risk systems, conceptually defined as a human-environment system comprising the alluvial plain's physiography, the flood defence infrastructure in place and the people, their property and their activities in the protected area. As stressor they considered flood waves of various size and shape, propagated in the catchment area, and as response they looked at the consequences of these floods. One might, however, also look at the robustness of the flood defences, or of the river, or of any other subsystem or constituent of the flood risk system. In this paper, we focus on the river and more in particular on the river as a discharge system and not in any other function or from any other geo-ecosystem service point of view.

2.1 | River systems from a flood risk perspective

Various definitions of flood risk are recognised (Klijn, Kreibich, de Moel, & Penning-Rowsell, 2015; Samuels et al., 2009) and various helpful frameworks for investigating flood risk have been identified (e.g., SPRC (Source-pathway-receptor-consequence, cf. FLOODsite, 2009). If we isolate the river system according to these alternative definitions, a river qualifies primarily as a hazard and at the same time as a source of flooding. In the case of embanked rivers, one might even speak of a hazard that is partly man-made or at least humanly-aggravated. By qualifying a river as hazard, we could, according to Klijn et al. (2015), recognise both the hazard's probability distribution and the exposure related to these flood probabilities. In lowland rivers, however, the exposure to floods is usually effectively delimited by flood defences, which means that we can limit ourselves to answering the question whether a river is more or less hazardous because of the flood levels it produces. After all, these determine the load on the flood defences and hence the degree of hazardousness of the river, whereas they also determine the head of the water through the breach in case of the defence's failure and thus the rate of breach growth, the inflow speed and the final extent and depth of the flood.

If we were to know exactly the probability of discharges, flood wave shape and the flood levels related to these discharges and flood wave shapes at each location along the river, we could establish how hazardous a river is. However, neither of these can exactly be known in the range that we are interested in nowadays. In many countries “the century flood” is still regarded as the most (or only) relevant design flood, but new flood protection standards in the Netherlands relate to the failure probability of the defences and range from 1/100 per year to as little as 1/100,000 per year, depending on location. Despite many efforts to derive discharges and flood levels for such rare floods by very sophisticated modelling exercises (Brandsma & Buishand, 1999; Hegnauer, Beersma, Van den Boogaard, Buishand, & Passchier, 2014), we must admit that we are dealing with substantial uncertainties (Mosselman, 2018). The more so when we consider climate change, which in itself is certain, but has as yet deeply uncertain consequences for the river discharges in different climatic zones and orographic regions (Sperna Weiland et al., 2015). This urges to consider uncertainties, which could be tackled by over-dimensioning the flood defences along the rivers, or by transforming our rivers into more robust discharge systems. The latter requires that we at least have a shared notion about what that would entail. In this paper, we therefore first analyse our current river systems; more specifically the three Rhine River branches and the Meuse River.

2.2 | Robust rivers?

From a flood discharge point of view, a robust river can be characterised as a river that conveys a flood wave as smoothly as possible. Smooth conveyance requires a smooth channel and smooth floodplain geomorphology, that is, without obstacles, irregular planform or sudden irregularities in geomorphology or vegetation structure. As over the past 150 years the Rhine and Meuse Rivers have lost more than half their previously available floodplain area by closing off spillways and moving embankments towards the river (Klijn et al., 2013; Klijn, Asselman, Silva, & Stone, 2002), the flood levels along these rivers have gone up. The fact that constraining rivers by constructing and raising embankments causes flood levels in rivers to rise, has been recognised and documented for a long time (Monstadt, 2008; Pinter, Jemberie, Remo, Heine, & Ickes, 2008, 2010; Heine & Pinter, 2012). The principle is shown in Figure 1.

In the 1990s various investigations were carried out to identify whether, where, and why the smoothness of the floodplains of the Rhine River branches (HKV, 1997; Klijn, Baan, & Gijsbers, 1999; WL and RIZA, 1999) and the Meuse River (Van der Lee & Visser, 2000) was in any way jeopardised. The prime approach consisted of a scrutiny of

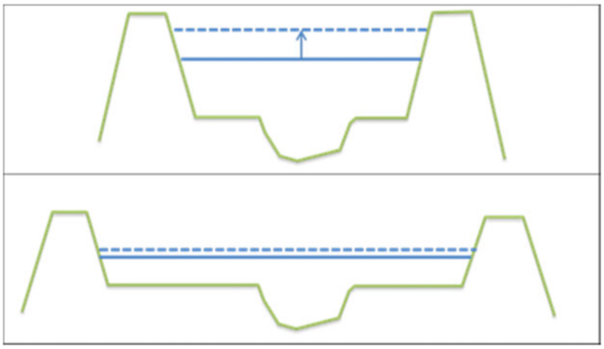

FIGURE 1 Degree of water level rise with increasing river discharge in a river with a narrow cross section versus one with a wide cross section of equal capacity

the water level slope at flood stage. Although trained alluvial rivers show a very smooth slope during average discharges, obstacles and bottlenecks are immediately revealed when the floodplains are contributing to the discharge process, that is, during floods that significantly exceed bankfull discharge. Then the water is pushed up by irregularities and the longitudinal water level profile becomes bumpy, showing the exact locations of obstacles or bottlenecks. By this method the urban bottlenecks at Nijmegen, Zutphen, Deventer and Kampen were identified (WL and RIZA, 1999), but also many smaller obstacles related to bridge abutments, ferry quays or industrial mounds. Some of these bottlenecks have been mitigated by Room for the River measures such as the iconic relocation of the embankment opposite the city of Nijmegen and the construction of an appealing blue-green bypass around the city of Kampen (see Klijn et al., 2013; Sijmons et al., 2017). But not all have been removed entirely by the recent interventions, as the current situation in Figures 2 and 3 shows.

About 20 years later, with the Room for the River programme almost fully implemented, Asselman and Hendriks (2016) followed the same approach to identify remaining obstacles or bottlenecks in the planform of the floodplains, in behalf of the Delta Programme which aims at adapting the country to the anticipated effects of climate change (Van Alphen, 2016). We then noted that the slope of the river differed substantially at different discharges. Bottlenecks became more or less acute, suddenly sprung up and sometimes disappeared. But most striking was the notion that each river had a markedly different water level slope whereas the difference in water level for different discharges varied per river as well. This called for some deeper deliberations, and not so much a closer look, but rather a look from a larger distance, as we shall argue.

