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INFLUENCE OF LOAD INTERDEPENDENCIES OF FLOOD DEFENCES ON PROBABILITIES AND RISKS AT THE BOVENRIJN/IJSSEL AREA, THE NETHERLANDS

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ABSTRACT: In the Netherlands, flood risk analysis is usually carried out for a location, without considering potential flood defence failures in upstream areas. This may result in significant over- or underestimation of flood risks. The effect of upstream failures on failure probabilities and flood risks in other areas is called load interdependence of flood defences. This effect can be both positive and negative: loads on a certain defence can increase and decrease due to failures upstream. In this research a framework was developed which enables the consideration of these interdependencies in a probabilistic framework. This was done by using Monte Carlo with Importance Sampling and a fast inundation model, which enables considering many scenarios with many different breaches. The case considered was the Bovenrijn/IJssel area in the Netherlands, a lowland river area where dike breaches can have both positive and negative effects on the loads on other flood defence elements. The risk estimates and changes in water level probabilities in the considered area show a clear interrelation between loads on different elements of the flood defence system and demonstrate that the effects of dike breaches on loads and risks on other locations cannot be ignored in flood risk analysis.

Key Words: Flood Risk Analysis, dike safety, load interdependencies, system behavior, dike breaches

1. INTRODUCTION

66% of the Netherlands is located below sea level. A large part of the flood-prone area is protected by flood defences, which divide the area into dike rings: areas surrounded by flood defences and higher grounds. Along the rivers there are many of these dike rings. Flood risk analyses in the Netherlands are generally carried out per dike ring area. The VNK2-project is an example of this (Jongejan *et al.*, 2011). In an approach using dike rings, it is very difficult to account for all relations and interdependencies between the loads on different dike rings during a flood event. Not accounting for these effects can cause serious over- or underestimation of the total risk(Courage et al., 2013). The effect of these so-called load interdependencies is, however, generally not taken into account in flood risk analysis (Apel et al., 2009; van Mierlo et al., 2008).

This paper proposes a method for assessing these interdependencies in a flood risk analysis for a (part of a) river basin with multiple river branches. It explains the nature of load interdependencies and discusses the developed method. A case in the Netherlands was analyzed using this method, which uses Monte Carlo techniques and a fast quasi-2D inundation model to do to a risk assessment for the considered area. The purpose of the development of this method was to better understand how to model these interdependencies and quantify their effect on water levels and flood damage. The main focus is on the modeling of negative effects: increase of loads and risks due to upstream breaches.

2. LOAD INTERDEPENDENCIES OF FLOOD DEFENCES

Load interdependencies of flood defences comprise the relation between loads on different (sections of) flood defences in a water system, or the effect that failure of one flood defence has on loads on other dikes at other locations in the system. These effects can be both positive and negative, depending on the system considered. In previous literature this effect has also been called river system behavior (Van Mierlo *et al.*, 2007), but as the term ‘load interdependence’ gives a better description of the physical process this term is used in this research.

Positive load interdependencies are universal, and also quite easy to understand. When a dike breaches, water flows out of the river, resulting in a decrease of the discharge, resulting in lower water levels downstream. Hence failure of an upstream flood defence reduces the loads and therefore the failure probabilities of dikes downstream. This effect is comparable to the principle of detention areas (Van Mierlo *et al.*, 2003; Vorogushyn *et al.*, 2012), which provide load relief by reducing the peak discharge flow. In the 2011 Mississippi floods, the use of extra emergency floodways reduced local and upstream water levels by approximately 0,5 to 0,8 meter, and prevented flooding (Olson and Morton, 2012). This is an example of a case where the physical processes behind load interdependencies were used to lower loads on flood defences. Although in cases with detention areas the outflow is controlled, it was shown for the Rhine in Germany that, for the part between Cologne and Rees, dike breaches can reduce the 1/5.000 year discharge at Rees from 17.500 m^3/s to 15.000 m^3/s (Apel *et al.*, 2009). However, the magnitude of the relieving effect depends significantly on for instance the size of the flooded polders, the time of breaching during a discharge wave (e.g. before/at/after the peak) as well as the shape of the discharge wave (van der Wiel, 2004). A study on the Bac Hung Hai polder, Vietnam showed that, due to load interdependencies dike reinforcements can increase risk if areas with little potential damage and a large relieving effect on other areas are strengthened (Diermanse *et al.*, 2007). This emphasizes the relevance of load interdependencies when considering for instance safety standards and prioritization of dike reinforcement. Also in terms of total damage or casualties in a flood event load interdependencies can have a significant influence. It was shown for the riverine area in the Netherlands that load interdependencies can reduce the societal risk in case of a flood event by approximately a factor 2 (de Bruijn *et al.*, 2014).

