CHAPTER 2

THE INFLUENCE OF FLOODPLAIN COMPARTMENTALIZATION ON FLOOD RISK WITHIN THE RHINE-MEUSE DELTA*

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Abstract: The present compartmentalization layout within the river polders in the Dutch Rhine-Meuse delta is the result of abandonment and partially removal of secondary dikes and the construction of modern infrastructure embankments. These structures will guide the flow of water in case the polder would inundate. Through the application of a 2D flood propagation model in the polder "*Land van Maas en Waal*" this study explores whether restoration or removal of old dike remnants would contribute to a reduction of the risk and damage during an inundation. A systematic set of 28 flood scenarios was simulated and for each scenario an additional damage and risk assessment was carried out. It is concluded that a simple removal or total restoration will not reduce flood damage, but that this must be achieved by a strategic compartment plan. With such a plan old dike remnants and present embankments can be used to keep water away from vulnerable and valuable areas for as long as possible and to guide the floodwater to areas that are considered less vulnerable

Keywords: flood risk, flood hazard, 2-D modelling, polders

1. INTRODUCTION

This study explores the role of historic and modern compartmentalisations on the potential damage resulting from inundation of river polders in the Rhine-Meuse delta. These polders are protected against river floods by primary dikes that are designed to prevent inundation for discharge peaks lower than the 1250-year

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recurrence time flood (or: annual probability of occurrence of 0.0008). For the Rhine this corresponds with a discharge of 16000 m^3/s at the Dutch/German border and 3800 m^3/s for the Meuse at the Dutch/Belgium border. However, since the magnitude of this design flood has to be determined by statistical extrapolation from a 100-year record of observations, there is a considerable uncertainty band around the estimated design discharge. Furthermore, it is anticipated that due to climate change peak flows in the Rhine and Meuse might increase during the forthcoming century (Middelkoop et al. 2000; Silva et al. 2001). For this reason, water management in the Netherlands considers a 'worst-case' scenario with an increase of the design discharge of the Rhine to 18000 m^3/s and for the Meuse to 4600 m^3/s (Silva et al. 2001). This rise in discharge implies that – when no measures are taken – the probability of overtopping or breaching of the dikes would increase as well and the safety of the polder and its inhabitants would fall below the required safety standard. Furthermore, there is a growing awareness that it is impossible to guarantee totally secure defence against floods: the inundation of river polders in the Netherlands therefore is no longer an unimaginable. Recently, the option of using retention areas outside the present high-water bed of the rivers is considered as flood reduction measure (Silva et al. 2001). Furthermore, the idea of appointing some river polders as temporary emergency retention basins has been put forward in order to alleviate flood risk in the densely populated and low-lying downstream parts of the Netherlands in case a flood higher than the design discharge would occur. To allow controlled flooding of certain polders, parts of the dike will be designed as spill-over that can withstand overtopping by large amounts of flood water without breaching. Before such decisions can be taken, the potential damage in different polders must be assessed, and measures to reduce damage in the eventual case of inundation must be thoroughly considered. This demands quantitative information on the hydraulic characteristics of the inundation process of a river polder, depending on the elevation, land use and the occurrence of embankments within the polder. These embankments subdivide a polder into different compartments, which greatly controls the rate and sequence of the inundation. The present-day compartmentalization of the polders consists of the remains of compartment dikes have been erected in historic times and embankment of modern infrastructure (highways, rail). Because of the effect of these embankments on the inundation, therefore, strategies to reduce the inundation damage of a polder should focus at the design of the compartmentalization layout to minimize the potential number of casualties and damage caused by the inundation.

The aim of this study was to determine the hydraulic characteristics (i.e. propagation rate, flow depth, inundation time) of the inundation of a river polder along the lower Rhine and Meuse rivers and the resulting damage, depending on the compartment layout of the polder. In addition to quantifying the effect of the present compartmentalization on the inundation propagation, we focused at assessing to what extent the inundation damage of river polders may be reduced by restoring the functioning of the old compartment dikes. For this purpose we simulated the inundation of a river polder using a two-dimensional flood propagation model for

Figure 1. Location of the study area

28 inundation scenarios. The scenarios are based on a set of seven different dike-failures including catastrophic breaches and controlled overtopping of different sections of the primary river dikes along the Waal and Meuse Rivers, and four combinations of modern and (restored) historic topographic layouts of the polder. Each inundation scenario was evaluated by assessing the potential damage caused by the inundation. The study was carried out for the polder "*Land van Maas en Waal*", located between the Waal (the largest distributary of the lower Rhine River) and the Meuse River (Figure 1).

2. HISTORIC BACKGROUND

By nature, the Rhine-Meuse delta is characterized by alluvial ridges with natural river levees intersecting low-lying back-swamps. During periods of increased river discharge these swamps were flooded and remained inundated for a long period due to poor drainage. The natural levees along the rivers consist mainly of sandy material and formed the natural higher ground in the area. When the first inhabitants entered the area, the levees were their natural choice for settlement and the starting point for the further development of the back-swamps. For protection against river flooding artificial mounds and dikes were constructed. The first dikes were built perpendicular to the natural levees, upstream from the settlement to divert the flood water around the settlement (Driessen 1994). The enclosure of the river area by dikes was completed between the 13th and 14th century. To exploit the agricultural potential of the back-swamps, the drainage was improved by digging a network of canals. Also, compartment dikes were raised within the polders to control drainage, and in the event of a dike breach, to prevent areas from flooding. Between the 16th and 19th century, a polder system was created surrounded by primary river dikes and with secondary dikes that formed closed compartments within the polder, each with its own drainage system of canals, sluices and pumps. The polder *Land van Maas en Waal* is a typical example of such a polder system (Figure 2). This defence system offered protection against smaller floods but it could not avoid that occasionally large floods overtopped or breached the primary river dikes (e.g., Driessen 1994). During the onset of the flood, the system of compartments diverted the flow of the floodwater and delayed the propagation by forcing the water to fill up the polder compartment by compartment (Hesselink et al. 2003). This increased the time for evacuation and distributed the impact of the flood more evenly over the polder.