This look from a larger distance involves an analysis of the slope of the flood water levels in different rivers for a relevant range of discharges. In addition to a better look at the slope itself, we focus on the relationship between flood levels (h, in metres above datum) and discharge (Q in m^3/s), as this may prove the key in considerations about whether or not and to what degree we can cope with uncertainty about a river's discharge, now and in the future. We propose to use the Q–h relationship as an indicator for the sensitivity of different rivers and river stretches to uncertainties about the discharge regime. From a flood risk perspective its relevance is then obvious, as flood level relates to both flooding probability and consequences of flooding (Figure 3).

3 | MATERIAL AND METHODS: SOME BACKGROUNDS ON OUR OBJECT OF RESEARCH AND ON THE MODELLING

The Rhine and Meuse Rivers are the largest rivers in the Netherlands (Figure 4). The Rhine River originates in Switzerland and has a length of 1,320 km. Its average discharge, where it enters the Netherlands at Lobith, is about 2,200 m^3/s. The 1/1250 per year design discharge, which applied until

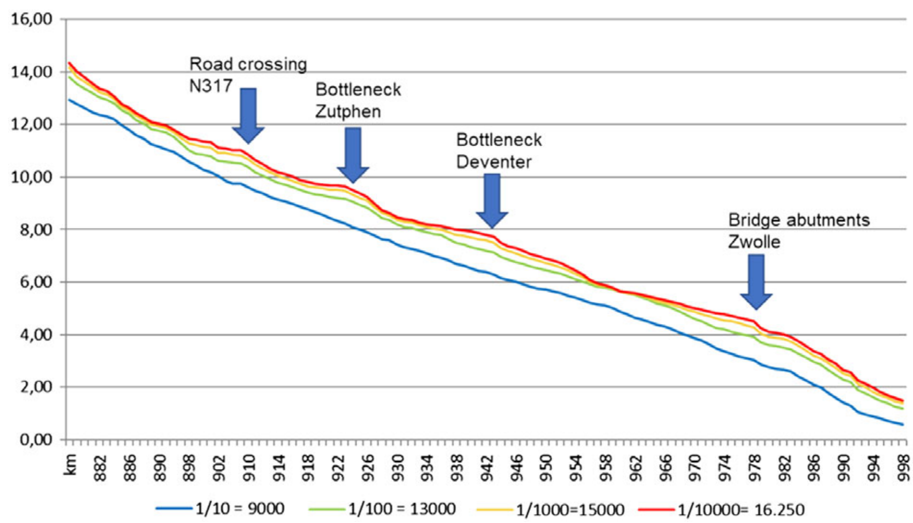

FIGURE 2 Slope of the IJssel River at 4 successive flood stages, corresponding with about 1/10 to 1/10,000 per year discharges in the Rhine River at Lobith, showing increasingly marked set up of flood levels as caused by obstacles and urban bottlenecks

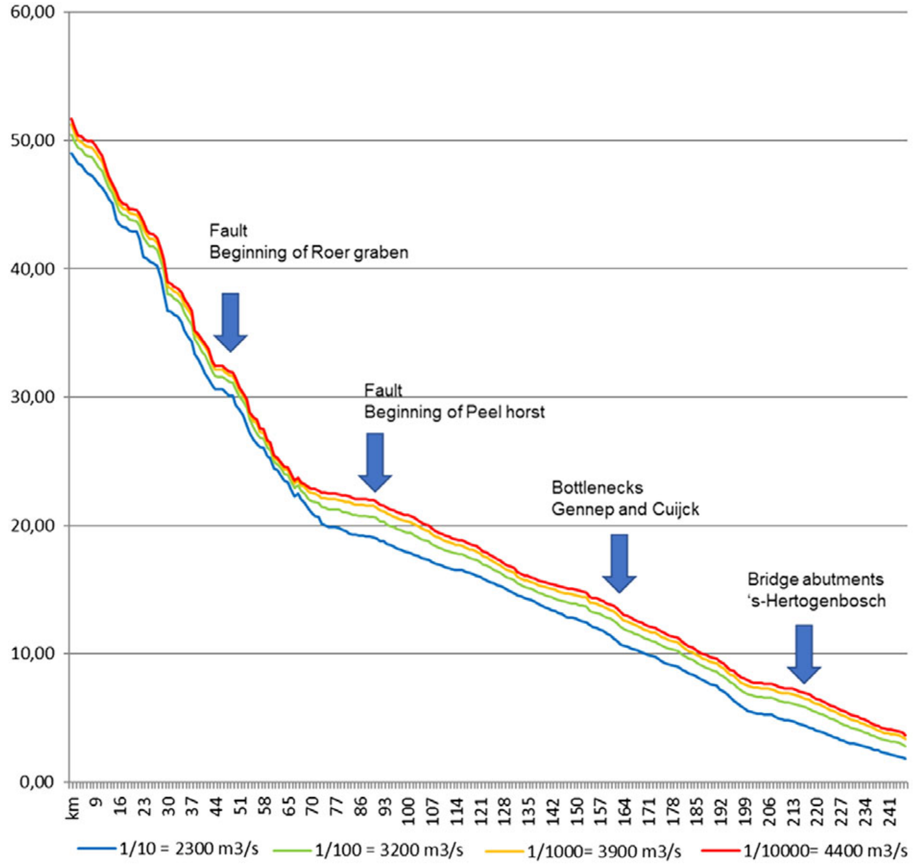

FIGURE 3 Slope of the Meuse River at 4 successive flood stages, corresponding with about 1/10 to 1/10,000 per year discharges at Eijsden, showing distinct differences between the steep upper Meuse, the remainder of the Meuse Valley (until km 150) and the embanked lower Meuse

2017, was 16,000 m^3/s. Shortly after the German–Dutch border, the river splits into three major distributaries: the Waal-Merwede, the Nederrijn-Lek and the IJssel which during flood stage receive proportions of the discharge of about 6:2:1, respectively. The land adjacent to the Rhine distributaries is almost entirely protected by embankments (Picture 1).

The Meuse River originates in France and has a length of about 900 km. The average discharge at the Belgian–Dutch border is 230 m^3/s. The 1/1250 per year design discharge which applied until 2017 was 3,800 m^3/s. The upstream part of the Meuse River in the Netherlands still flows through a natural valley, which together with its gravel-bed largely explains the steep slope until km 53 (Figure 3). The geomorphology in the following stretch is heavily influenced by a succession of tectonic features, with characteristic large meanders in the Roer Valley graben (km 53–90) in contrast to an incised straight river through the Peel horst (km 90–110). At a limited number of locations embankments have been raised to protect individual villages. The downstream part of the Meuse River (from km 150) is, however, embanked over its entire length, just like the Rhine branches.