Negative load interdependencies are less common and only a few locations have been identified where these effects can occur. Negative effects occur in cases where, due to the geometry of the system water can flow from one river, over land, into another river with a lower water level. In the Netherlands, in extreme situations the design water level in the Waal river is approximately 2 to 3 meters higher than in the Meuse (Courage *et al.*, 2013). A breach in the Waal dike can cause water to flow from the Waal river into the Meuse river by breaching or overtopping of the Meuse dike from the polder side. Considering the fact that peak discharges for Maas and Waal are correlated there is a realistic chance that this will lead to more extreme water levels at the Meuse. Vrouwenvelder *et al.* (2010) showed that water levels corresponding with a 1/1.250 year discharge in the Meuse may increase by almost a meter. A similar situation can occur at the Bovenrijn/IJssel area in the Netherlands, where water can ‘shortcut’ over land, thus changing the discharge distribution at the main river branches in the Netherlands, as shown in Figure 1. This area is used for the case study in this paper. Negative load interdependencies are seldom taken into account in flood risk analysis. In many cases they are indeed insignificant. However, in some cases such as the example of the Land van Maas en Waal and the Bovenrijn/IJssel area ignoring these effects can lead to a serious error in risk and flood probability estimates.

Another example of load interdependencies considered in the Netherlands is the cascade effect, where water flows from one dike ring into another. This was for instance considered by ter Horst (2012). However strictly speaking this is not a case of load interdependencies, as dike rings are administrative entities. However, as in the Bovenrijn/IJssel area there are several dike rings also the cascade effect is considered. Therefore in this study three types of effects of load interdependencies are considered:

- Load relief of downstream dikes
- Shortcutting to other rivers/river branches
- Cascade effects between different dike rings

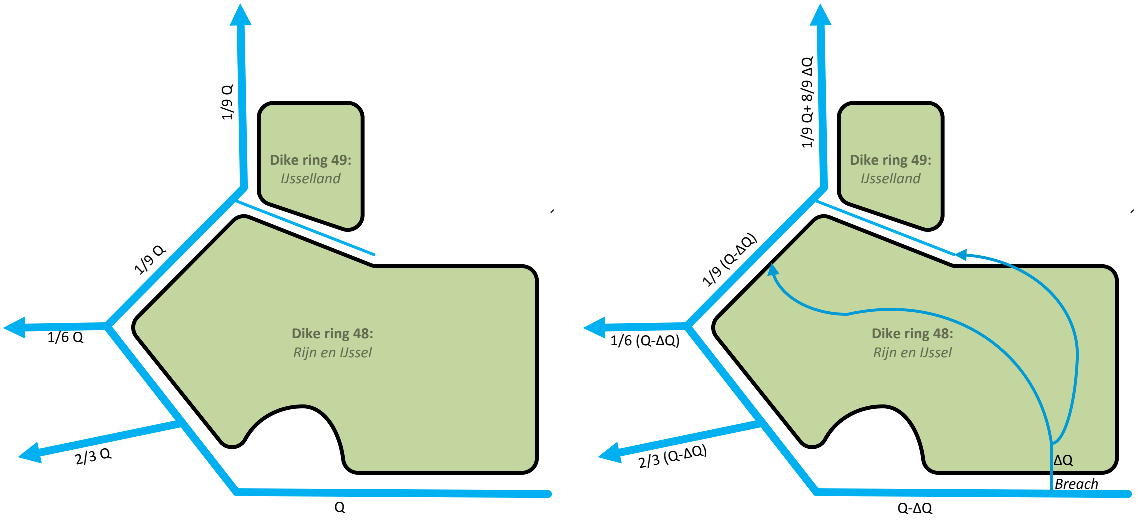

Figure 1: Change in discharge distribution due to shortcutting at the Bovenrijn/IJssel area, the Netherlands. Left is the given situation, right is the situation including shortcutting (time effects are ignored)

For the modelling of the first aspect several options have been suggested in literature (Apel *et al.*, 2009; de Bruijn *et al.*, 2014), however modelling shortcutting and cascade effects is more difficult, as was shown by Courage *et al.*, (2013). When considering negative load interdependencies the flooding has to be modelled properly, as well as the interaction between flooded land and rivers and vice versa. A very case specific aspect for instance is that dikes can also fail from inner side, due to high flood levels. In those cases the geotechnical behavior of dikes is different.

3. COMPUTATIONAL FRAMEWORK AND ITS APPLICATION IN THE CASE STUDY

3.1 General framework

Based on the demands defined in the preceding paragraphs and the available models and data for the Bovenrijn/IJssel area, a computational framework was defined (Figure 2). This framework is for some parts very similar to the framework used by De Bruijn *et al.* (2013) for the assessment of societal risks in the Netherlands. However, it has been adapted to be able to assess negative load interdependencies and it is now applied to economic risk instead of casualty risk.

