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Research paper

Enhancing flood risk system robustness in practice: insights from two river valleys[†]

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ABSTRACT

Decisions about flood risk management are usually based on the reduction in flood risk compared to the cost of the strategy. It is common practice to express this flood risk (the combination of flood probabilities and potential flood damages) in a single number. The downside of this approach is that explicit information about how the system responds to the whole range of possible water levels or river discharges is lacking. This type of information is relevant when a robust system is desired. We consider robust (fluvial) flood risk systems to have the ability to remain functioning under a range of possible river discharges. This paper analyses system robustness for different system configurations of two embanked river valleys in the Netherlands: the IJssel River valley and the Meuse River valley. Comparing the results of these cases provides us with clues about how to enhance a flood risk system's robustness. The IJssel case shows that a system with embankments that will not breach when overflown scores best on overall system robustness. The Meuse case shows that systems with differentiation in protection levels along the river score best on overall robustness. Furthermore, we found that in systems with high protection standards, the most effective way to increase system robustness is by increasing the system's response proportionality. This means that the consequences of flooding increase proportionally to an increase in river discharge. These findings confirm that a system robustness perspective may help to develop strategies that reduce the flood risks without increasing the vulnerability to beyond-design floods.

Keywords: System robustness; flood risk; variability; uncertainty; resilience

1 Introduction

Increased policy focus on vulnerability, as one of the components of flood risk, was triggered by recent disasters in, for example, New Orleans in 2005 and Japan in 2011, both unexpected events that exceeded the protection standards. Despite these events and the fact that risks increase due to population growth and economic development in flood-prone areas (IPCC 2012, Jongman *et al*. 2012, Klijn *et al*. 2012), many countries organize flood risk management primarily around flood defences and protection standards.

Flood risk in terms of expected annual damage, quantified by the combined probabilities and consequences of all possible flood events in a region, is an effective decision criterion to compare different types of measures, from strengthening embankments to land-use planning. However, the use of a single risk estimate as decision criterion has also been criticized for a number of reasons (see also Mens and Klijn 2014):

- It may not meet the decision needs of all stakeholders (Downton *et al*. 2005);
- It assumes risk neutrality, while the public is generally risk averse (Merz *et al*. 2009);
- Risk is uncertain, since many assumptions are needed to calculate risk, especially for systems with an extremely high protection standard (as in the Netherlands) (De Moel *et al*. 2012);
- It does not distinguish between low-probability/high-consequence and high-probability/low-consequence risks (Kaplan and Garrick 1981, Merz *et al*. 2009).

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The main concern with using risk analysis in decision-support is how to deal with uncertainty. Downton *et al*. (2005) argue that practitioners should communicate better about uncertainties in estimates and how they are handled in developing strategic alternatives, whereas others focus on developing quantitative uncertainty analysis methods in support of flood risk management (Hall and Solomatine 2008). Uncertainty may be a reason to consider additional decision criteria besides the single-value flood risk estimate, for example, the severity, duration and controllability of the risk (Stirling 1998). In addition, some authors propose taking into account worst-case scenarios (Merz *et al*. 2010) or start so-called possibilistic thinking instead of probabilistic thinking (Clarke 2005). Thus, in addition to the traditional comparison of flood risk and costs, it is recommended to analyse the 'what if design conditions are exceeded' scenario.

In the literature on socioecological systems, the proposed way to deal with uncertainties is to aim for a robust or resilient system, instead of trying to control external disturbances (Folke 2006). Among other things, control means the variability of the system is reduced to make its behaviour better predictable: floods hardly happen. However, the downside of too much control is that unanticipated events may cause surprise and crisis (Holling 1996): when a flood does happen, it may turn into a disaster. The idea of steering on system persistence (thereby allowing disturbances) instead of system stability was first introduced by Holling (1973) for ecosystem management, and later extended to the management of socioecological systems (Carpenter *et al*. 2001, Walker and Salt 2006). This type of management is often called 'resilient'. In the field of flood risk management, however, the term resilience is associated with the ability to recover from the response to a disturbance (De Bruijn 2005), which is a narrower interpretation than that of the ecological and socioecological literature. To avoid confusion, we use the term system robustness when we mean the ability to remain functioning under a range of possible disturbance magnitudes (Mens *et al*. 2011).