For both rivers the fact that the rivers are embanked implies that floods do not cause harm very often, because they use to remain confined between the embankments. If, however, the embankments fail, the protected land is flooded by rivers that rise high above the land, shedding through rapidly developing breaches in those embankments.

We calculated the flood levels for both rivers by applying a hydraulic model. This was done for a large range of discharges, because the Netherlands has recently adopted flood protection standards based on probability of breaching and no longer based on the probability of exceedance of design water levels related to one single design discharge (Van der Most et al., 2014). This requires that we take into account the whole range of relevant flood levels. For the Rhine River, flood levels were calculated for a range of discharges between 6,000 and 20,000 m^3/s, corresponding with a probability of occurrence of about 1/5 to <1/1,000,000 per year. For the Meuse River, discharges were simulated ranging from 1,300 to 5,000 m^3/s, corresponding with a similar span of occurrence probability. The model we used was the delta model (Prinsen, Sperna Weiland, Ruijgh, & E., 2015), a 2D hydrodynamic model based on WAQUA (Leendertse, 1967; Stelling, 1983). WAQUA has been operational as the legally prescribed basis of design conditions for safety against flooding since the 1980s. WAQUA models are therefore continuously updated, tested and re-calibrated by Rijkswaterstaat (data) and Deltares (code and schematisation). We used the version with the 2015 planform and morphology,

FIGURE 4 The Meuse River enters the Netherlands from Belgium in the south and the Rhine River enters from Germany at the eastern border and then branches into Waal, Nederrijn-Lek and IJssel

that is, assuming that the Room-for-the-River programme (Klijn et al., 2013; Sijmons et al., 2017) had been fully implemented.

From all the simulated discharges, we selected those with probabilities of occurrence of about 1/10, 1/100, 1/1000 and 1/10,000 per year. Thus, we can account for the different size of the Rhine River branches and the slight deviations from the predefined discharge distribution. The corresponding discharges were derived from the GRADE research on discharge probabilities (Hegnauer et al., 2014). The flood levels we thus obtained differ by a factor of 10 in occurrence probability, sometimes addressed as decimation heights (DH). This approach can be understood as a kind of scaling, which allows making a comparison between the different distributaries of the Rhine River as well as with the Meuse River, despite a notably different discharge regime for the latter.

More specifically we used the following discharges for the Rhine River: 9000, 13,000, 15,000 and 16,250 m^3/s, implying discharge steps of 4,000, 2,000 and 1,250 m^3/s (+44%, +15%, +8%), respectively. That diminishing increase partly explains why the DH we shall show below become smaller with each step. A second reason is that the more extreme discharges are effectively subdued by peak attenuation as a consequence of extensive flooding upstream in Germany.

For the Meuse River the 1/10, 1/100, 1/1000 and 1/10,000 per year discharges have also been derived from the GRADE research. They correspond with about 2,300, 3,200, 3,900, and 4,400 m^3/s at Eijsden, for which we used available delta model results for 2,276, 3,280, 3,954 m^3/s, and a weighted mean of results for 4,004 and 4,600 m^3/s, respectively. The differences between the discharges are thus about 900, 700 and 500 m^3/s (+45%, +21% and +11%). In percentage these are larger differences than in the Rhine River because the Meuse is not subject to effective peak attenuation upstream of its entry point into the Netherlands.

4 | RESULTS

4.1 | Slopes of different rivers at different discharges

When we look at one river only, we can plot the calculated flood levels over the length of the river. We did so according to the standard Rhine kilometrization ("chainage"), which starts at the Schaffhausen waterfall in Switzerland, and the Meuse kilometrization, which starts at the Belgian–Dutch border. But in order to make a comparison between the slopes of the Meuse River and those of the Rhine River branches, we had to move the Meuse kilometres in such a

PICTURE 1 About 30% of the Netherlands lies entirely below sea level, whereas another 30% consists of alluvial plains protected against river floods by embankments (picture: Heemkundevereniging Leeuwen, 1995)

way that the two rivers connect quite nicely at both the lower end where they meet, as well as where a confluence used to exist until 1904. And we left out the Meuse Valley, because this is largely unembanked and its behaviour strongly influenced by geological features.

In Figure 5 we first show the slope of the three Rhine River branches from the German–Dutch border where the Rhine is still one river and down to where the lower boundary condition becomes dominant for the flood water levels, that is, at river kilometre 950. Downstream from that point the water levels that are calculated with the delta model are no longer relevant for flood management, because the lower boundaries in the model do not account for tides, storm surges, or wind drag. Moreover, a practical argument is that data on all three Rhine River distributaries are available only until this point.

The figure shows that the water levels for a 1/10 flood in the Nederrijn-Lek and IJssel Rivers largely correspond, except for the most downstream part of the IJssel where the flood levels are somewhat higher. The Waal shows slightly higher flood levels for this discharge. For a 1/100 flood (not shown) the same applies.

When we look at more extreme floods (shown is the 1/10,000 per year flood), the Nederrijn-Lek and IJssel Rivers still have similar water levels and an almost corresponding slope, but for these discharges the downstream part of the IJssel significantly deviates from the Nederrijn-Lek. The explanation is that a bypass built under the Room-for-the-River programme provides extra space and hence conveyance capacity for floods exceeding the 1/100 flood. For these extreme discharges the Waal branch rises between 1 and 2 m above its distributaries. We can also see in the figure that for extreme discharges the bottleneck at Nijmegen is not entirely removed by the relocation of the embankment (hump at km 887), as well as that the downstream half of the river is relatively the narrowest; the flood levels between km 915 and 950 are pushed up well above those in the other distributaries and the slope no longer has a concave shape, but rather becomes convex.