3.2 Description of the case study area and its characteristics

The case study area considered is the Bovenrijn/IJssel area, which comprises the Rhine from Wesel in Germany to the IJssel near Zwolle, the Netherlands. This area was chosen as it was identified by Van Mierlo (2005) as one of the main areas in the Netherlands where negative load interdependencies can have a significant influence on flood risks. The area considered contains 6 dike rings with 21 representative breach locations along the river. An overview of the area is given in Figure 3. The elevation difference between the upstream and downstream polders is approximately 15 meters, most of the dike rings neighbor elevated areas which cannot flood. The discharge distribution of the different river branches is shown in Figure 1.

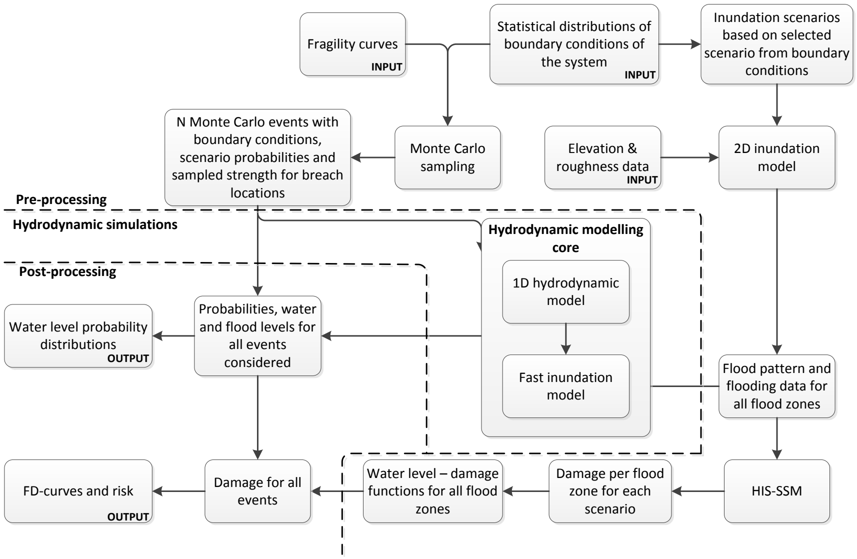

Figure 2 Overview of the computational framework

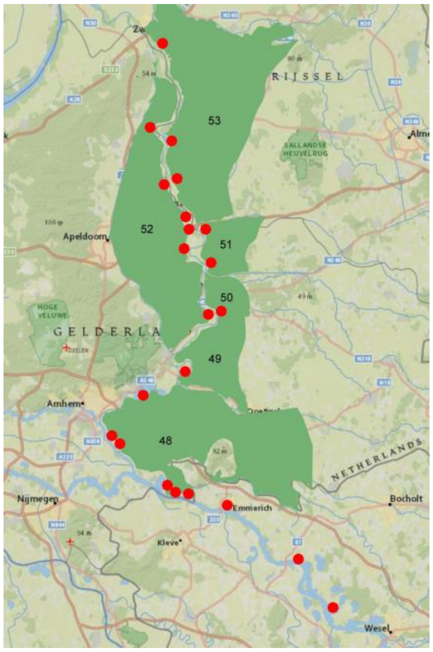

Figure 3 Case study area with breach locations (in red) and relevant dike rings

3.3 Sampling of boundary conditions and dike strength

The first part of the framework consists of the modelling of the different stochasts, specifically the river discharge and dike strength. Diermanse *et al.* (2014) showed that Monte Carlo with Importance Sampling is a reliable method for this type of problems. As the boundary condition for river discharge and the dike breach locations considered are the same as in Diermanse *et al.* (2014), the same sampling strategy and fragility curves can be used. In order to obtain a stable Monte Carlo calculation 1.000 samples were needed. For the modelling of breaches from the polder side the fragility curves were slightly adapted, based on expert judgment. For these cases the relative contribution of macrostability failures was increased, while piping failures were ignored.

3.4 Choice of hydrodynamic model

In addition to the tool developed by De Bruijn *et al.* (2013), this framework has been developed to deal with negative load interdependencies. Hence, a different model or modelling technique has to be used, as overland flow needs to be modeled as well. 2D modelling techniques are a very suitable tool to do so. These were also applied by Vrouwenvelder *et al.* (2010) for the case of the Waal and Meuse, however in this case only one breach was considered per run, and the aim is to consider multiple breaches per scenario. Therefore a very large number of time consuming 2D simulations would be needed. Faster solutions of the same type are 2D storage cell models and 3Di modelling (Bates *et al.*, 2000; Stelling, 2012), however as there are no calibrated 2D storage cell models available for the case study area and 3Di is still being developed these techniques were not suitable for the case study. In this case the choice was made to use a quasi 2D model which was calibrated using 2D scenarios as shown in Figure 4.