The idea of using system robustness as a decision criterion in addition to damage risk, fatality risk and costs, was already tried out in De Bruijn *et al*. (2008) and Klijn *et al*. (2012), but only in a qualitative manner. A quantitative method for system robustness analysis was introduced by Mens *et al*. (2011) and improved by Mens and Klijn (2014). The following criteria together provide an indication of system robustness (see Figure 1):

(1) Resistance threshold, or the smallest river discharge that will cause substantial economic damage;
(2) Response proportionality, or the sensitivity of the response to changes in discharge;
(3) Manageability, or how easy the system can recover from the flood consequences.

The last criterion relates to some critical level of damage from which recovery will be very difficult.

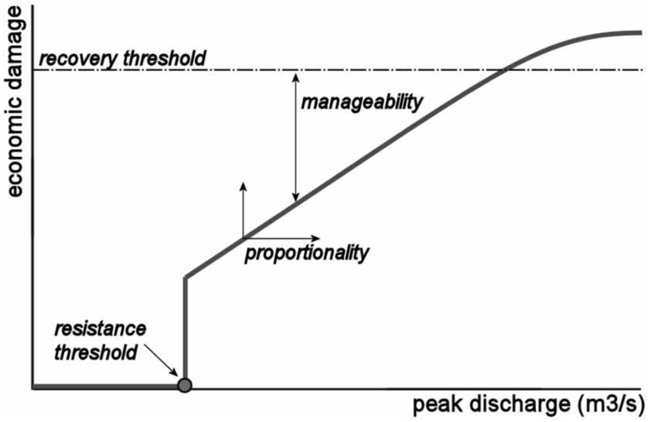

Figure 1 Theoretic response curve of a flood risk system (adapted from Mens *et al*. 2011).

In this paper, we compare system robustness to discharge waves of two embanked river valleys: the IJssel River valley and the Meuse River valley. The analyses provide insight into the system response to a range of river discharge waves, including the extreme ones. We compare the results of both cases and draw some generic conclusions about how to enhance the system robustness of embanked river valleys.

2 Method: quantification of system robustness

2.1 *Response curve*

Quantifying system robustness starts by constructing a so-called response curve: the relationship between peak discharge and flood damage, from which the system robustness criteria can be derived (Mens *et al*. 2011). The response curve can be obtained from the following information, which typically underlies a flood risk analysis:

- River discharge–frequency curve;
- Water-level frequency curve at each breach location;
- Relationship between river water level and flood damage;
- Critical water levels at each breach location, which initiate flooding.

To obtain a response curve for an entire river valley, damages of all possible breach locations have to be combined. However, because of the uncertainty about embankment strength, it is unknown which embankment will breach first. Many combinations are possible, each with a unique damage sum. It is very unlikely in embanked river valleys, if not hydraulically impossible, to have all breaches occurring within one flood event, simply because there is not enough water to flood the entire system. Therefore, we developed a method to obtain a damage estimate corresponding to each discharge wave. First, for a given discharge wave, the damages of each breach location are collected. We take into account that, depending on the protection standards, some locations will have zero damage at the chosen discharge, because the critical water level is not yet exceeded.

The critical water level equals the design water level when only the failure mechanism overflow is taken into account. In other cases, a critical water level has to be selected based on fragility curves. Second, the damage estimates are added up in all possible combinations, but with a maximum of four dike-ring areas. With that we assumed that at a given river discharge, each combination of breach locations has an equal probability of occurrence. Finally, we calculate the median of the damage. The procedure is repeated for a range of river discharges.

2.2 *System robustness criteria*

The system robustness criteria are derived from the response curves of each alternative system configuration. The first criterion, resistance threshold (the lowest discharge causing damage), may be lower than the design discharge, due to uncertainty about the embankment strength. If fragility curves are available, it can be quantified as the discharge where the conditional probability of flooding is greater than 0.1 for one or more breach locations. This approach was followed for the IJssel case. For the Meuse case, fragility curves were not yet available. Therefore, the resistance threshold was estimated as the discharge corresponding to $T = 250$ years (Asselman *et al.* in prep.). At this return period, the discharge is 500 $\mathrm{m}^3\,\mathrm{s}^{-1}$ lower than the design discharge and the water levels are 0.5–0.6 m lower than the dike height. This is a very rough estimate, but it does not influence the conclusions of the paper.