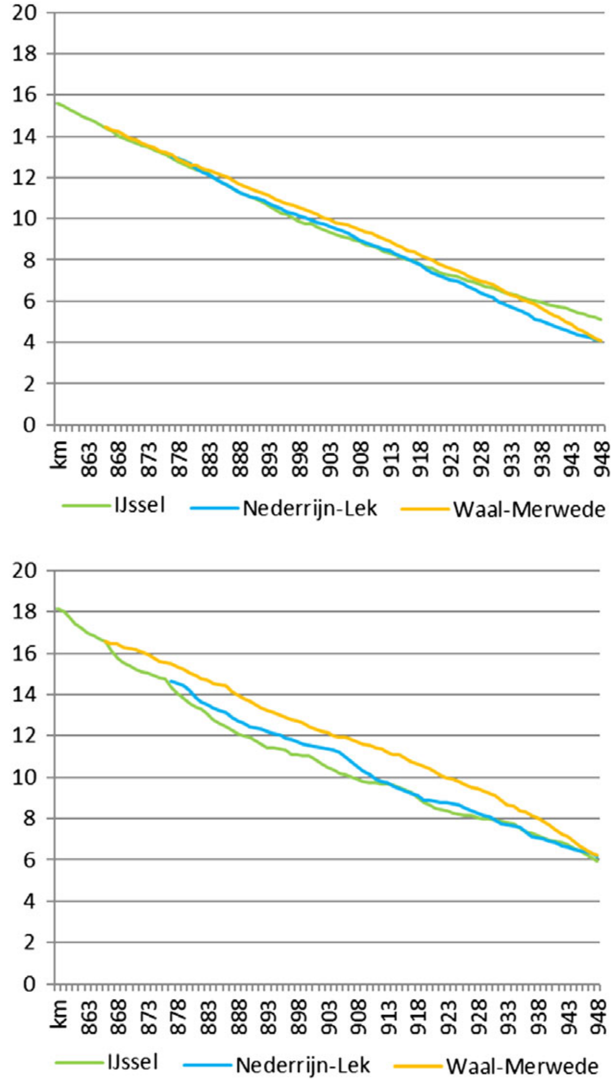

FIGURE 5 Slope of the three Rhine River branches between the German–Dutch border and km 950 for a 1/10 (top) and 1/10,000 per year flood (bottom)

This analysis already shows that the Waal River is relatively tight for the discharge it conveys, and hence sensitive to uncertainties about the exact discharge to be coped with, as evidenced by the increase in difference between the flood level in this river and the other Rhine River branches with increasing discharge (Figure 5, compare bottom to top): the Waal River rises to about 2 m above the Nederrijn-Lek. This relative tightness can be partly explained by the separation of the Waal and Meuse Rivers at km 924–926 in 1904, which was undertaken to prevent the frequent flooding of parts of the alluvial plains adjacent to the Meuse River by floods on the Rhine River. As a result, the Waal River could no longer convey part of its discharge through the lower stretches of the Meuse and had to accommodate a larger portion of the Rhine discharge by itself between km 926 and 948; but without having been enlarged for that purpose (cf. Klijn et al., 2002). It does explain the significantly higher embankments along this stretch.

Figure 6 shows the slope of the embanked part of the Meuse River relative to that on the Rhine River branches.

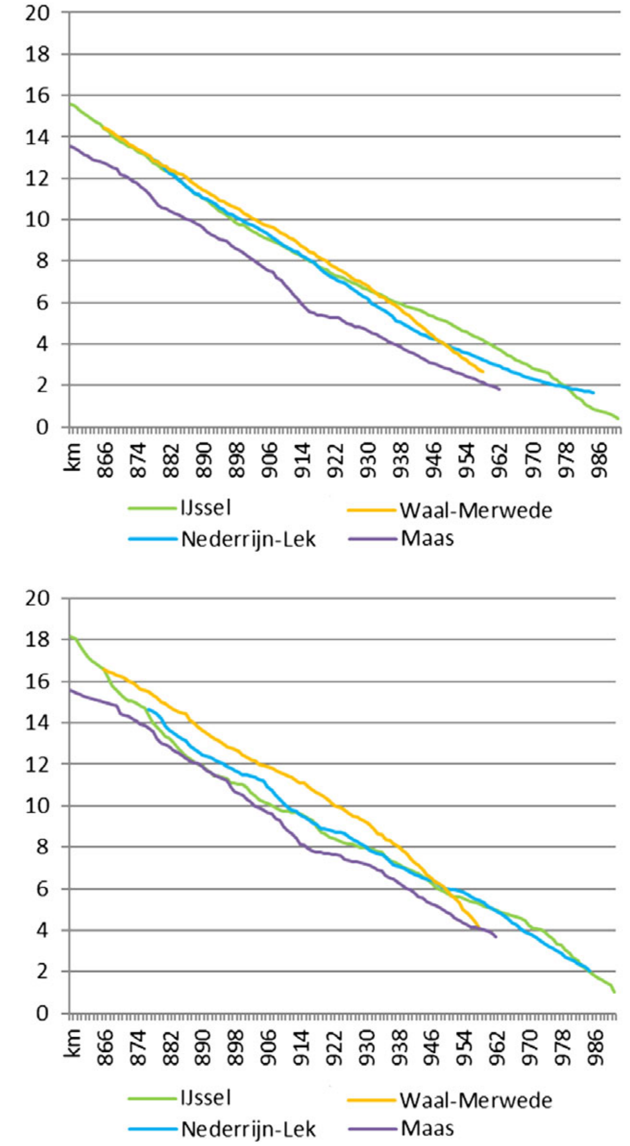

FIGURE 6 Slope of the fully embanked lowland part of the Meuse River in comparison to the three Rhine River branches for a 1/10 (top) and 1/10,000 flood (bottom)

For the 1/10 per year flood the Meuse River shows water levels that are about 2 m lower than those on the Rhine River branches, although near the end they approach those of the Waal River. As the Meuse and Waal Rivers connect in the western part of the country, this is according to expectation. With increasing discharge, the flood levels of the Meuse come closer to those of the IJssel and Nederrijn-Lek, but the Waal maintains the same difference. It thus seems that the Meuse River is relatively wide for frequent floods (e.g., 1/10), but almost as tight as the Waal River when it comes to more extreme floods (1/100–1/10,000). This is to be expected in a river which is fully canalised for navigation purposes, and hence can support a main channel that is overdimensioned with respect to the discharge regime (c.f. De Vries, 1947), but in contrast has narrow floodplains and abundant meanders which reduce the conveyance capacity during extreme floods.

4.2 | The *Q–h* relationship as indicator for robustness

The analysis of the slope of the different rivers already revealed that they are not equally sensitive to increases in discharge volume, or uncertainties about these discharges. But especially the difference in height between the water levels for the different discharges showed large differences between rivers and river stretches. Based on that observation, we propose to use the discharge–flood level relationship as a measure for the robustness of a river for uncertainties in discharge. This measure directly relates to the well-known stage–discharge relationship (Fread, 1975; Knight, Demetriou, & Hamed, 1984), but whereas the latter is used to estimate a river's discharge from a measured stage on a certain location, the discharge–flood level relationship rather serves to show the flood levels along a river's entire length for a range of given discharges.

For any river, whether natural or embanked, this *Q–h* relationship reflects how much the flood levels rise with a certain increase of the discharge. In alluvial rivers, given a certain sediment composition and hydraulic roughness of bed and floodplains (ceteris paribus clause) this *Q–h* relationship is primarily determined by the planform of the river and the morphology of the floodplain. In relatively wide and shallow rivers, a slight increase of the discharge causes less rise of the flood levels than the same additional discharge would in a narrow, deep channel of equal capacity (see Figure 1).