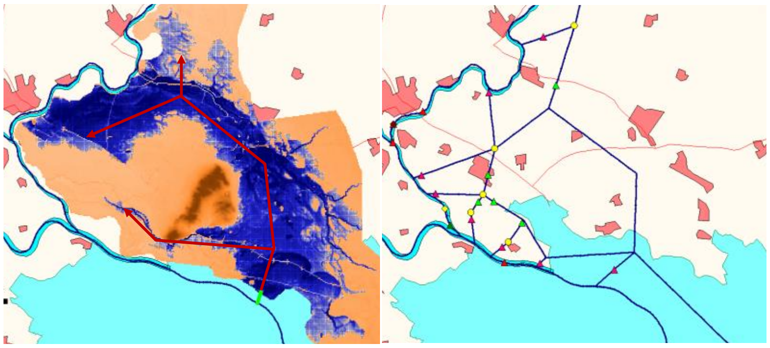

Figure 4 Visualisation of construction of the quasi-2D model

For the 2D scenarios a 1D2D schematization is used, in which the river is modelled in 1D. The breach growth is simulated using the Verheij vd Knaap formula for breach growth in sand dikes (Verheij, 2002), where the breach width grows to a width of 200 meters. For the rivers a 1D Sobek 2.12 model for the Netherlands has been combined with a 1D model for the German part of the Rhine, which was obtained from the Bundesanstalt fur Gewasserkunde. The 2D model used is a Delft-FLS schematization which was also used for calculating VNK2 flood scenarios in this area. For the quasi-2D schematization 4 different methods of modelling are used. Areas with a more or less constant water level are modeled as storage reservoirs, while sloping areas are modeled as very wide river branches. To connect these parts rectangular dummy cross sections are used with a very low friction coefficient. Secondary flood defences and flood defences separating dike rings are modeled as weirs and assumed unbreachable and at a height based on elevation maps. Calibration is done using 2D scenarios, which results in deviations in water levels of less than 0.5 meters and deviations in breach discharges of less than 10% compared to 2D calculations.

3.5 Calculating economic damage

In the Netherlands, it is common practice to calculate damage using the HIS-SSM model (Kok *et al.*, 2005), using damage functions, land use and flood data. However, in this study, due to the use of the 1D model, no detailed flood depth map is available. Therefore the area is split up into flood zones based on the different types of areas in the fast inundation model. For 13 different 2D scenarios, the economic damage for the different flood zones is derived using HIS-SSM. This results in water level – damage curves for the different areas, which provide a good fit to the 2D data. After correcting the curves for small structural errors the difference between the derived curves and HIS-SSM is only 6%.

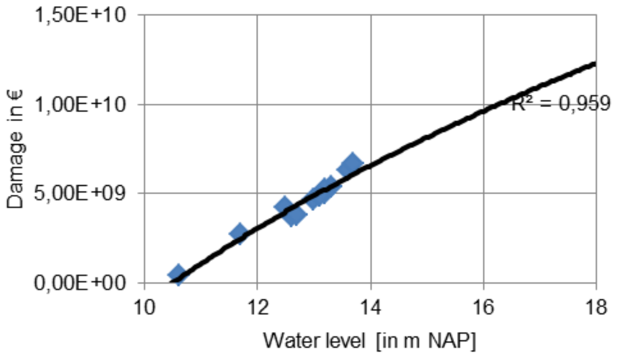

Figure 5 Water level - damage curve for a part of dike ring 48

4. CASE STUDY RESULTS

4.1 Considered scenarios

In order to investigate the effects of load interdependencies for the case study area 5 different scenarios(Table 1) are considered with the following 4 options:

- Breaches from a river: determines whether breaches can occur at all
- Shortcutting possible: determines whether water can flow back into the river. In these cases the discharge coefficient for flow from polder to river was set to be 0. If breaches are considered but shortcutting is not, only positive load interdependencies can be observed in the results for water levels.
- Breaches from polder: determines whether dikes can fail from the polder side of the dike. If not possible no triggers for polder water levels were defined for the different dike breaches.
- Cascade possible: determines whether water can flow from one dike ring to another. If not possible the separating dikes between dike ring areas were set to a height of 99 meters.