During the 20th century the condition of the main river channels and quality of the primary river dikes had greatly improved, and inundation of a river polder

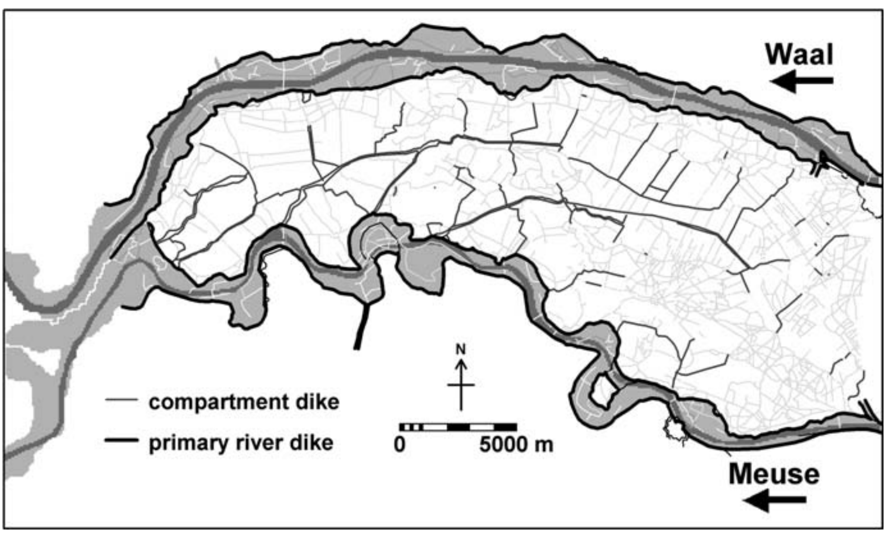

Figure 2. Historic map of the Land van Maas en Waal around 1850

in the Netherlands has not occurred since 1926. As a consequence, the appreciation and valuation of maintaining a secondary defence system within the polders declined and many compartmentalization dikes were subject of neglect or were completely removed. Large-scale development of the polder, with rapid expansion of urban and industrial area and land reallocation contributed to their decline. Embanked infrastructure gradually developed as additional compartmentalizing elements within the polder. This started in the late 19th century with railway lines and progressively developed in the 20th century with the construction of highways and motorways. Although these embankments were not designed as flood barriers, they will play a significant role in directing the floodwaters in case of inundation. Viaducts and bridges will funnel water and create increased flow-velocities. With the coinciding decline of the secondary dike system by end of the 20th century, the old compartment system was replaced by a non-systematic compartmentalization of the polder consisting of old dike remnants and new embankments.

3. INUNDATION SCENARIOS

The evaluation of the inundations was carried out for different combinations of failure of the primary river dikes and topographic layouts of the polder.

3.1. Dike Failures

A dike failure can be either a catastrophic breach or a controlled overtopping of the dike at a predetermined spill-over location. In total seven failures were simulated at five locations, five spill-overs and two breaches. Three locations are along the Waal river and two along the Meuse (Figure 3). At Weurt and Overasselt, both a breach and an overtopping were simulated. The choice for the locations was based on three considerations: 1) they are distributed more or less evenly along the rivers, so that differences between the scenarios will become sufficiently apparent; 2) they are not located too far downstream because that would result in very small inundations; and 3) they are positioned in between urban areas, because it would be unrealistic to construct a spill-over near a village. The location of Weurt for the breaching scenario was chosen because of the availability of historic data from the 1805 flood-reconstruction simulations carried out by Hesselink (2002).

3.2. Spill-Overs

The aim of a spill-over into a retention area is to cut off the peak of a flood wave in order to alleviate the flood risk in downstream areas. When compared to a dike breach, a spill-over allows controlled inundation over a pre-defined dike stretch, at an a-priori known flood stage in the river. As no scour hole develops, the amount of water entering the polder depends on the river discharge and eventual technical means to reduce the level of the spill-over threshold. To optimise the effect of the spill-over on reducing the downstream river flood stages, the peak of the flood wave

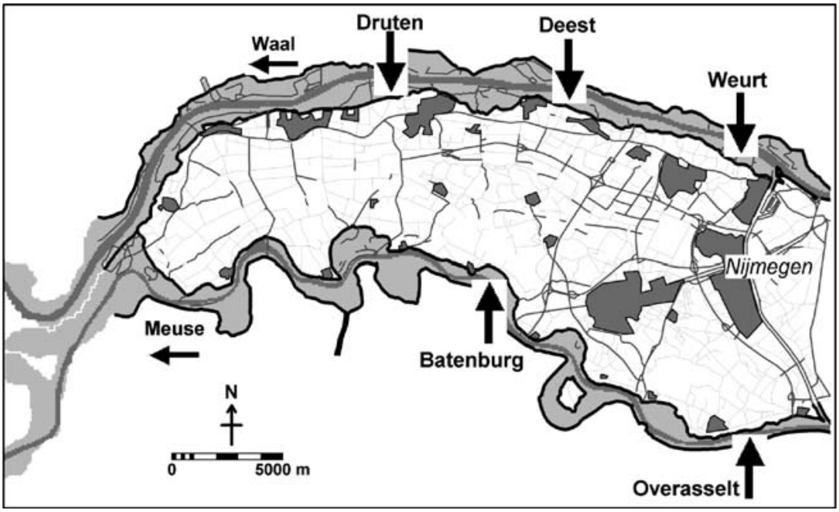

Figure 3. Location of the spill-overs and dike breaches

has to be cut off at exactly the right moment. In this study we considered a spill-over that will be activated as soon as the present-day design discharge of the Waal and Meuse rivers are exceeded, which is $10160\,m^3/s$ and $3800\,m^3/s$ respectively. At that moment the threshold height of the dike is reduced by 20 cm over a width of 525 meters for the Waal and 300 meters for the Meuse.

3.3. Breaches

The dimensions of the Weurt breach (i.e. gap width and scour hole depth, Figure 4) are based on the historic dike breach that occurred at this location in 1805. This flood disaster was reconstructed in detail by Hesselink (2002). The breach location along the Meuse river was selected near Overasselt since a dike breach occurred here in 1820 (Driessen 1994), although this event was not documented and analysed in the same detail as the 1805 flood. The dimensions of this breach and the scour hole were therefore not based on documentation, but on circumstantial evidence, like comparison with other Meuse dike breaches and shape of the reconstructed dike.

Apart from the ultimate dimensions of the dike breach, the rate at which the breach develops determines the amount of water flowing into the polder. In this study it was assumed that the final dimensions of the dike breach gap and scour hole were reached 3 hours after the dike collapsed.

3.4. Topography

Four different lay-outs of the polder interior were constructed, based on: A) a current Digital Terrain Model provided by the Province of Gelderland (Van Mierlo

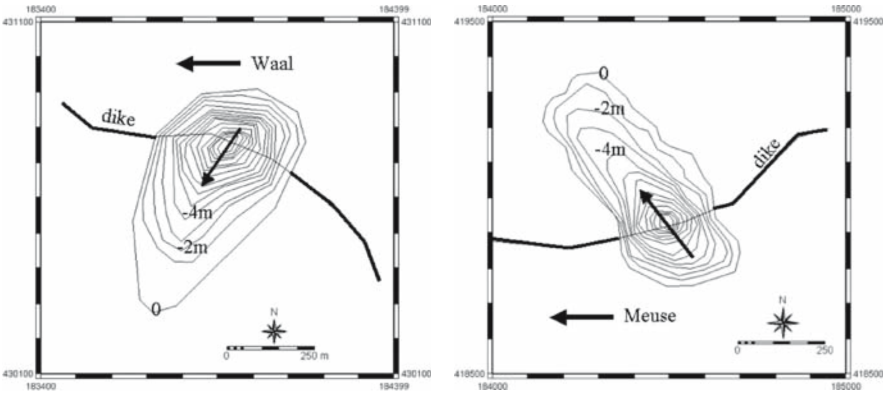

Figure 4. Dimensions of the dike breach near Weurt (left) and of the dike breach near Overasselt (right)

et al. 2001) and B) on the DTM of the polder as it was in the first half of the 19th century, reconstructed by Hesselink (2002) with a complete compartmentalization (Figure 5). The historic DTM is based on 35868 elevation points measured between 1950 and 1965 (before large land levelling and re-allocation schemes had taken place), complemented with data from a land survey carried out along five transects in the beginning of the 19th century and dike-height measurements carried out in 1801. The current DTM is derived from a laser-altimetric survey with a vertical accuracy of a few centimetres. Comparison between the topographic maps