For a first impression of the *Q–h* relationship, we established the difference in flood levels for subsequent discharge levels which differ by a factor of 10 in probability of occurrence. We obtained these "decimation heights" for each "river kilometre" by simply subtracting the calculated flood water levels for the 1/10, 1/100, 1/1000 and 1/10,000 per year floods, respectively. Figures 7 and 8 provide the main results.

4.2.1 | Rhine River branches

Figure 7 shows the cumulative DH for the three branches of the Rhine River, each starting at the German–Dutch border (at Lobith, km 859). The figure shows the differences in flood water levels with probabilities of occurrence from 1/10 to 1/10,000 per year. Especially the differences between the three river branches, with the same discharge regime, and between river stretches in each river are telling.

In the figure, the starting point on the left is the same for all three river branches. It lies upstream of the bifurcation points (at respectively km 868 and km 879), which is relevant for the interpretation of the figure. Because these bifurcation points are constrained to prevent too large a share of the discharge to turn off to the right, they significantly set up the water levels. This effect is reflected by the shooting jumps in the middle and bottom graph of Figure 7 at km 868 and 879. Better, hence, to neglect the left parts of the graphs. This being said, Figure 7 shows the following:

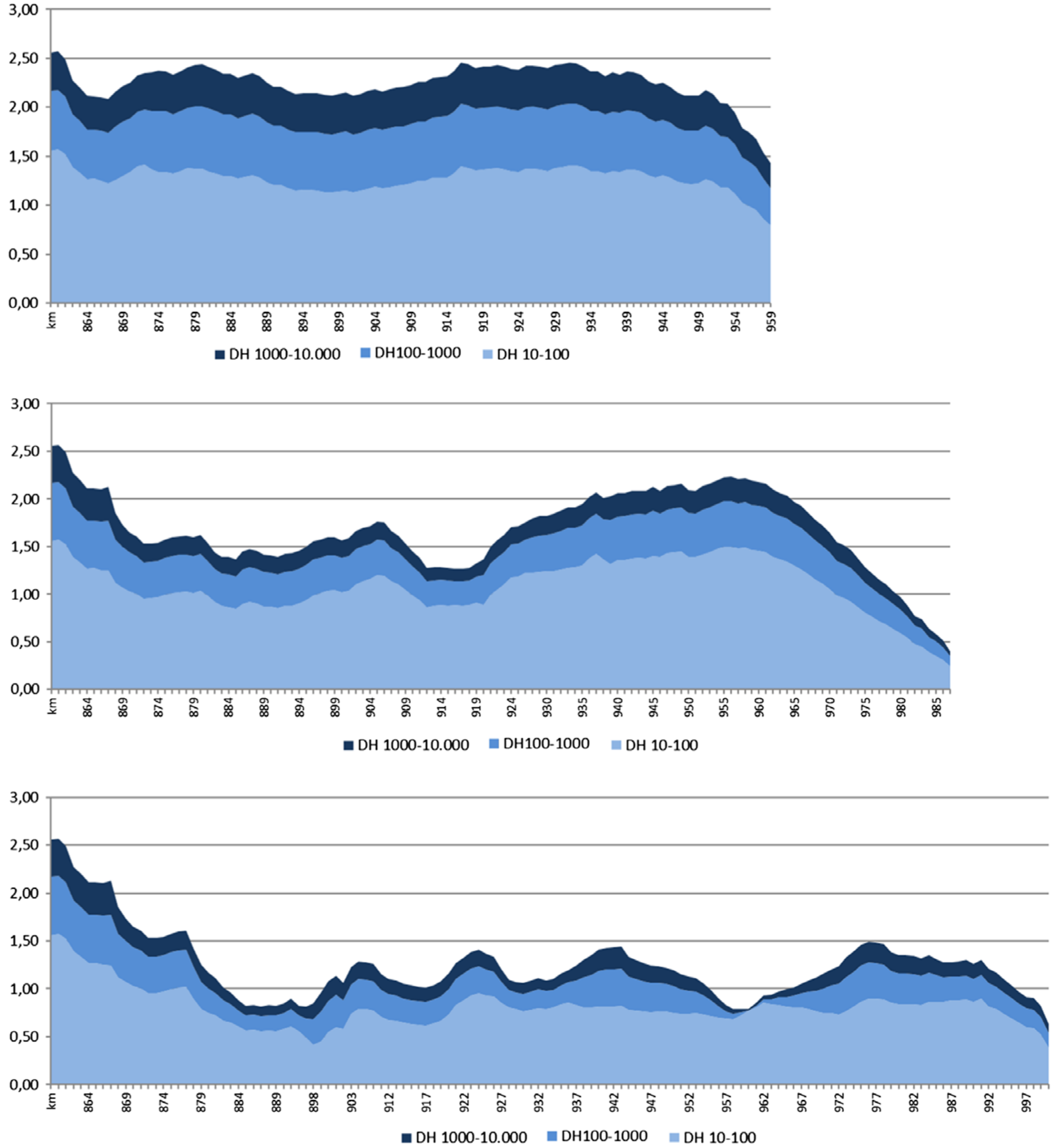

FIGURE 7 Cumulative decimation heights for Bovenrijn-Waal (top), Bovenrijn-Nederrijn/Lek and Bovenrijn-IJssel (bottom). Mark that the rivers have different length (as loosely indicated by the different width of the graphs)

- The Waal River (top) shows large increases in flood levels with increasing discharge, by about 2 to 2.5 m for the whole range. This reflects that the Waal River is relatively narrow, and consequently sensitive to uncertainties in the discharge at Lobith. Especially upstream of km 885 the river's discharge is hampered by the remaining bottleneck at the city of Nijmegen. Also, the stretch between km 926 and 948 is narrow, as remarked earlier, because the river was deprived of substantial discharge capacity by the separation of the Maas and Waal Rivers in 1904 at km 924–926 (Klijn et al., 2002). The difference between the 1/10 and the 1/10,000 per year flood levels amounts to almost 2.5 m in these stretches.
- The Nederrijn-Lek (middle) shows total differences in flood level for the presented cumulative decimation range of about 1.5 m, until about km 925. Further downstream this increases to more than 2 m, which is probably due to the genesis and history of this river. It only became one of the main channels of the Rhine River quite recently, after the closure of two older channel belts (Kromme Rijn and Hollandsche IJssel, formerly branching off at respectively km 926 and 952) when the