Scenario:	***Breaches from river***	***Shortcutting possible?***	***Breaches from polder***	***Cascade possible***
With breaches	*Yes*	*Yes*	*Yes*	*Yes*
No polder breaches	*Yes*	*Yes*	*No*	*Yes*
No shortcutting	*Yes*	*No*	*No*	*Yes*
No cascade	*Yes*	*Yes*	*Yes*	*No*
No breaches	*No*	*No*	*No*	*No*

Table 1 Overview of the considered scenarios

4.2 Effects on water levels

For the case without shortcutting it can be expected that water levels lower when going further downstream compared to the situation without breaches, while for the case with shortcutting water levels could increase at the IJssel for the same Rhine discharge. Figure 6 shows the resulting water levels for 4 locations in the case study area: Spijk, at the upstream part of the Rhine, Giesbeek at the most upstream breach location along the IJssel, Deventer, located halfway the IJssel, and IJsselcentrale, the most downstream point. It can indeed be observed that for the case without shortcutting, so when only considering positive load interdependencies, water levels are increasingly reduced for locations further downstream. When also considering shortcutting effects, water levels can be higher than expected at certain locations in the IJssel, especially next to the lowest parts of dike rings 48 and 53 (Giesbeek and

IJsselcentrale). However, at the most downstream location IJsselcentrale the negative effects on water levels never outweigh the positive effects, only for Giesbeek the negative effects cause higher water levels than the case without breaches.

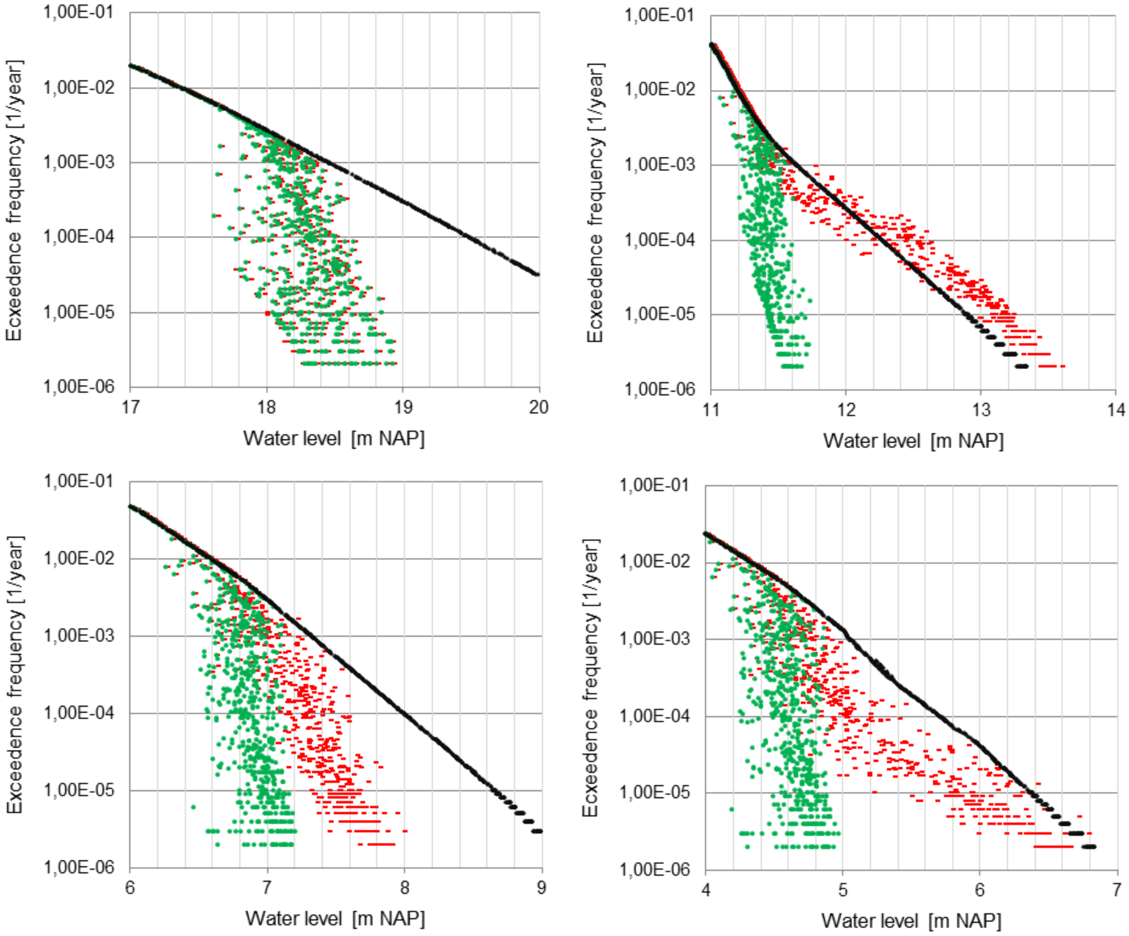

Figure 6 Water levels for different cases for 4 locations. Green: only positive load interdependencies Red: negative and positive load interdependencies Black: without considering breaches. (a) Spijk (b) Giesbeek (c) Deventer (d) IJsselcentrale