The second criterion, proportionality (the sensitivity of the damage for changes in discharge), is measured by the maximum slope of the response curve. The resulting value represents the additional damage that is caused by increasing the discharge peak by a volume increase of 1 $\mathrm{m}^3\,\mathrm{s}^{-1}$. To obtain a score between 0 and 1, this value is divided by the largest damage of all configurations. In formula:

$$\mathrm{Proportionality}_i = 1 - \frac{S_{\max_i}}{\max(D_i)}, \tag{1}$$

where $S_{\max_i}$ is the maximum slope of response curve of configuration i and $\max(D_i)$ is the maximum damage over all configurations.

The third criterion, manageability, is scored on a scale of 0 (no recovery) to 1 (easy recovery). In Mens and Klijn (2014) we assumed that recovery is difficult when the flood damage exceeds 5% of the regional GDP. If the damage exceeds 5% of the national GDP, the zone of no recovery is reached. We give a score based on the height of the damage when the resistance threshold is exceeded compared to the two recovery thresholds. If the damage passes the first recovery threshold zone immediately, then it receives a score of 0.5. If the damage reaches the first recovery threshold at the maximum discharge, it receives a score of 1. When the damage increases proportionally, it will first stay below the recovery threshold and at higher discharges it will cross the recovery threshold. In that case, the recovery zone is not clear and the score will be between 0.5 and 1. We assume that the longer it stays below the threshold, the higher the score.

3 Cases IJssel and Meuse

3.1 *IJssel case*

The IJssel River is one of the three branches of the Rhine River. The IJssel River valley consists of six dike-ring areas (see Figure 2). Each dike-ring area is protected from flooding by a ring of flood defences and adjacent high grounds, which are designed to withstand river discharge waves that occur on average once in 1250 years.

The future IJssel River discharges are uncertain, because of natural variability, uncertain climate change and unknown distribution of water over the three Rhine River branches. Therefore, it is relevant to evaluate proposed strategies on how the adapted system will deal with a range of discharges, instead of optimizing the strategy for just one design discharge. As a result of the mentioned uncertainties, the discharge frequencies are uncertain. Instead of trying to calculate the frequencies, we analyse the flood impacts for a range of discharges for which the system should be prepared.

The IJssel case builds on available data from Mens and Klijn (2014), in which flood risk and system robustness were calculated using several alternative system configurations. We reused these data to discuss what enhances the system's robustness. The IJssel design discharge was estimated at 2560 $\mathrm{m}^3\,\mathrm{s}^{-1}$. For the flood damage calculations in that study, it was assumed that embankments breach when the local water level reaches its peak (for discharge waves with $Q_{\mathrm{peak}} < 2560\ \mathrm{m}^3\mathrm{s}^{-1}$), or when the local design water level is exceeded (for discharge waves with $Q_{\mathrm{peak}} > 2560\ \mathrm{m}^3\mathrm{s}^{-1}$).

The system robustness analysis requires a choice on the maximum river discharge for which consequences are calculated. One option is to use the future design discharge according to the worst-case climate-change projection. According to the Dutch Delta Programme (DeltaProgramme 2013), the Netherlands should prepare for a design discharge of the Rhine River of 18,000 $\mathrm{m}^3\,\mathrm{s}^{-1}$ in the coming 50–100 years. However, the maximum discharge of the IJssel River also depends on how the Rhine discharge is distributed over the Rhine branches. In Mens and Klijn (2014) the percentage of the discharge that diverts from the Rhine River to the IJssel River was varied between 15% and 18%. Assuming a maximum fraction of 18%, the worst-case discharge for the IJssel yields 3250 $\mathrm{m}^3\,\mathrm{s}^{-1}$. This was rounded off to 3300 $\mathrm{m}^3\,\mathrm{s}^{-1}$.

Following Asselman *et al.* (in prep.), the reference system is as close as possible to the projected situation of 2015, when projects currently being implemented will be finalized. It is assumed that at that time each dike-ring area will meet the required flood probability.

