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Flood damage reduction by compartmentalization of a dike ring: comparing the effectiveness of three strategies

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Abstract

Compartmentalization of dike ring areas is currently seen as one of the promising options for managing or reducing the risk of flooding. Recently, several studies on the effectiveness of subdividing dike ring areas by means of compartmentalization dikes were published. These studies show that the total damage after a flood could indeed be smaller, but that the damage could also turn out to be larger on a local level. The available studies on compartmentalization usually consider only one dike pattern in the area concerned. This article develops, assesses and compares three fundamentally different strategies, based on different configurations of the compartmentalization dikes. Not only do we examine the effects of the most probable flood scenarios, we also look at the worst-case scenario, whereby the water is able to flood into the dike ring area from all sides. The spatial layout of the area codetermines the effectiveness of each strategy. Dike ring area 14, which lies in the west of the Netherlands and that covers some cities, like Amsterdam, Rotterdam and The Hague, was chosen as the area of application. The results show that for this dike ring, the secondary dike strategy is most effective in reducing the number of expected victims under different flood scenarios.

Introduction

The Netherlands is located in the Rhine–Meuse estuary. About a quarter of the Dutch land surface lies under sea water level and about two-thirds can be flooded by water from the sea, lakes or rivers when flood defence mechanisms fail. Since the Middle Ages, the Dutch have created dikes for flood protection and reclamation of land. In spite of these dikes, the Dutch have suffered many large floods in history. In 1953, the last serious flood occurred in the south-western part of the country.

After this flood, the Delta Committee was established for improving the Dutch flood policy. The lower areas, threatened by surrounding water, were partitioned into dike ring areas. Primary water-retaining structures (dams, dikes and dunes) or higher grounds border a dike ring area. Safety standards were formulated for every dike ring area, based on an economic optimization (Delta Commissie, 1960). The Dutch flood safety policy is still based on the results of this committee. The safety standard is expressed in terms of the return period of a high water level. The safety standards for dike ring areas in the Netherlands have been laid down in the Act on Flood Defences and are as follows: a return period of 10 000 years for densely populated areas along the coast, 4000 years for less densely populated areas along the coast, 1250 years for areas along the rivers and 2000 years for the areas along the most downstream stretches of the rivers that experience influence from the sea.

The focus on maintaining very high standards with respect to primary water defences has taken away the interest in protective measures within the dike ring areas. The result is that in the hypothetical case of failure in a primary water defence structure, the damage will be relatively large. For this reason, in the past few years, there has been growing interest in measures within the dike rings that can reduce the flood risk (Ten Brinke and Bannink, 2004; VNK, 2005).

One of the options to reduce flood risk, other than strengthening the primary water defence structures, is to compartmentalize the dike ring areas. Recently, several studies on the effectiveness of subdividing dike ring areas by means of compartmentalization dikes were published. These studies show that the total damage after a flood could indeed be smaller, but that the damage could also turn out to be larger on a local level (Theunissen *et al.*, 2006). Alkema and Middelkoop (2005) argue that compartmentalization of a dike ring area can become effective in reducing flood risks only when compartmentalization dikes are strategically built or removed. There are various strategies for compartmentalization, whereby the configuration of the compartments in an area is of importance. The objective of this paper is to elaborate three fundamentally different compartmentalization strategies and assess their effectiveness in one specific dike ring area, viz. dike ring area 14, which covers a large part of western Netherlands (Figure 1).

Three compartmentalization strategies

Compartmentalization is subdividing one whole into separate parts (compartments). The objective of this is to reduce the effects of a dike breach. In case of a disaster, only part of the whole is damaged or lost. In addition, time is gained for countermeasures in order to avoid consequences that are even more serious. The idea of compartmentalizing is a familiar concept in security management. For instance, buildings have fire-resistant partition walls to prevent a fire, which started on one side of the building, from spreading to other parts. Ships often have a double hull in order to prevent the hold from filling up with water should a leak occur on the outside. At the same time, the double hull ensures that hazardous cargo remains on board. Banks have safes to protect valuable goods from burglars or fire. Emergency service personnel wear protective clothing and oxygen masks if hazardous substances end up in the environment.