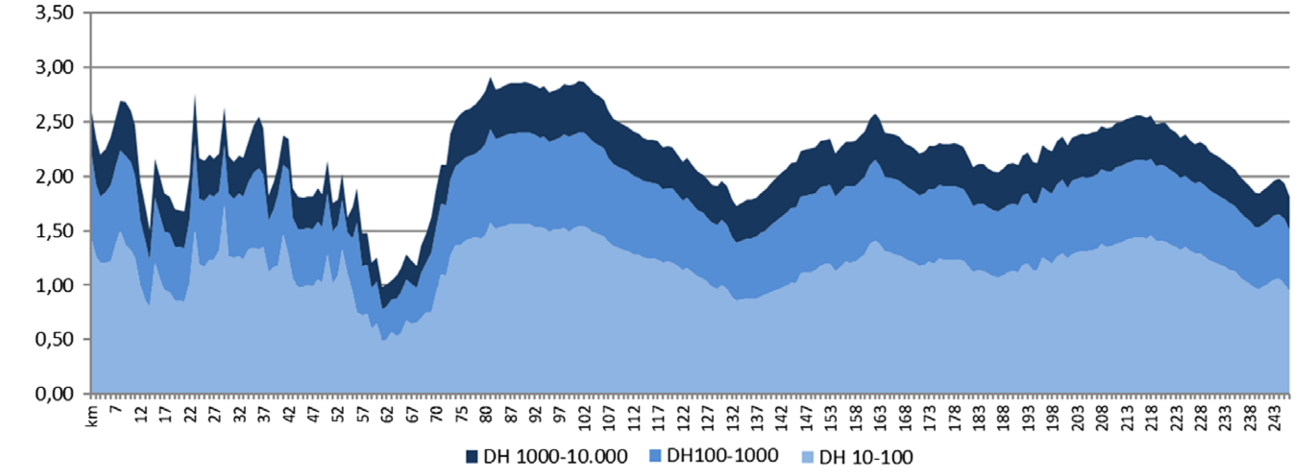

FIGURE 8 Cumulative decimation heights for the Meuse River between the Belgian–Dutch border and the estuary

rivers were fully embanked during the 14th century (Kleinhans, Klijn, Cohen, & Middelkoop, 2013).

- On the IJssel River (bottom) the difference in water levels between a 1/10 and a 1/10,000 per year flood remains limited to less than 1.5 m. Locally, not even 1.0 m is reached. This reflects a relatively spacious river, in which uncertainties about the discharge at Lobith do not immediately cause large deviations in flood level. The IJssel River already had wide floodplains, but recently, in the context of making Room for Rivers, on three locations embankments have been set back and two bypasses have been added, namely at km 961 and km 991 (c.f. Klijn et al., 2013).

Overall, we may conclude that among the three Rhine branches the IJssel River is the most robust to uncertainties about the discharge at Lobith. The Waal, in contrast, is the least robust of the three. A first important comment on this conclusion is that we actually need to account for the unequal distribution of an increase in Rhine discharge over the three distributaries. Nevertheless, we might expect the size of each distributary to correspond to its respective share of the discharge.

A second comment is that, because the Waal River also gets the largest share of the Upper Rhine River's discharge, namely, 2/3 of it, the Waal is the least sensitive to deviations of the predefined discharge distribution. An extra 100 m^3/s means less than 1% of the almost 11,000 m^3/s it is prepared for, whereas for the IJssel River this same 100 m^3/s would mean an increase of more than 5%. This is a typical problem in a delta setting with branching distributaries. It means that the robustness with respect to other sources of uncertainty may be different from the one established for uncertainty about the river discharge.

4.2.2 | Meuse River

Figure 8 shows the cumulative DH of the Meuse River in the Netherlands. This river strongly changes character between the entry point near Maastricht to its reaching the estuarine region of Biesbosch and Hollands Diep. This was already obvious from the slope of this river, as shown in Figure 3, but again reflected in Figure 8. In the upstream stretches (left), we see marked peaks (until about km 53) around a value of about 1.5–2.2 m. These result from local water set-ups which do, however, not extend far upstream because the river is still quite steep here. The average DH are similar to those of the Nederrijn-Lek. Some of the peaks may have been caused by recent embanking, but identifying the real cause requires closer scrutiny of the slope of the river (c.f. Asselman & Hendriks, 2016).

Between km 53 and km 90, the river flows through the Roer Valley graben. The valley is very wide here, and the river used to be characterised by large meanders, nowadays cut off to facilitate navigation. The slope of the river is gentle in this stretch, partly because further downstream the river cuts through the uplifted Peel horst which forms an elongated natural bottleneck. This tectonic setting of horst and graben explains the variations in valley width and river sinuosity along the river. It also explains the lower DH in the graph until about km 70, as a result of the ample "space to breath", followed by high DH between km 70 and 90 (c.f., Figure 8 with Figure 3). The river valley is narrow between km 90 and 150, but primarily due to the geological setting and not so much because of human interference, except for peaks which can be attributed to weirs and bridge abutments.

From about km 150 the Meuse River is embanked, first one-sided and from km 165 on both sides. The cumulative DH (1/10 → 1/10,000) remain above 2.0 m until km 235. These values were also found for the Waal River, but not on the Nederrijn-Lek nor on the IJssel River. We might conclude that the embanked Meuse is not a very robust river, but we need to emphasise that the Meuse has to cope with a more dynamic discharge regime than the Rhine River.

Between km 190 and 230 we see relatively large cumulative DH. This stretch seems quite tight. The largest DH can be traced back to two major road bridges with abutments (km 217–220).

5 | DISCUSSION AND CONCLUSIONS

In this paper we have looked at the robustness of rivers from a flood risk management perspective. This means that we consider rivers as a hazard and flood water levels as a key factor for both the failure probability of flood defences and the likely consequences of their failure through the flooding process. The lower the flood levels become, the less hazardous a river is.

We argued that a river may be considered robust if it is not sensitive to uncertainties about the discharge or changes in the discharge into the future. This implies that the flood water levels should not be sensitive to uncertainties about the precise discharge amounts and probabilities, the exact design discharge volume, the possible occurrence of beyond-design discharges, on any other uncertainty about the extreme end of the discharge regime. For a start, we called a river robust when it has an even conveyance capacity without irregularities in the flood level slopes. And in this context, we heartily supported the approach of scrutinising flood level slopes along a river's length as being perfectly suited to identify obstacles and bottlenecks, especially in embanked rivers. In fact, this approach has been essential for locating and designing the most efficacious interventions in the context of the Room for the Rivers programme for the Netherlands; especially the removal of obstacles, the relocation of embankments and the deployment of bypasses. And we still regard it an unsurpassed method.