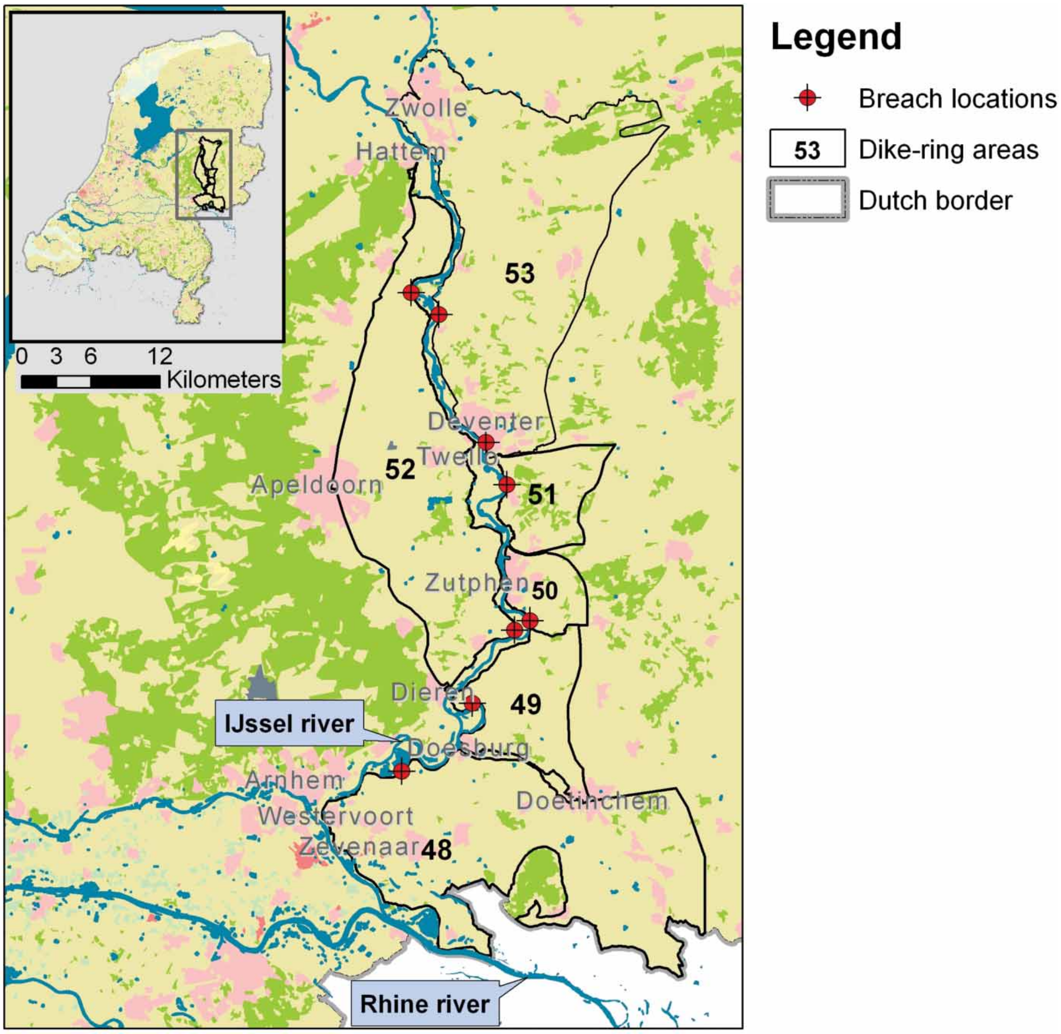

Figure 2 IJssel River valley with dike-ring areas and breach locations indicated (Mens and Klijn 2014).

We compared the following alternative configurations with the reference system, where a configuration is the combination of river geometry, embankment location and strength and land use:

- IJssel_CE, Conventional Embankments: embankments are raised by Δh (location-dependent) that corresponds to a change in discharge from $T = 1250$ years to $T = 5000$ years;
- IJssel_RR, Room for the River: the floodplains are lowered such that the water level at the current design discharge is reached at a higher discharge. The ΔQ is about 260 $m^3 s^{-1}$, which corresponds to the change in discharge in CE;
- IJssel_UE1, 'Unbreachable' Embankments, version 1: all embankments are strengthened (not raised) such that they become practically 'unbreachable'. Water may, hence, flow over the flood defence and still cause flood damage;
- IJssel_UE2, 'Unbreachable' Embankments, version 2: like UE1, but embankments near cities are raised by 0.5 m.