4.3 Effects on economic risk

The effects on the economic risk are visualized using FD-curves (i.e. frequency-damage curves), which show the relation between damage and exceedence frequency. The area below the curve is equal to the total risk for the considered area. Figure 7 shows the FD-curves for the considered area as well as some of the subareas. From the figures it can be seen that for the total area, when considering breaches, shortcutting lowers the total damage: when shortcutting is not considered the total damage is higher. Thus shortcutting mitigates flood damage at the right bank of the IJssel. This is an attribute of the case study area: the potential damage on the left bank is very small compared to the damage on the right bank. Therefore the same holds for the case without breaches from the polder side: although water can flow out through existing breaches, polder breaches are found to mitigate the total damage. When considering the left bank it can be seen that not accounting for shortcutting effects has an enormous effect on the damage in this area. Thus the risk in dike ring 52 (the left bank of the IJssel) is for a large part determined by scenarios where water shortcuts from breaches along the Bovenrijn towards the IJssel river, thus altering the discharge distribution. For the studied area the cascade effect seem to have almost no effect on the total risk. However for specific locations it does have a large influence, as can be seen from the curve for dike ring 51, where the risk for the case without cascade effects is much lower than in the other cases. Therefore it seems as if the cascade effect redistributes the risk over the area. This is confirmed by Table 2 which shows the total risk as well as the risk without cascade effects for the different subareas. It can be seen that cascade effects redistribute the risk over the different dike rings in the case study area. For instance, for dike ring 51 the risk when considering cascade effects is approximately 6 times higher than when not considering them, while the risk for the total area is the same.

Area	Economic risk [10^6 €/year]	Economic risk without cascade [10^6 €/year]	Difference in risk caused by cascade effect [10^6 €/year]	Procentual difference when considering cascade effects
Total area	27,4	27,3	+0,1	+0,4%
Right bank	26,4	26,4	-	-
Dike ring 48	10,8	13,1	-2,3	-17,6%
Dike ring 49	1,4	1,0	+0,4	+40%
Dike ring 50	3,5	2,4	+1,1	+45,8%
Dike ring 51	0,3	0,046	+0,25	+543%
Dike ring 52	0,98	0,88	+0,1	+11.4%
Dike ring 53	10,4	9,8	+0,6	+6.12%

Table 2 Economic risk for the different dike rings with and without cascade effects

4.4 Effects on the number of breaches

Due to load interdependencies, the number of breaches for each location will differ per scenario. The results for the number of breaches for the different scenarios for a set of breach locations are shown in Table 3. From this table it can be seen that especially at IJsselcentrale and Giesbeek there are many breaches triggered by high polder water levels, which is due to the fact that these locations are at the lowest parts of dike rings 53 and 48. For the case without shortcutting it can be seen that at Gemaal Terwolde (dike ring 52) there are very little breaches, which is in line with the very low damage found for that dike ring for that case. It can also be seen that for the most upstream location, Germany_2, the number of breaches is the same for all cases: no relief is considered there.

Breach location	***With breaches***		***No polder breaches***		***No shortcutting***		***No breaches***	
	River	*Polder*	*River*	*Polder*	*River*	*Polder*	*River*	*Polder*
IJsselcentrale	112	222	228	0	39	0	86	137
Olst	113	55	162	0	16	0	45	6
Gemaal Terwolde	306	0	275	0	15	0	209	0
Deventer	219	4	203	0	15	0	112	0
Giesbeek	158	326	325	0	121	0	156	337
Loo	132	82	168	0	57	0	164	151
Spijk	83	71	95	0	91	0	86	74
Germany_2	352	0	352	0	352	0	352	0