We also argued, however, that taking an ever-closer look at irregularities in the profile may result in not seeing the forest for the trees. For stepping backward and looking at the slope of the river from a larger distance already revealed marked differences between the Netherlands' main rivers. The differences between the flood water levels for floods with different probabilities of occurrence (between 1/10 and 1/10,000) made us see even better where rivers might be too narrow over more prolonged stretches. Against that background, we proposed to use the discharge–flood level (*Q*–*h*) relationship as indicator for a river's robustness, and more specifically to use a range of successive DH.

By plotting the cumulative DH for the three Rhine River branches and the Meuse River in a stacked graph we obtained indications of the sensitivity of these rivers to uncertainties in discharge along the entire river courses. We thus found that the Waal River is the least robust in view of deviations from the expected discharges at Lobith, whereas the IJssel River appears the most robust. Uncertainties about the Rhine River's discharge may sooner cause things to go wrong along the Waal River than along the IJssel River. This experience makes us believe that our approach, that is, interpreting the *Q*–*h* relationship by assessing DH, may prove applicable on embanked alluvial rivers worldwide and may allow the comparison of very different rivers in very different climatic settings. But obviously we need trials on alluvial rivers elsewhere to establish whether this claim holds. Yet it may be very difficult to achieve reliable modelling results for rivers which are much more dynamic than ours, for example, with braiding or meandering channels and rapid morphological changes or vegetation development in the floodplains. Perhaps the applicability of our approach is therefore limited to heavily regulated alluvial rivers, that are also closely monitored and maintained and can hence be reliably modelled. The alluvial stretches of several European rivers might qualify for application, however, like the Po River, the Danube River, or the Elbe River, and quite likely also the embanked sections of the Mississippi River and Sacramento River in the USA.

Finally, we want to emphasise that our current definition of robustness for rivers deviates from that of Mens (2015) in the sense that it pertains to the river alone instead of to the entire flood risk system and it is limited to the river's function of discharging water. Elsewhere (Asselman & Klijn, 2016; Klijn et al., 2018), we showed that higher river flood levels in the Rhine and Meuse Rivers translate into an increase in consequence of flooding. To our opinion, this provides a valid argumentation to at least prevent that climate change results in higher flood levels and hence to enhance the conveyance capacity of our rivers. Our current analysis of the *Q*–*h* relationship, in addition, taught us that this should preferably be done by enlarging the floodplain area, as this not only leads to less hazardous rivers but also makes our rivers more robust and hence contributes to a more robust flood risk system along our major rivers.

ORCID

Frans Klijn https://orcid.org/0000-0003-2590-5570

REFERENCES

Asselman, N. E. M. & Hendriks, A. (2016). *Hydraulische knelpunten Rijntakken en Maas; een analyse op basis van verhanglijnen.* Deltares report 1230044-000, Delft, Netherlands.

Asselman, N. E. M. & Klijn, F. (2016). *Making room for rivers: Quantification of benefits from a flood risk perspective.* FLOODrisk 2016, 3rd European Conference on Flood Risk Management, Innovation, Implementation, Integration. 18–20 October 2016 – Lyon, France.

Brandsma, T. & Buishand, T.A. (1999). *Rainfall generator for the Rhine basin: Multi-site generation of weather variables by nearest-neighbour resampling.* KNMI publication 186-II, KNMI, De Bilt, The Netherlands.

De Bruijn, K. M. (2005). *Resilience and flood risk management: A systems approach applied to lowland rivers*. Delft, The Netherlands: Delft University Press.

De Bruijn, K. M., Buurman, J., Mens, M., Dahm, R., & Klijn, F. (2017). Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science and Policy*, *70*(2017), 21–30.

De Bruijn, K. M., Klijn, F., McGahey, C., Mens, M. & Wolfert, H. (2008). *Long-term strategies for flood risk management: scenario definition and strategic alternative design.* FLOODsite report T14-08-01, FLOODsite consortium. Retrieved from http://www.floodsite.net.

De Vries, J. W. (1947, 1947). De Maasverbetering voltooid. *De Ingenieur*, *59*(32), 75–80.

FLOODsite. (2009). *Flood risk assessment and flood risk management. An introduction and guidance based on experiences and findings of FLOODsite (an EU-funded Integrated Project).* Deltares | Delft Hydraulics, Delft, the Netherlands/E-publication. Retrieved from http://www.floodsite.net.

Folke, C. (2006). Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, *16*, 253–267.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, *15*.

Fread, D. L. (1975). Computation of stage–discharge relationships affected by unsteady flow. *Journal of the American Water Resources Association (JAWRA)*, *11*(2), 213–228.

Hegnauer, M., Beersma, J.J., Van den Boogaard, H. F. P., Buishand, T. A. & Passchier, R. H. (2014). *Generator of Rainfall and Discharge Extremes (GRADE) for the Rhine and Meuse basins. Final report of GRADE 2.0.* Deltares-rapport 1209424-004, Delft.

Heine, R. A., & Pinter, N. (2012). Levee effects upon flood levels: An empirical assessment. *Hydrological Processes*, *26*, 3225–3240.

HKV. (1997). *Hydraulische knelpunten Nederlandse Rijntakken – een inventarisatie.* HKV rapport PR116, Lelystad, the Netherlands.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology, Evolution, and Systematics*, *4*, 1–23.

Jansen, P. P., Van Bendegom, L., Van den Berg, J., De Vries, M., & Zanen, A. (1979). *Principles of river engineering. The non-tidal alluvial river*. London, England: San Francisco, CA: Melbourne, Australia: Pitman Publishing Ltd.

Johnson, C. L., & Priest, S. J. (2008, 2008). Flood risk Management in England: A changing landscape of risk responsibility? *International Journal of Water Resources Development*, *24*(4), 513–525.

Jongman, B., Ward, P. J., & Aerts, J. C. J. H. (2012). Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change*, *22*(4), 823–835.

Kleinhans, M. G., Klijn, F., Cohen, K. M., & Middelkoop, H. J. H. (2013). *Wat wil de rivier zelf eigenlijk? Deltares-report 1207829*. Utrecht: Utrecht University and Deltares.

Klijn, F., Asselman, N., Silva, W., & Stone, K. (2002). Ruimteverlies van Rijn en Maas verkend. *Het WATERschap*, *2002*(13), 590–601.