To implement CE (conventional embankments) into the model, the fragility curves were adjusted, whereas for RR ('room for the river') the stage–discharge relationship was adjusted. For UE ('unbreachable' embankments), the fragility curves for mechanisms other than overflow were removed, so flooding would only initiate when the design water level is exceeded (without breaching). In UE2 the fragility curves near large cities were adjusted such that they represent 0.5 m higher embankments.

3.2 *Meuse case*

The Meuse River has a larger capacity than the IJssel River with a design discharge of 3800 $m^3 s^{-1}$ ($T = 1250$ years). The part of the Meuse River valley that we focus on also consists of six dike-ring areas (Figure 3). In contrast to the IJssel River valley, not all dike-ring areas are valley shaped. The ones north of the river are entirely surrounded by embankments, whereas the other ones have higher grounds in the south. In the western (downstream) part of the river, water levels are also influenced by the sea level and storm surges. The embankments in this part are designed to withstand water levels that are exceeded on average once in 2000 years. This water level may be caused by different combinations of sea water level and river discharge. However, for the purpose of this paper we assume that the

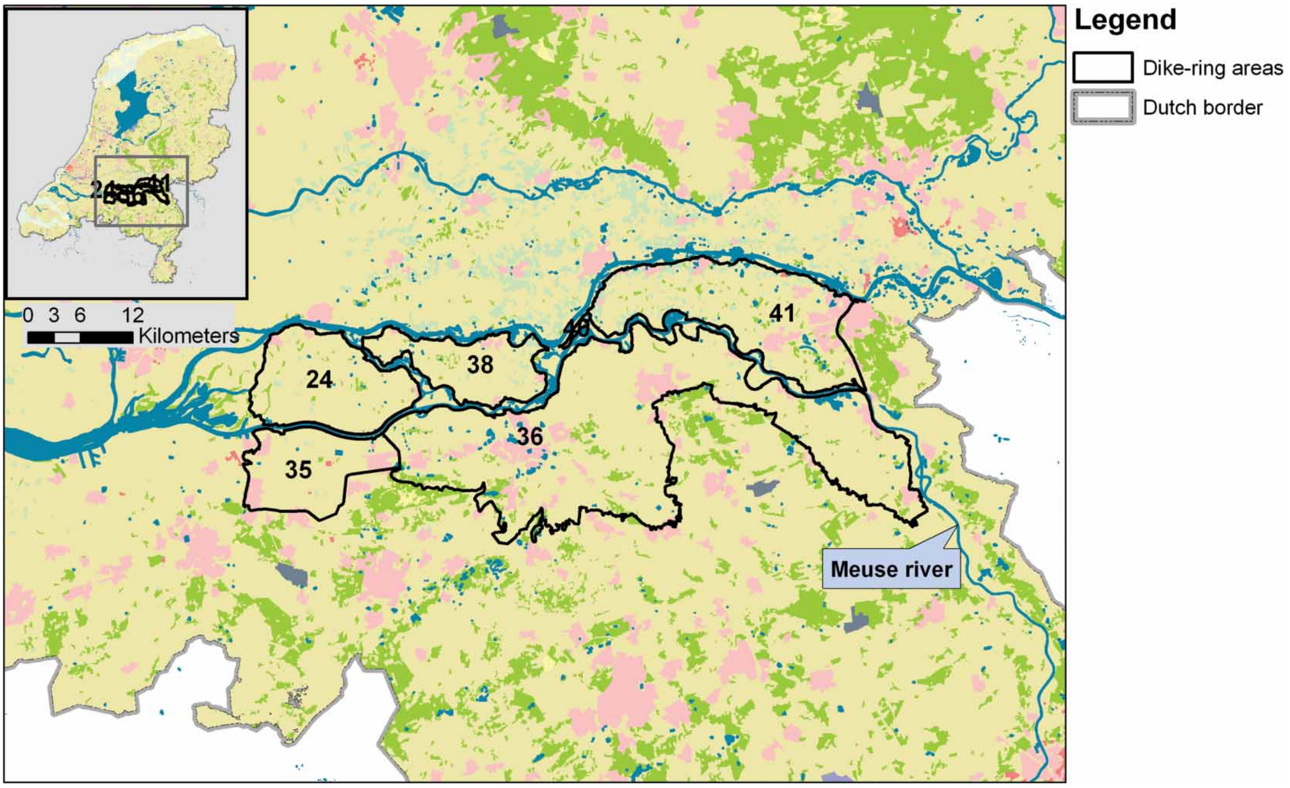

Figure 3 Meuse River valley with dike-ring areas indicated.

design water levels for the western part also correspond to a discharge of 3800 $m^3 s^{-1}$.