Table 3 Number of breaches for different cases

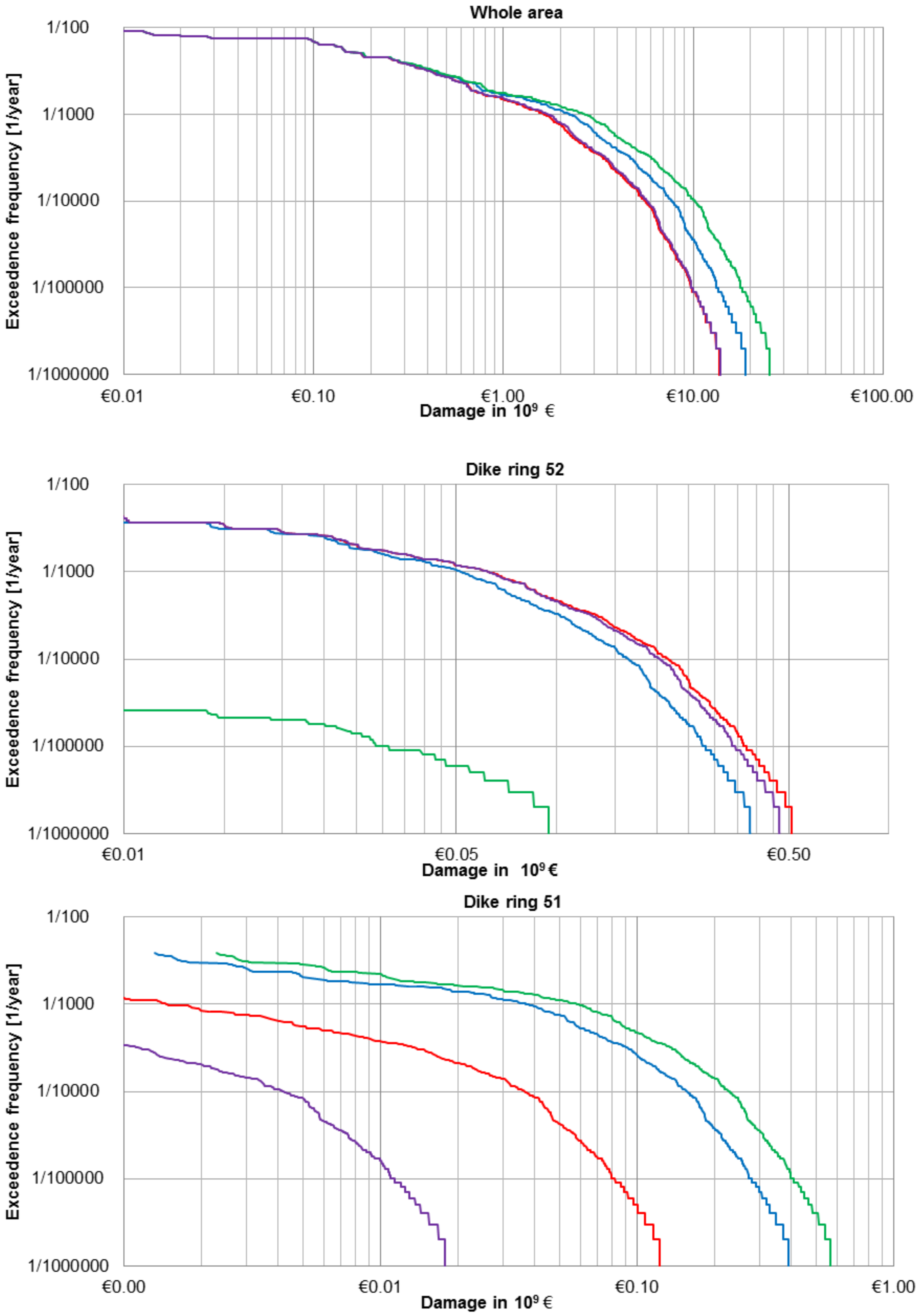

Figure 7 Results for economic damage for cases with breaches (red), without polder breaches (blue), no shortcutting (green) and no cascade effect (purple).

5. DISCUSSION

From the results for the case study area it appears that there is a large interdependence between loads on different locations in the considered river branches. From the resulting water levels it appears that at certain locations the increase in water level due to breach outflow could outweigh the positive effect caused by upstream breaches. However in most cases this is not the case. The number of polder breaches at certain locations shows a clear relation with this effect: for locations with a large amount of polder side failures the negative effects on water levels are larger than for other locations, although in general positive effects on water levels dominate. In the considered situation failure mechanisms were considered only water level dependent, thus the reduction of number of failures due to lower water levels is very sensible. In reality however, piping failures are very time-dependent (Vorogushyn *et al.*, 2009), therefore for a single case the discharge at the lower boundary of de IJssel is investigated to get a grip on the effect of breaches on the durations of the loads. Figure 8 shows the discharge waves for the cases with breaches and without breaches, and it can indeed be observed that, while the peak discharge is lower the duration of the high water is increased considerably. This emphasizes the importance of taking into account load durations when considering effects of dike breaches on risks in future studies. Another aspect is that due to the uncertainty in dike strength stemming from the standard deviation in the fragility curve, the water levels also become uncertain for a given discharge: in the water level graphs a variation in water levels at a certain discharge can be observed, as is shown in Figure 9. It can also be observed that when only considering positive load interdependencies, more downstream locations seem to have an asymptotically bounded water level determined by the dike strengths and number of potential breaches upstream, this was also shown by De Bruijn *et al.* (2013).