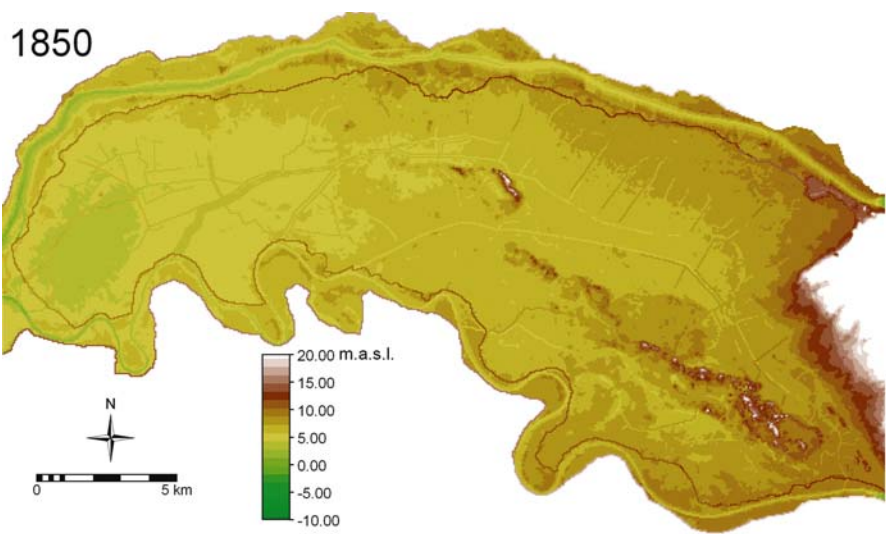

Figure 5a. Digital Elevation Model (DEM) of the study area around 1850

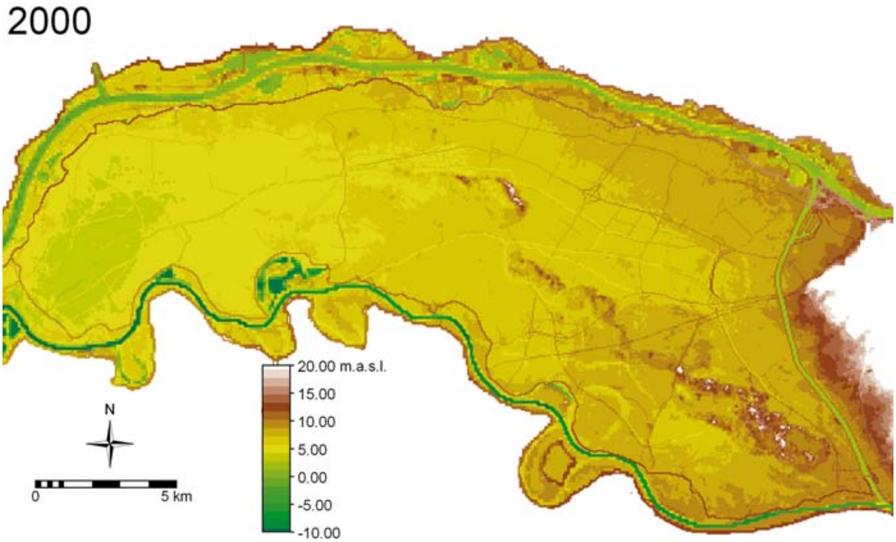

Figure 5b. Digital Elevation Model (DEM) of the study area around 2000

of 1850 and 2000 showed which former secondary dikes had disappeared and which remnants had survived. A field survey provided information of the height of these elements and of the embankments of modern infrastructure. For modelling purposes a grid size of 75 meters was chosen and a check with elevation points derived from

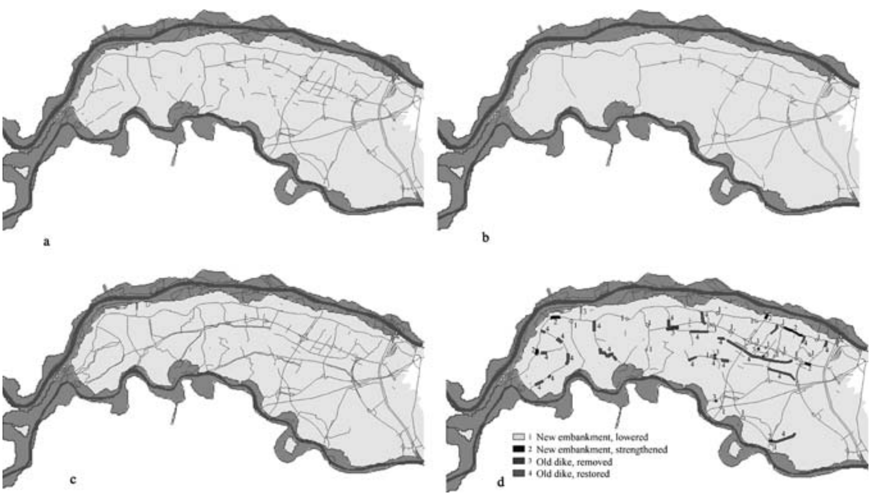

Figure 6. The 4 compartment layouts. Top-left: Present situation (A). Top-right: All old elements removed (B). Lower-left: All old elements restored (C). Lower-right: Strategic adaptations (D)

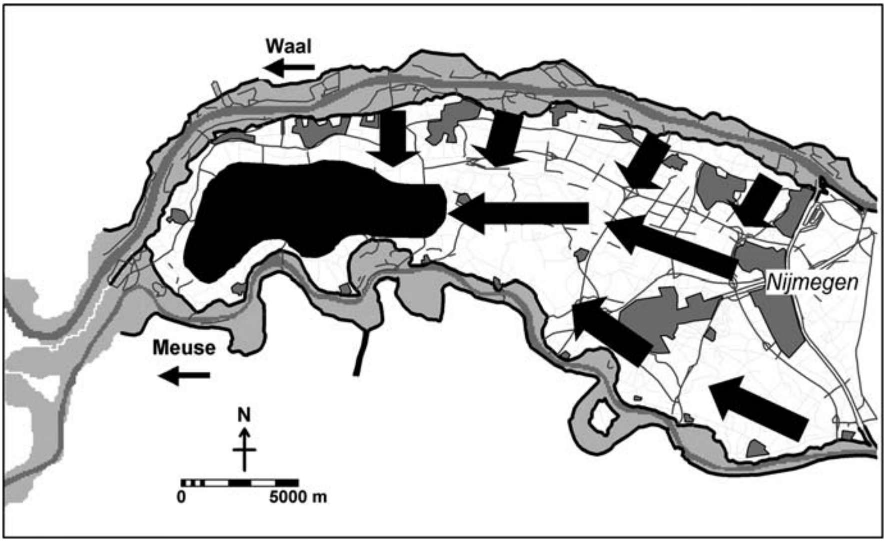

Figure 7. Strategic plan to use old and new barriers to keep the water away from vulnerable areas for as long as possible and to guide it towards less vulnerable parts of the polder

the topographic map showed that vertical accuracy was within 10 cm for 90% of the control points. The four different layouts are (Figure 6):

A: Present situation, including dike remnants and modern embankments (present);
B: Present situation with all remnants removed (cleaned-up);
C: Present situation with the 1850 compartmentalization complete restored (restored);
D: Present situation with strategic adaptations to protect vulnerable (urban) areas (strategic).