The data for this case were obtained from a recent policy study (Asselman *et al.* in prep.), where flood risks were calculated for different system configurations. Flood simulations and corresponding damage were available for all dike-ring areas and for different river discharges.

We analysed the system robustness for discharges up to 4600 $m^3 s^{-1}$, because the design discharge is expected to increase to 4600 $m^3 s^{-1}$ according to the most extreme climate change scenario for the year 2100 (Asselman *et al.* in prep.). Higher discharges are deemed physically impossible, due to extensive flooding further upstream where protection standards are lower.

In the reference configuration, floods may occur at a lower discharge than the design discharge, because embankments are currently not designed to resist the failure mechanism *piping*. We assumed that piping may start to occur at a discharge of about 3300 $m^3 s^{-1}$, which has a return period of 250 years. This corresponds to 0.5– 0.6 m lower water levels depending on the location.

We compared the following alternative configurations for the Meuse River valley:

- Meuse_CE, Conventional embankments: embankments are raised to withstand a discharge of 4200 $m^3 s^{-1}$. However, embankments may still fail due to piping, thus floods may occur at a lower discharge of 3700 $m^3 s^{-1}$;
- Meuse_RR, Room for the river: measures are taken to adapt the stage–discharge relationships. The design water levels will thus be lowered, but not at all locations. For areas where this measure has no effect, floods may still occur at a discharge of 3300 $m^3 s^{-1}$ (as in the reference) but the total flood damage will be much smaller;
- Meuse_CE/RR, A combination of raising embankments and giving room to the river. Floods may occur at a discharge of 3700 $m^3 s^{-1}$. Due to the water-level lowering at some

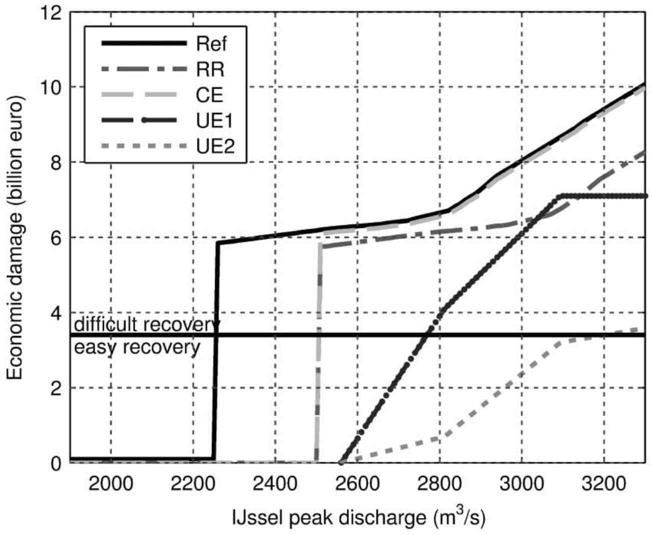

Figure 4 Response curves of the IJssel system configurations (Mens and Klijn 2014).

Table 1 Overview of system robustness scores of the IJssel River valley (Mens and Klijn 2014)

		IJssel_REF	IJssel_CE	IJssel_RR	IJssel_UE1	IJssel_UE2
System robustness criterion	Indicator	Reference	Conventional embankments	Making room for the river	'Unbreachable' embankments	'Unbreachable' embankments differentiated in height
Resistance threshold	a	0.7	0.8	0.8	0.8	0.8
Proportionality	b	0.4	0.4	0.4	1	1
Manageability	c	0.5	0.5	0.5	0.7	1

Note: Grey tones indicate an increase compared to the reference.

[a] Discharge where conditional flood probability >0.1, relative to maximum discharge (3300 m^3 s^{-1} = 1).

[b] Largest change in damage for discharge increase of 1 m^3 s^{-1}, relative to maximum damage.

[c] Recovery zone (no recovery = 0, difficult recovery = 0.5, easy recovery = 1).