Klijn, F., Asselman, N. E. M., & Wagenaar, D. (2018, 2018). Room for Rivers: Risk reduction by enhancing the flood conveyance capacity of the Netherlands' large rivers. *Geosciences*, *8*, 224 20 pp.

Klijn, F., Baan, P. & Gijsbers, P. (1999). *Verkenning flessenhalzen.* Delft Hydraulics report R3294.73, Delft.

Klijn, F., de Bruin, D., de Hoog, M., Jansen, S., & Sijmons, D. (2013). Design quality of Room-for-the-River measures in The Netherlands: Role and assessment of the Quality Team (Q-team). *Journal of River Basin Management*, *11*(3), 287–299.

Klijn, F., Kreibich, H., de Moel, H., & Penning-Rowsell, E. (2015). Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation. *Mitigation and Adaptation Strategies to Global Change (MITI)*, *20*(6), 845–864.

Klijn, F., Van Buuren, M., & Van Rooij, S. A. M. (2004, 2004). Flood risk management strategies for an uncertain future: Living with Rhine River floods in The Netherlands? *Ambio*, *33*(3), 141–147.

Knight, D. W., Demetriou, J. D., & Hamed, M. E. (1984). Stage discharge relationships for compound channels. In K. V. H. Smith (Ed.), *Channels and channel control structures* (pp. 445–459). Berlin, Heidelberg: Springer.

Leendertse, J.J. (1967). *Aspects of a computational model for long period water wave propagation.* Technical report RM-5294-PR, Rand Corporation, Santa Monica, California.

Mens, M. J. P. (2015). *System robustness analysis in support of flood and drought management*. Amsterdam: IOS Press BV.

Mens, M. J. P., & Klijn, F. (2015). The added value of system robustness analysis for flood risk management illustrated by a case on the IJssel River. *Natural Hazards and Earth System Sciences*, *15*(2015), 213–223.

Mens, M. J. P., Klijn, F., de Bruijn, K. M., & van Beek, E. (2011, 2011). The meaning of system robustness for flood risk management. *Environmental Science and Policy*, *14*(8), 1121–1131.

Mens, M. J. P., Schielen, R., & Klijn, F. (2015, 2015). Enhancing flood risk system robustness in practice: Insights from two river valleys. *Journal of River Basin Management*, *13*(3), 297–304.

Monstadt, J. (2008, 2008). The relocation of a dyke on the River Elbe, floodplain management as a challenge for intersectoral and multilevel coordination. In T. Moss & J. Monstadt (Eds.), *Restoring floodplains in Europe. Policy contexts and project experiences* (pp. 229–258). London: IWA publishing.

Mosselman, E. (2006). Les valeurs rares et extrêmes dans la gestion des risques d'inondation aux Pays-Bas. *La Houille Blanche, SHF*, *5*, 66–68.

Mosselman, E. (2018). Modelling in applied hydraulics: More accurate in decision–making than in science? In P. Gourbesville, J. Cunge, & G. Caignaert (Eds.), *Advances in hydroInformatics; SimHydro 2017: Choosing the right model in applied hydraulics, 14–16 June 2017, Sophia Antipolis*.

Pinter, N., Jemberie, A. A., Remo, J. W. F., Heine, R. A., & Ickes, B. S. (2008). Flood trends and river engineering on the Mississippi River system. *Geophysical Research Letters*, *35*, L23404.

Pinter, N., Jemberie, A. A., Remo, J. W. F., Heine, R. A., & Ickes, B. S. (2010). Cumulative impacts of river engineering, Mississippi and Lower Missouri rivers. *River Research and Applications*, *26*, 546–571.

Prinsen, G., Sperna Weiland, F., & Ruijgh, E. (2015). The Delta model for fresh water policy analysis in The Netherlands. *Water Resources Management*, *29*(2), 645–661.

Samuels, P. G., Morris, M. W., Sayers, P., Creutin, J.-D., Kortenhaus, A., Klijn, F., … Schanze, J. (2009). Advances in flood risk management from the FLOODsite project. In Samuels, et al. (Eds.), *Flood risk management: Research and practice* (pp. 433–443). London: Taylor & Francis Group.

Samuels, P. G., Morris, M. W., Sayers, P., Creutin, J-D., Kortenhaus, A., Klijn, F., … Schanze, J. (2010). *A framework for Integrated Flood Risk Management.* 1st IAHR European Division Congress, May 2010, Edinburgh, UK.

Sijmons, D., Feddes, Y., Luiten, E., Feddes, F., & Nolden, M. (2017). *Room for the river – Safe and attractive landscapes*. Wageningen: Uitgeverij Blauwdruk. isbn:978-94-92474-96-4.

Sperna Weiland, F., Beersma, J., Hegnauer, M. & Bouaziz, L. (2015). *Implications of the KNMI'14 climate scenarios for the future discharge of the Rhine and Meuse.* Deltares report 1220042-000-ZWS-0004, Delft.

Stelling, G.S. (1983). *On the construction of computational methods for shallow water flow problems.* PhD thesis, Delft University of Technology, Delft, the Netherlands.

The Royal Society. (2014). *Resilience to extreme weather.* The Royal Society Science Policy Centre report 02/14, London, UK.

Van Alphen, J. (2016). The Delta Programme and updated flood risk management policies in The Netherlands. *Journal for Flood Risk Management*, *9*(4), 310–319.

Van der Lee, W. & Visser, M. (2000). *Inventarisatie lokale hydraulische knelpunten Maas.* HKV rapport PR162.70, Lelystad, The Netherlands.

Van der Most H., Tánczos, I., De Bruijn, K.M. & Wagenaar, D. (2014). *New, risk-based standards for flood protection in the Netherlands.* Proceedings of the 6th international conference on flood management (ICFM6), September 2014, Sao Paulo, Brazil.

Van Heezik, A. (2008) *Battle over the Rivers. Two hundred years of river policy in the Netherlands*. Haarlem and The Hague, The Netherlands: The Dutch Ministry of Transport, Public Works and Water Management.

Vis, M., Klijn, F., De Bruijn, K. M., & Van Buuren, M. (2003). Resilience strategies for flood risk management in The Netherlands. *Journal for River Basin Management*, *2003*(1), 33–40.

WL and RIZA. (1999) *Stedelijke knelpunten.* RvR-rapport 99.11, RWSDON, Arnhem.

How to cite this article: Klijn F, Asselman N, Mosselman E. Robust river systems: On assessing the sensitivity of embanked rivers to discharge uncertainties, exemplified for the Netherlands' main rivers. *J Flood Risk Management*. 2018;e12511. https://doi.org/10.1111/jfr3.12511