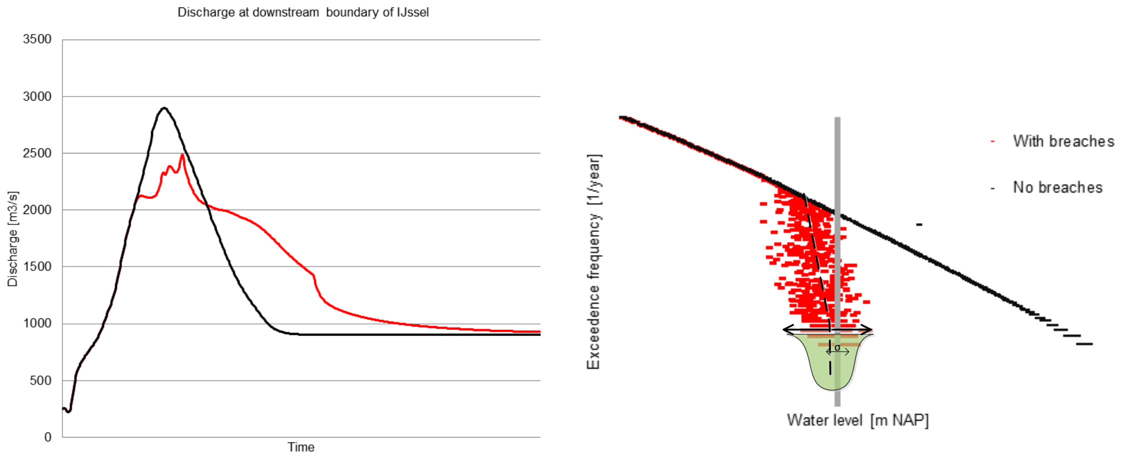

Figure 8 & 9: Effects of breaches on shape of discharge wave and water levels

In terms of economic risk load interdependencies do not have a significant influence on the total risk in the considered area. However, this is a case specific result, for other cases this could be completely different. What can be observed is that for different cases the risk is redistributed over the area. The fact that for certain dike rings (not) accounting for the cascade effect can cause a risk which is 6 times higher and caused by a different type of flooding (over land instead of from the river) shows that accounting for cascade effects can be very important when reinforcing dikes and especially when prioritizing dike reinforcement projects. As Diermanse *et al.* (2007) already showed for a case in Vietnam, the interdependence between different dike reaches can completely alter the prioritization strategy to be used. Accounting for load interdependencies in dike design is more difficult: when considering positive interdependence this implies that all dike reaches in a system are dependent on the safety level of the other dike reaches, meaning that all safety levels are dependent. Practically this means that a dike reinforcement project upstream would lower safety levels at all downstream dikes. Theoretically this could result in an optimized flood protection system, however, politically this is infeasible, as upstream dike rings are then considered as emergency storage areas for downstream areas. In some cases however it can be of importance to account for negative effects in the design, as this can increase the economic risk for a certain reach, which justifies a higher safety standard. Another application in the field of economic risk estimations is when calculating the Maximum Probable Damage; for this type of calculations considering load interdependencies can have a large influence. Although in the case study the economic risk for cases with and without considering breaches were the same for the area, this will generally not be the case. De Bruijn *et al.* (2014) showed that the same holds for loss of life estimations, although negative effects are of less importance as evacuation times are generally very large in case of shortcutting.

6. CONCLUSIONS

This paper has demonstrated the effects load interdependencies of flood defences can have on flood risk estimates as well as water level statistics for different locations in a river basin. Different cases were considered with different types of effects of interdependencies using a method based on Monte Carlo simulation and a quasi-2D flood model. The application of the method to the case of the Bovenrijn/IJssel has led to the following general conclusions:

1. Load interdependencies of flood defences can have a significant effect on flood risk estimates. Both negative and positive effects need to be considered in order to obtain an accurate flood risk estimate for the considered case study area.

2. When considering load interdependencies the water level resulting from a certain discharge is no longer a fixed water level but a value in a range of water levels, determined by the uncertainty of the strength of upstream dikes. Also, when considering water levels for more downstream locations it can be expected that these locations have a maximum water level determined by the number of upstream breaches and their strength.

3. The method used performed quite well and the case study results were in line with what could be physically expected. However, given the change in shape of the discharge wave and the associated increase in duration of the discharge wave it was indicated that time dependence of failures should be taken into account.

4. In the future it is advised that load interdependencies are taken into account in prioritization of dike reinforcements and Maximum Probable Damage estimates. Negative load interdependencies should be taken into account for dike design, as these lead to a higher economic risk for certain dike reaches.

Although the method gave promising and physically sensible results for the case study area further improvements could be made on the following aspects:

1. As breaches lower maximum water levels but increase load duration, time dependent failures are more important. Therefore it is important to account for time dependent failures in future studies.

2. The accuracy of the quasi-2D model could be improved by using a better calibration strategy. Although the breach discharges were quite accurately reproduced, flood levels for some location still showed a considerable deviation. Using optimization techniques might improve this.

3. For the failure mechanism for dikes from the polder side some general assumptions based on expert judgment were made. A better geotechnical study on this type of failures could improve the schematization of these failures.

In general it can be concluded that when doing a flood risk analysis load interdependencies should at least be considered qualitatively to assess whether their influence is relevant for the area considered. Given the results in this and other studies, the influence of their effects is not negligible, although for some applications and some cases it can be easily concluded that it is either unnecessary or unwise to take these effects into account.

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