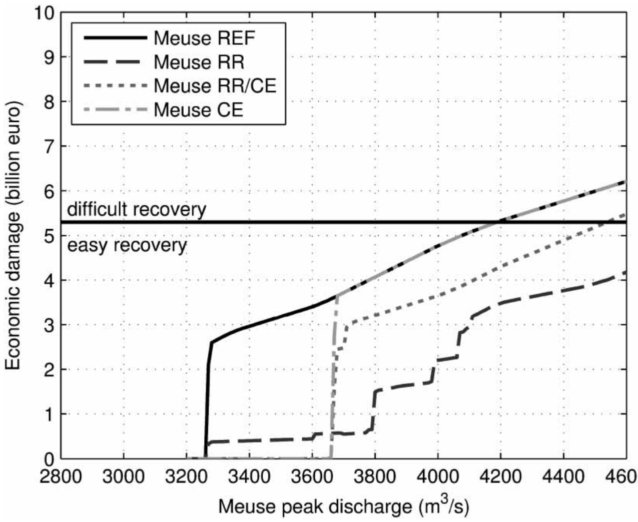

Figure 5 Response curves of the Meuse system configurations.

locations, the damage at higher discharges will be smaller than in the reference.

4 Results

4.1 *IJssel River valley*

The response curve and the robustness scores of the IJssel case are given in Figure 4 and Table 1. The two recovery thresholds are taken from Mens and Klijn (2014): 3.4 × 10^9 euro (= 5% of GDP of the provinces of Gelderland and Overijssel in the year 2000) and 21 × 10^9 euro (5% of the Netherlands GDP in the year 2000). The second threshold is not visible in Figure 4, which means that it is unlikely that flooding in the IJssel River valley will result in an unmanageable situation without recovery. The resistance threshold is increased in all configurations, whereas the proportionality and the manageability are only enhanced in the configurations with 'unbreachable' embankments.

4.2 *Meuse River valley*

The response curve and the robustness scores of the Meuse case are given in Figure 5 and Table 2. The two recovery thresholds are 5.3 × 10^9 euro (=5% of GDP of the provinces of Noord-Brabant and Gelderland in the year 2000; www.statline.cbs.nl, accessed 3 May 2013) and 21 × 10^9 euro (5% of the Netherlands GDP in the year 2000). Here, the second threshold is also too high to be shown in the figure. The resistance threshold is only higher in the configurations where embankments are raised. In contrast to IJssel_RR, the resistance threshold of Meuse_RR is similar to the reference situation. The proportionality is enhanced in all configurations except Meuse_CE (raising embankments). The manageability is enhanced in Meuse_RR and Meuse_ RR/CE.

Table 2 Overview of system robustness scores of the Meuse River valley

		Meuse_REF	Meuse_CE	Meuse_RR	Meuse_RR/CE
System robustness criterion	Indicator	Reference	Conventional embankment raising	Making room for the river	Making room for the river and raising embankments
Resistance threshold	a	0.7	0.8	0.7	0.8
Proportionality	b	0.7	0.6	0.9	0.8
Manageability	c	0.8	0.8	1.0	0.9

Note: Grey tones indicate for each criterion a decrease (dark grey) and an increase (light grey) compared to the reference.

[a] Discharge where critical water level is exceeded, relative to maximum discharge (4600 m^3 s^{-1} = 1).

[b] Largest change in damage for discharge increase of 1 m^3 s^{-1}, relative to maximum damage.

[c] Recovery zone (no recovery = 0, difficult recovery = 0.5, easy recovery = 1).

5 Discussion

5.1 *What enhances system robustness?*

From the two example river valleys, we learned that two types of measures have a strong effect on system robustness: the 'unbreachable' embankments in the IJssel case and making room for the river in the Meuse case. In both cases, the resistance threshold was not adapted, but instead the damage was reduced. More importantly, in these alternative system configurations, the damage increases more proportionally with a discharge increase. However, making room for the river in the IJssel case (IJssel_RR) has a minor effect on proportionality. This can be explained as follows.

The IJssel case was a theoretic study in which we could lower the water levels in the model homogeneously along the entire river (IJssel_RR). This resulted in a new protection level that was equal for each dike-ring area. The Meuse case is more realistic in the sense that sets of measures were chosen by stakeholders. As a consequence, the water-level lowering in Meuse_RR varied for the dike-ring areas and therefore some embankments are relatively higher than others. This means that when the system's resistance threshold is exceeded, not all dike-ring areas will be flooded simultaneously. This resulted in a differentiation in protection levels for the Meuse. It is this differentiation that has a strong effect on proportionality. We found a similar effect with IJssel_UE2, where 'unbreachable' embankment heights were differentiated and proportionality scores well.