The aim of layout D is to reduce the impact of the flood in terms of damage or risk by selective changes in the present compartment layout. This involves both repair of previously removed dikes as well as removal of dike sections. The adopted strategy aims at directing the water flow away from, or around the urban areas and to guide it towards the less vulnerable agricultural areas in the centre of the polder (Figure 7).

4. THE 2D-FLOOD PROPAGATION MODEL DELFT-FLS

To assess the effects of linear elements within the polder on the flood characteristics, we used the two-dimensional flood propagation model Delft-FLS, developed at WL | Delft Hydraulics (Stelling 1998). This model was designed to simulate overland flow over initially dry land and through complex topography. It includes internal boundary conditions that allow the correct modelling of dike-breach scenarios, which makes it very suitable tool to simulate dike-failure related floods in polder areas. The scheme used in Delft-FLS is based upon the following characteristics:

- The approximation of the continuity equation is such that a) mass is conserved, not only globally but also locally and b) the total water depth is guaranteed to be always positive which excludes the necessity of flooding-and-drying procedures;
- The momentum equation is approximated such that a proper momentum balance is fulfilled near large gradients.

The combination of positive water depths and mass-conservation assures a stable numerical solution. A proper momentum balance provides that this stable solution converges. The robust numerical scheme allows for the correct simulation of sub-critical and super-critical flow. Further information regarding the model properties can be found in Stelling (1998) and Hesselink et al. (2003).

4.1. Data Requirements

Delft-FLS requires the following information:

- An accurate digital terrain model (DTM) that includes all topographical features with their correct heights and depths, like dikes, embankments, channels, sluices, tunnels, etc.;
- Land surface cover information in terms of hydraulic roughness coefficients both for 'dry' (polder) and the 'wet' (channels) surfaces;
- Discharge or water-level time-series at the inflow boundary and a stage-discharge relation at the outflow boundary;
- Dimensions of the dike breach and their development through time.

All spatial data has to be available in raster format.

4.2. Model Output

The model produces three types of output: 1) raster maps at predefined time-steps that show the spatial distribution of the water depth and flow-velocity; 2) time-series at regular intervals of the water level and flow-velocity at predefined locations and discharges though predefined cross-sections; and 3) animation file showing the dynamic behaviour of the flood as it propagates through the polder.

4.3. Model Sensitivity

Hesselink et al. (2003) carried out a sensitivity analysis of inundation patterns simulated with Delft-FLS for varying surface roughness and topographic detail in the same area as the present study. They concluded that hydraulic roughness affects the speed at which the polder fills, but does not influence the maximum inundation depth. Furthermore, the model results were highly sensitive to the terrain topography and the inclusion of secondary compartment dikes within the polder. Alkema and De Roo (in press) tested the model on the inundation of the Ziltendorfer polder during the 1997 Oder flood in Germany. This polder is comparable in size and land-use, although it is not as compartmentalized as the *Land van Maas en Waal*. The results of this study also confirmed the model sensitivity reliability, with the addition that for accurate water depth predictions a good discharge-stage curve is essential. These studies demonstrated that the Delft-FLS model is well capable of accurately simulating inundation depth and propagation rate of an inundation. Validation of other parameters, such as flow velocity, was not possible from these studies.

5. BOUNDARY CONDITIONS AND MODEL CALIBRATION

5.1. River Discharge

In accordance with the upper estimates of future design discharge (1250-yr recurrence time) due to climate change considered by Dutch water management (Silva et al. 2001) we carried out model simulations for a design flood equal to 18,000 m^3/s for the Rhine at the Dutch/German border and 4600 m^3/s for the Meuse at the Dutch/Belgian border. Assuming that the Waal River then discharges 63,5% of the Rhine discharge the corresponding peak discharge in the Waal River equals 11,400 m^3/s. The shape of this increased design flood wave was obtained from Dutch Institute for Water Management and Waste Water Treatment (RIZA, pers. comm., Figure 8). Likewise, the peak-discharge of the Maas will reduce as it travels downstream. Near the study area it is estimated that the peak discharge will be reduced by approximately 1000 m^3/s, giving a peak discharge of around 3650 m^3/s, but the width of the flood wave is much more stretched than further upstream (RIZA, pers. comm.).

5.2. Stage Discharge Relations Waal and Meuse

Stage-discharge relations of the Waal and Meuse Rivers at the downstream boundaries of the modelling area (villages of Opijnen and Empel) were provided by the water authorities of the Province of Gelderland (Figure 9). During the model

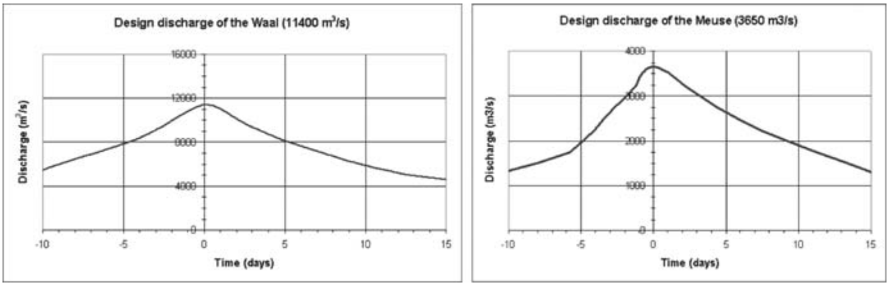

Figure 8. Discharge curve of the Waal used in this study (left) and that for the Meuse (right)

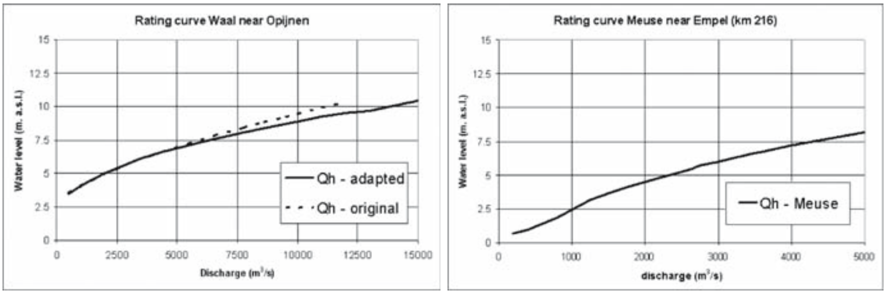

Figure 9. Stage-discharge curves for the Waal near Opijnen (left) and for the Meuse near Empel (right)

calibration the relation for the Waal River was slightly adapted to compensate for errors in the representation of the riverbed in the DTM. For the Meuse this was not necessary.