The three general security strategies mentioned above – partition, double hull and value protection – can be translated into the case of flood security (Figure 2). The first strategy is the partition strategy (similar to dividing a building for fire safety). For a dike ring area, this means that the area is divided into compartments of similar dimensions, whereby each compartment has an almost equal flood probability. Which compartment will be flooded depends on the breach location in the primary water-retaining structure.

The second strategy is the double-hull strategy, where a secondary retaining structure is located behind the primary structure. The flood probability varies per compartment: the probability that the area between the primary and the secondary retaining structure is flooded is larger than the probability that the area behind the secondary structure is flooded.

The third strategy is the value-protection strategy (comparable to a safe, protective clothing or oxygen mask). In the case of flood safety, separate dikes surround the most valuable areas inside a dike ring area. The flood probability

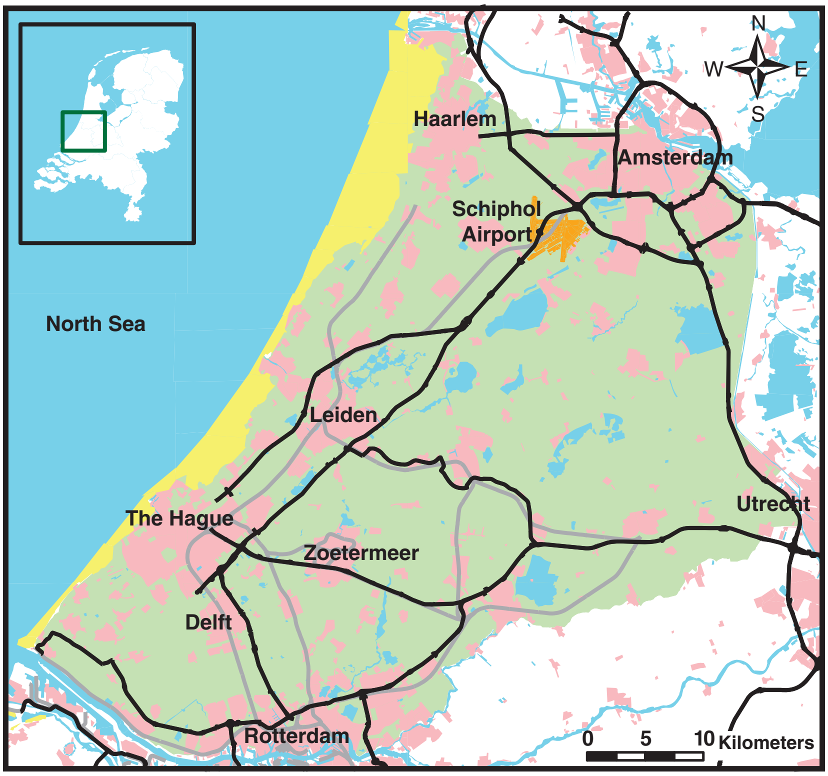

Figure 1 Dike ring area 14 in the Netherlands.

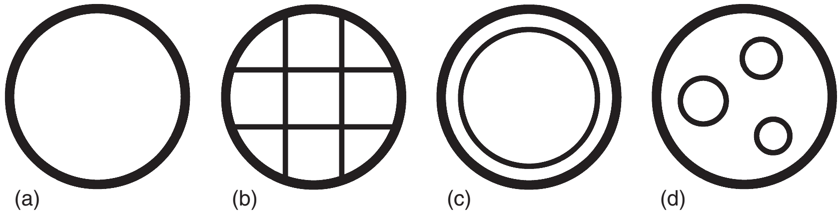

Figure 2 Schematic representation of a plain dike ring area (a), a partitioned dike ring area (b), a secondary dike (c) and a dike ring with additional value protection (d).

for the separately ringed area is smaller than the flood probability for the rest of the dike ring area. This strategy of value protection is comparable to the ancient strategy of dwelling mounds (Oost and Hoekstra, 2007).