Also without differentiation, 'unbreachable' embankments have a strong effect on proportionality and robustness. This is because less water is flowing into the dike-ring area, since the embankments will only overflow and not breach. This automatically causes a more proportional increase in the damage with increasing discharge. Furthermore it reduces the flood extent and flood depths, which has a positive effect on manageability, since the damage stays further away from the recovery threshold. Making room for the river, even if protection levels are not differentiated (IJssel_RR), does reduce flood extent and flood depths and therefore has a positive effect on robustness. However, in the IJssel case this effect was minor, partly because the chosen water-level reduction was only 10–20 cm.

Robustness is less positively influenced by conventional embankment raising, which is supported by both cases (Meuse_CE and IJssel_CE): the resistance threshold is higher, but the proportionality is lower than the reference. This means that it seems to be safer, because higher discharges are needed to cause flooding, but once the embankments fail the damage approaches the recovery threshold immediately. In the IJssel case the damage exceeds the recovery threshold, whereas in the Meuse case the damage stays below this threshold. In the Meuse, not only the flood damage is smaller, but also the recovery threshold is higher. Apparently, this region is economically better able to recover.

5.2 *How realistic are 'unbreachable' embankments?*

We assume that 'unbreachable' embankments will never fail. In practice, it may be difficult or at least expensive to construct an embankment of which the probability of structural failure and thus breaching can be neglected. We use 'neglected' because a zero failure probability is geotechnically impossible. Currently, design criteria for conventional embankments in the Netherlands require the failure probability due to 'other' failure mechanisms than overtopping (such as piping) to be less than 10% of the design standard (Rijkswaterstaat 2007). 'Unbreachable' embankments can be defined as embankments for which these design criteria are a factor 10 stricter, thus less than 1% of the design standard (see also De Bruijn *et al*. 2012). This means, for dike-ring areas with a design standard of 1/1250 per year, that the probability of embankment failure due to 'other failure mechanisms' is smaller than 1/125,000 per year. Additionally, 'unbreachable' embankments could be designed such that the probability of breaching due to overtopping is also less than 1% of the design standard. If this is implemented, we feel that the probability of failure (in the sense of breaching) may be neglected. However, further research is needed to explore the technical feasibility and costs of changing a conventional embankment into an unbreachable one.

6 Conclusion

A risk approach is key to modern flood risk management, but for deciding about the most desirable system configuration in view of uncertain discharges, a robustness perspective may be of additional value. We analysed the flood consequences of the IJssel River valley and Meuse River valley in terms of economic damage for four alternative system configurations. Based on the results, we conclude that the following types of measures increase robustness in river valleys:

- Differentiation in protection standards;
- Limit flood extent and flood water depths. This can be achieved by ensuring a limited difference between design water levels and the elevation of the protected area, for example, by building 'unbreachable' embankments or giving room to the river.

Of all studied alternative configurations of the IJssel River valley, the one with 'unbreachable' embankments (version 2) increases the system's robustness most. This alternative combines both types of measures as described earlier in the paper. However, there are practical limitations to construct 'unbreachable' embankments, such as costs and available space.

Of all studied configurations of the Meuse River valley, the one that gives more room for the river at specific locations increases the system's robustness most. Similar to the most robust IJssel configuration, this is mainly caused by differentiating the protection standards and thereby significantly increasing the proportionality of the flood damage.

We feel that these conclusions apply to all embanked river valleys with a natural relief, and with hydraulic system behaviour. Hydraulic system behaviour ensures that when water flows over the embankments at one location, water levels elsewhere will be lowered. Measures that reduce the water level (like giving room to the river) will be extra effective in areas where the stage–discharge relation is steep, thus where an increase in discharge causes a large increase in water level. This is regularly the case near large cities. Although space may be limited to relocate the embankments, a bypass or widening the floodplain across the river may be effective. ‘Unbreachable’ embankments will have a limited effect on system robustness in small polder areas that will fill up very quickly, causing large water depths and thus casualties and damage.

We conclude that a system robustness perspective makes explicit what happens if protection standards are exceeded. It thus helps in developing strategies that reduce the flood risks without increasing the vulnerability to beyond-design floods.

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