5.3. Surface Roughness Coefficients

The flow of water is hindered by the resistance of surface features. The surface roughness depends largely on the type of land cover and is often expressed as Manning's coefficient. Table 1 gives an overview of the land cover classes and the corresponding values of Manning's coefficients as they are found in literature (e.g. Chow 1959; Albertson and Simons 1964; Barnes 1967) with the exception of the values for the riverbed and the floodplain. The latter were obtained by model calibration and partially correct for inaccuracies in the representation of the riverbed. This explains their low values. Figure 10 shows the resulting surface roughness map.

5.4. Model Calibration

The discharges that are used as boundary condition in this study have never been recorded in the Waal and Meuse, so no measured water levels are available to calibrate the model. However, previous modelling studies have provided estimates

Table 1. Roughness values for different land cover types used in the model simulations

Land cover type	Manning's coeff.	Land cover type	Manning's coeff.
Riverbed	0.008	Heather	0.050
Floodplain	0.011	Main road	0.020
Urban area	0.100	Railway	0.020
Forest	0.150	Secondary road	0.015
Arable land	0.050	Water	0.012
Dike	0.030	Grassland	0.018

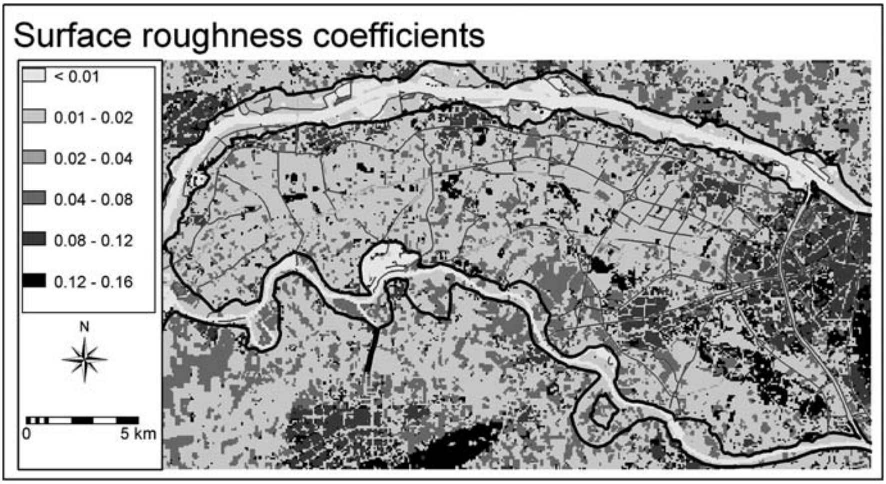

Figure 10. Manning's surface roughness coefficients

Table 2. Comparison between water stage predictions of previous studies and the results of this study at various locations along the rivers

WAAL	Nijmegen (km885)	Bridge A50 (km894)	Druten (km904)	Ben. Leeuwen (km911)	Dreumel (km920)
Previous studies	15.00m	13.60m	12.50m	11.80m	10.80m
This study	14.99m	13.64m	12.48m	12.07m	10.93m
MEUSE	Heumen (km(166)	Overasselt (km171)	Batenburg (km185)	Heerewaarden (km205)	
Previous studies	12.70m	12.00m	10.10m	7.30m	
This study	12.20m	11.90m	10.10m	7.54m	

of flood water levels in the rivers occurring at these extreme discharges (WL|Delft Hydraulics, pers. comm.). The outcomes of these studies were used to verify the water stages in the rivers calculated in this study (Table 2).

6. FLOOD HAZARD ASSESSMENT

The model results, hourly maps of flow-velocity and water depth, were transformed into seven indicator maps that describe the various aspects of a flood. For each of the 28 scenarios a set of these indicator maps was calculated. Figures 11a–g show such a set for a catastrophic dike breach near Weurt with the present topography.

All maps are the result of an aggregation of 150 hours of simulation time (150 hourly maps). Maximum water depth and maximum flow velocity were derived

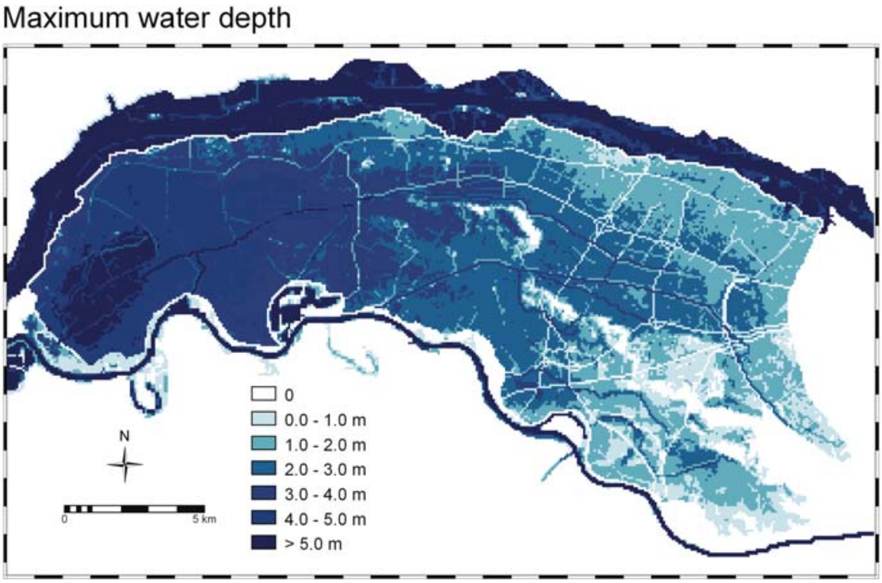

Figure 11a. Flood hazard indicator maps; Water depth

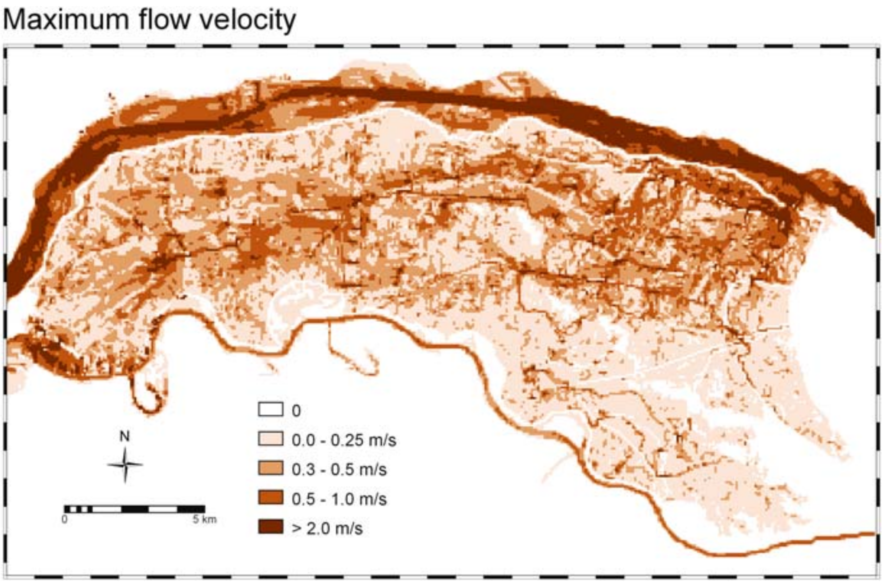

Figure 11b. Flood hazard indicator maps; Flow velocity

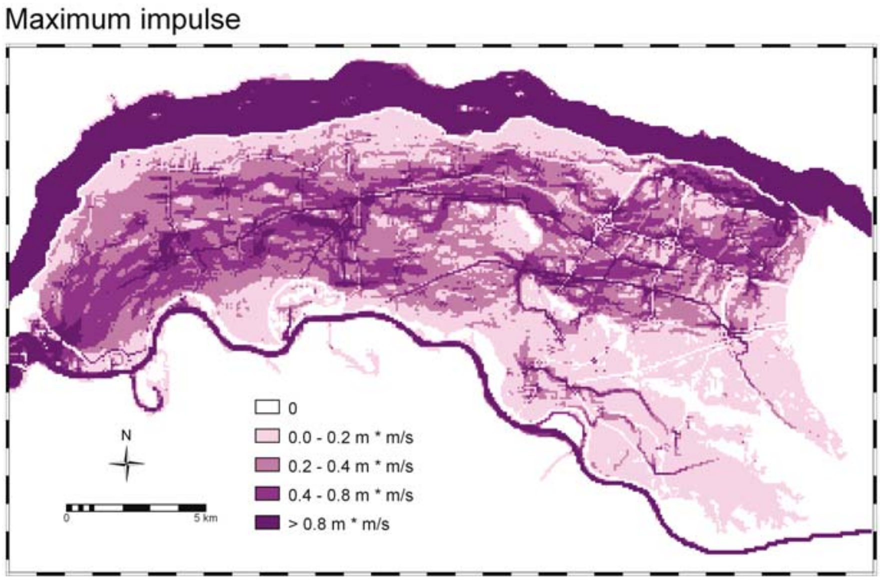

Figure 11c. Flood hazard indicator maps; Impulse

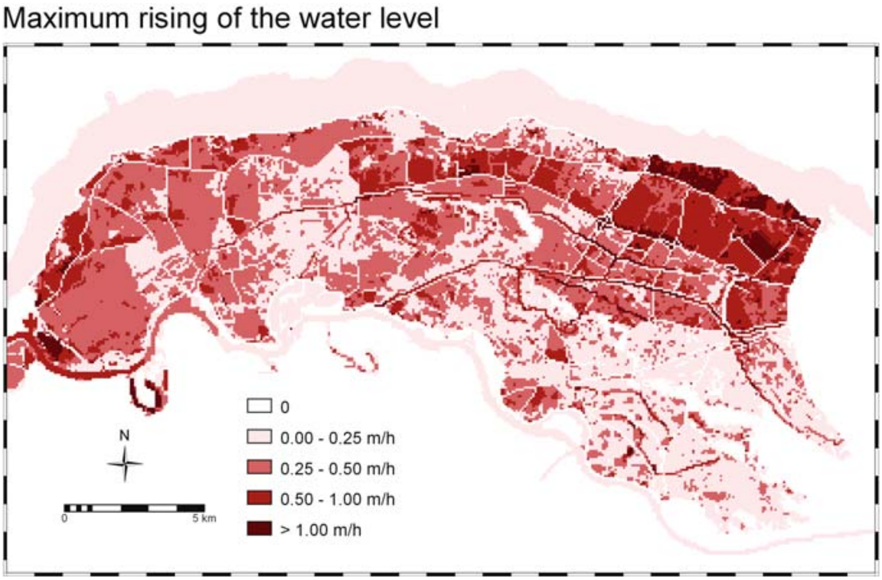

Figure 11d. Flood hazard indicator maps; Rising of the water level

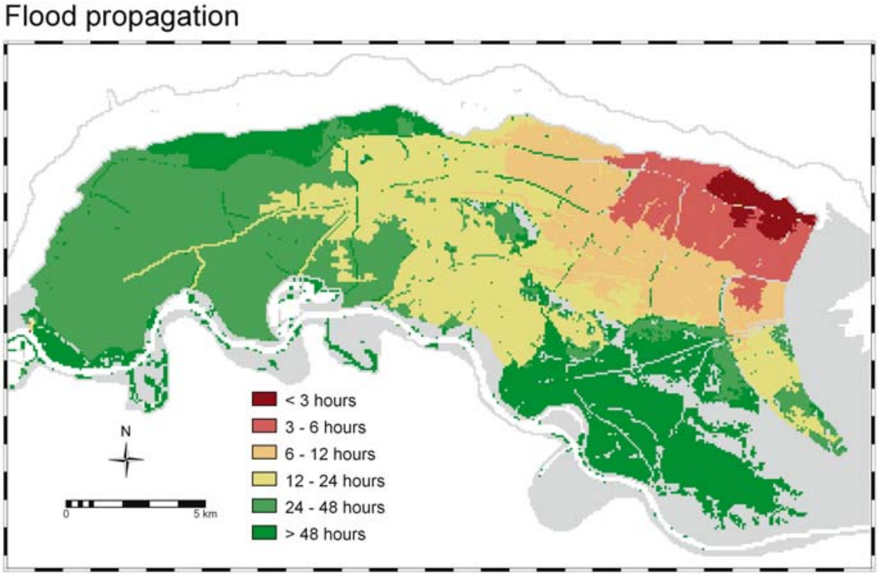

Figure 11e. Flood hazard indicator maps; Flood propagation

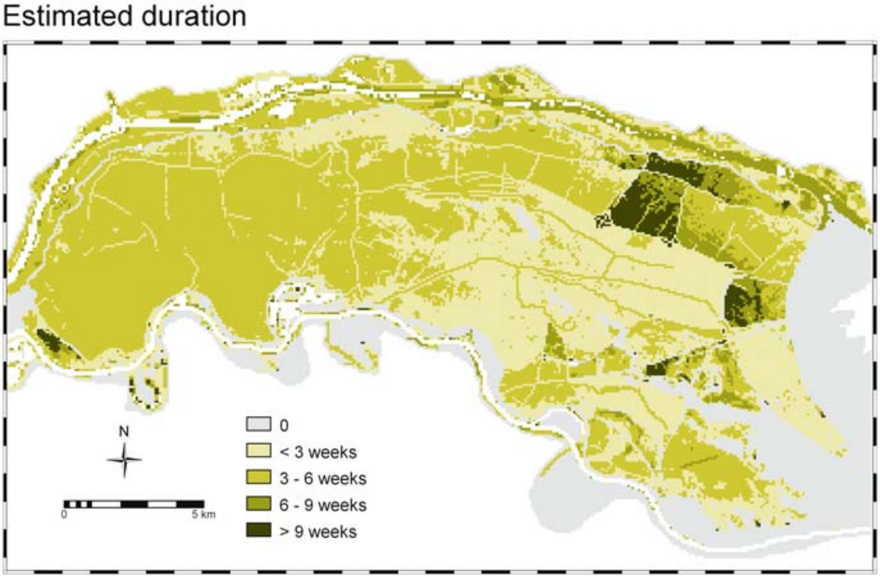

Figure 11f. Flood hazard indicator maps; Duration

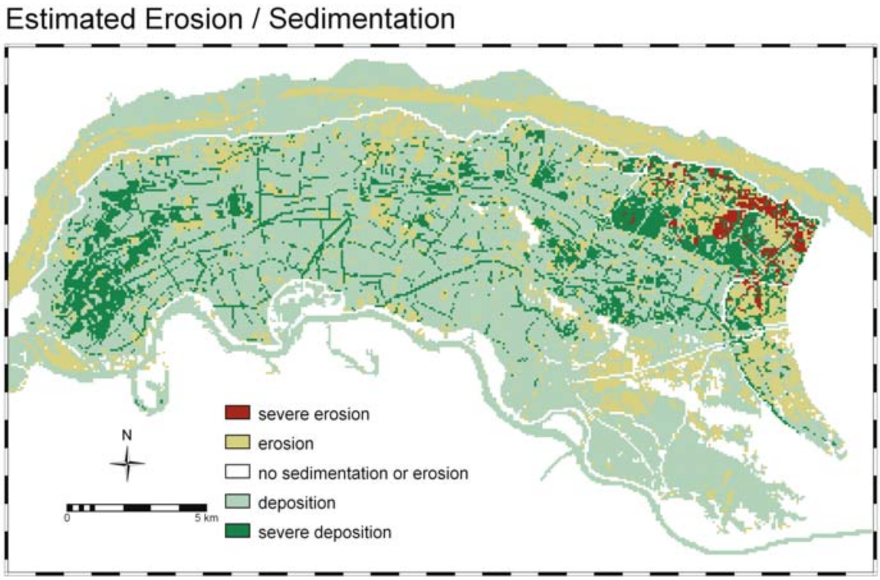

Figure 11g. Flood hazard indicator maps; Sedimentation / Erosion

directly from the water depth and flow-velocity maps that were generated by Delft-FLS. The indicator "impulse" was calculated as the product of the water depth and the flow velocity at each time step. It indicates the momentum of the water flow. The indicator "maximum rising" is based on the difference of water depth at a certain time step and the water depth at an hour earlier. It shows those locations where the water level will rise very quickly. The indicator map "flood propagation" shows how the floodwater moves through the polder and how barriers such as dikes and embankments diverted it. It gives an estimated time of arrival for the first floodwater in hours after the dike-breach. The indicator map "duration" is based on a natural draining of the polder near its lowest point (lower left corner, towards the Meuse river) through a 75-m wide gap in the Meuse primary river dike. The indicator map "sedimentation/erosion" gives a rough estimate on sedimentation and erosion rates. It is based on the Rouse criterion that gives the ratio between the upward lifting forces in the turbulent flow and the downward oriented gravitational forces. This criterion was calculated at the hourly time steps, for sediment particles with a diameter of 210 μm. Three additional assumptions were made: 1) The sediment-load of the water that has flown into the area decreases linearly with time; 2) The input of sediment at a certain location at a certain time depends on the amount of inflowing water and the change in storage; and 3) sedimentation and erosion occur only in the first 150 hours of the flood. This approach does not give absolute values for sedimentation and erosion, but provides an indication of where large accumulations may be expected.

7. FLOOD DAMAGE ESTIMATION

A standard way used to estimate flood damage is the so-called stage-damage curve, that describes for each land cover type the damage factor on a scale from 0 (no damage) to 1 (complete destruction) as a function of inundation depth (Figure 12). The absolute damage is obtained by multiplying the damage factor with the value of the unit.

In the Netherlands, a standardized method has been developed by the Directorate-General for Public Works and Water Management (Rijkswaterstaat) to estimate the possible monetary damage for flood scenarios (Kok et al. 2002). This method was applied to the 28 flood scenarios in our study. An example of the damage map is given in Figure 13. The summed-up totals for all scenarios are listed in Table 3.

7.1. Multi-Parameter Flood Hazard Estimation – An Example

Flood damage estimation methods based on depth-damage curves have several limitations. Firstly, there is usually lack of data to establish reliable curves. Secondly, the methods often only consider maximum water depth to estimate the damage, neglecting other relevant flood parameters, such as flow velocity, sedimentation and duration of the inundation. Thirdly, all consequences of the flood are expressed as monetary losses due to inundation, while aspects related to evacuation success, such as warning time and speed of the rising of the water level, are not considered. Therefore, a more elaborated impact assessment method was developed for this study that is based on the set of indicators that was calculated for each scenario (Figure 11: max. water depth; max. flow velocity; max. impulse; max. rate of water level rise; flood propagation time; flood duration). This approach is derived from decision support systems described by Beinat and Nijkamp (1998) and Van Herwijnen (1999).

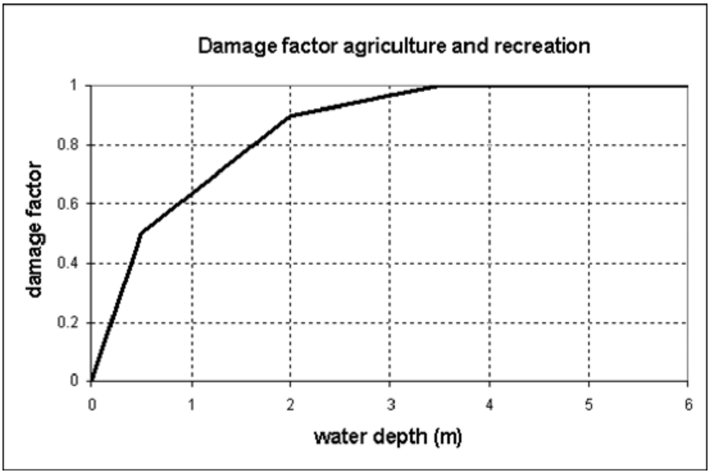

Figure 12. Stage-damage curve for agriculture and recreational areas (source: Kok et al., 2002)

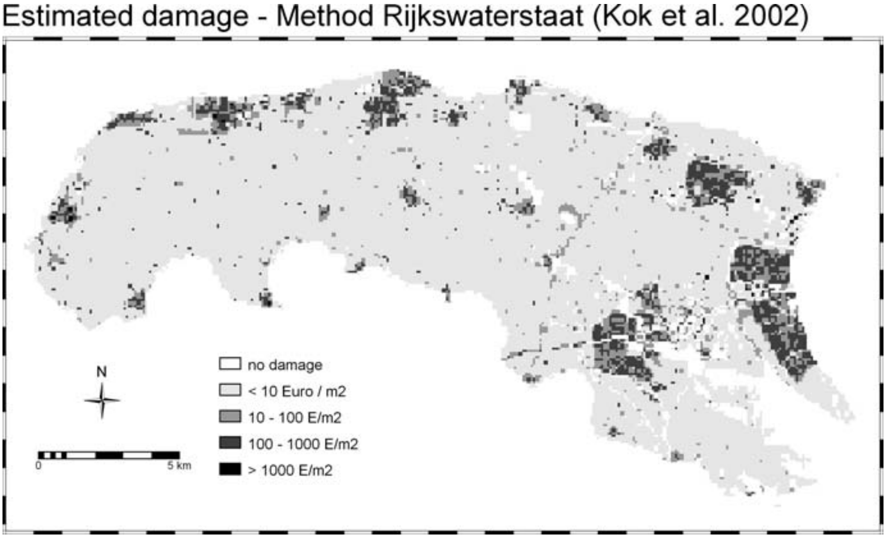

Figure 13. Flood damage map in Euros/m^2, based on the method of Rijkswaterstaat

Aggregation of the indictors was done in three steps: 1) Rescaling of the indicator value range to a normalized scale of 0 to 1; 2) Assigning weights to each indicator; and 3) Defining one of the scenarios as standard and to calculate for all other scenarios the ratio value. The process of normalization and weight assignment is subjective, but it is transparent. It includes more than one aspect of a flood and it allows a wider interpretation of the consequences of inundation than just damage (money). This approach does not provide absolute risk, damage or casualties values, but presents hazard classes on an ordinal scale where low classes stand for low hazard and high classes for high hazard. Table 4 shows the weights and normalised values for an example where six parameters were used for the assessment.

Table 5 presents the results of this multi-parameter hazard assessment. It shows the aggregated total hazard values for all scenarios as ratio of the standard scenario, based on the assumed weights indicated in table 4.

Table 3. Overview of flood damage for the 28 scenarios (in million Euros)

	Type	Present situation (A)	Cleaned-Up situation (B)	Restored situation (C)	Selective changes (D)
1) Weurt	Breach	5400	5300	5500	4300
(Waal)	Spill-over	1900	1700	2000	905
2) Deest	Spill-over	740	740	761	711
3) Druten	Spill-over	627	629	645	588
4) Overasselt	Breach	2600	2600	2700	2500
(Maas)	Spill-over	1400	1400	1400	1300
5) Batenburg	Spill-over	859	906	907	946

Table 4. Example of normalizing and weighing a set of flood hazard parameters (weights are between brackets)

Water depth (0.2)		Impulse (0.2)		Rising (0.1)	
class	value	class	value	class	value
[m]	[-]	[m^2/s]	[-]	[m/h]	[-]
0	0	0	0	0	0
0.0–0.2	0.1	0.0–0.1	0.1	0.0–0.1	0.2
0.2–0.5	0.25	0.1–0.2	0.2	0.1–0.3	0.4
0.5–1.0	0.5	0.2–0.3	0.4	0.3–0.5	0.6
1.0–1.5	0.7	0.3–0.4	0.6	0.5–0.75	0.8
1.5–2.5	0.85	0.4–0.8	0.8	0.75–1.0	0.9
2.5–3.5	0.95	>0.8	1	>1.0	1
>3.5	1				
Duration (0.1)		**Sedimentation (0.1)**		**Propagation (0.3)**	
class	value	class	value	class	value
[weeks]	[-]	[-]	[-]	[hours]	[-]
0	0	severe erosion	1	0	0
<2	0.2	medium e.	0.85	<3	1
2–4	0.4	light e.	0.7	3–6	0.8
4–6	0.6	equilibrium	0.5	6–12	0.6
6–8	0.8	light depos.	0.7	12–24	0.4
>8	1	medium depos.	0.85	24–48	0.2
		severe depos.	1	>48	0.1

Table 5. Comparison of the aggregated relative hazard values for all scenarios. The scenario with a breach at Weurt and the present topography is used as standard

	Type	Present situation (A)	Cleaned-Up situation (B)	Restored situation (C)	Selective changes (D)
1) Weurt	Breach	1	0.98	1.01	0.89
(Waal)	Spill-over	0.46	0.45	0.50	0.35
2) Deest	Spill-over	0.32	0.32	0.34	0.31
3) Druten	Spill-over	0.23	0.24	0.24	0.20
4) Overasselt	Breach	0.63	0.64	0.65	0.59
(Maas)	Spill-over	0.4	0.40	0.41	0.37
5) Batenburg	Spill-over	0.33	0.35	0.35	0.33

8. RESULTS AND CONCLUSIONS

The results of 28 flood scenarios in terms of damage and relative hazard are shown in Tables 3 and 5. From these tables can be seen that the further downstream the failure locations are situated, the lower the damage and hazard because a smaller part of the polder is flooded. Failure at the most upstream located point of the polder will result in the highest damage. Furthermore, the damage and hazard associated with a catastrophic dike breach are significantly higher than in case of a spill-over inundation. The breaching of the dike creates an enormous gradient between the water level in the river and the low-lying polder surface. This results in a much higher flux of floodwater into the polder than of a controlled overtopping at a spill-over location. So from a safety and damage reduction point of view it can be concluded that it makes sense to prefer controlled overtopping over catastrophic breaching. Embankments and internal dikes not only control the inflowing flood water, but also create storage locations that drain badly and could extend the inundation time up to 2 months.

Comparison between the different topographies showed that the complete restoration of the old secondary dike systems does not result in a significant improvement, not for the damage nor for the hazard. The same holds for the scenarios where all the old dike-systems were removed. There are two explanations for this: 1) Most secondary dikes are too low to block the water flow completely and therefore do not affect significantly the maximum water depth in the polder. Especially for methods that only use the maximum water depth as hazard indicator, like the method of Rijkswaterstaat, the results will be similar. 2) Compartmentalizing has both positive and negative consequences. Inside the compartment the water level will rise faster and the maximum water depth may be higher than without the compartmentalization. Outside the compartment there will be a delay in the arrival time of the floodwater (or no flood at all) and the flow-velocities will be reduced. Whether the positive consequences outweigh the negative ones depends on the distribution of vulnerable (and valuable) areas – e.g. urban areas – in relation to the compartments. In the scenarios that consider the complete restoration or removal of old dikes the positive effects are balanced by the negative consequences. In the D-scenarios a strategic plan was developed with the aim of guiding the water away from the vulnerable urban areas where a lot of valuable property is concentrated. The water was guided to the more rural parts of the polder. This strategic approach does reduce the damage or hazard in the inundated area. It can therefore be concluded that complete restoration or removal will not improve the safety situation in the polder, unless a strategy is followed to protect the more vulnerable parts. Instead, this can be achieved by a well-designed compartment layout, comprising both modern and (repaired) historic embankments.

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