Flooding risks

In the Act on Flood Defences, the safety standards are quantified in terms of the exceeding frequency of water levels at the primary water-retaining structures. However, the probability of exceedance of water-retaining structures is not the only mechanism that can lead to failure of the defence structure. The flood probability of a dike ring consists of more failure mechanisms, like sliding of the inner slope and uplifting and piping (VNK, 2005).

A risk is a function of the probability of an accident and the corresponding consequences of that accident. Various risk definitions are used in the risk literature. According to the most common definition, which is also used in the study Flood Risks and Safety in the Netherlands, the risk is defined as the probability of failure times the consequences of failure (VNK, 2005).

In line with the Act on Flood Defences, Dutch flood policy is mainly focused on managing the probability of flooding. Limited attention is paid to the potential consequences of a possible flood. However, in the past few years, interest in the consequences has been growing. Research into the consequences mainly concentrates on three indicators: affected people, number of casualties and (direct and indirect) economic damage.

Most research into the possible flood damage in the Netherlands is focused on estimating the consequences of the most probable flood scenarios. This is understandable, as the consequences of these scenarios make the largest contribution towards the total flood risk within a dike ring area. The more extreme, but less likely floods will result in more substantial damage, but due to the small corresponding probability they hardly contribute to the total risk (VNK, 2005). Yet, it is advisable that these extreme flood scenarios are included. After all, even extreme floods cannot be excluded. Just like with 'external risks' (risks for the environment resulting from man-made accidents with hazardous materials), it is relevant to foresee and prevent substantial numbers of victims in relation to flood events (Ten Brinke and Bannink, 2004).

In this research, we pay attention to the 'system risk' of a flood in dike ring area 14. System risks are risks characterized by a very low chance but a large effect. The concept emerges from the financial sector and is used in relation to events that could ruin the complete financial market as opposed to a limited number of participants (OECD, 2003). Extreme floods form a system risk because the functioning of a complete region can be disrupted (Bočkarjova *et al.*, 2009). The focus on system risk deviates from the current focus in Dutch water management, which simply focuses on the largest risks, which generally are the larger chance–smaller effect events. When looking at system risks, one focuses on events that are more unlikely but have the greatest effect. In order to account for those events as well, we will include three flood scenarios with more than one breach location, so that the dike ring area is flooded from different sides. Because compartmentalization mainly reduces the flooded surface and so the consequences of a flood, the reduction of those consequences is the focal point of the study.

Dike ring area 14

The research area is dike ring area 14, which lies in the west of the Netherlands (Figure 1). In the west, the North Sea borders the area, while the estuary of the Rhine is situated in the south-eastern part. In the last centuries, several lakes were reclaimed. These land reclamation sites lay > 5 m below the average sea level.

The area is characterized by a high density and variation of land functions. Several cities lies in the area like The Hague, Leiden, Haarlem and parts of Amsterdam and Rotterdam. The total population of the area is about 3.3 million people. Figure 1 shows the dense infrastructure network in the area. The area has important industrial, commercial and governmental functions like Schiphol Airport, the capital of the country (Amsterdam), part of one of the world's largest harbours (Rotterdam) and the seat of government (The Hague). Numerous cultural – historical sites and natural values are situated in the dike ring area as well. Besides, there is a large agricultural output, because of the existence of greenhouses.

The safety standard for dike ring 14 is a return period of 10 000 years. The maximum possible damage is estimated at 290 billion euro, based on a scenario in which the whole dike ring area is inundated (VNK, 2005). Of all dike ring areas in the Netherlands, dike ring area 14 has the highest possible damage in the protected area per kilometre of primary dike (Ten Brinke and Bannink, 2004).

Flood scenarios dike ring area 14

We examine the most probable flood scenarios as well as less probable but more extreme scenarios. When elaborating the three compartmentalization strategies for dike ring area 14, first, the locations of potential threat were identified. Given the fact that water can potentially enter from all sides of the dike ring, five dike breach locations were chosen that are on different sides of the dike ring. The western part of dike ring 14 borders the sea, and so the threat is formed by a storm surge at sea. The southern part is situated at the estuary, where both the river and the sea influence the water levels along the dikes, and so the threat is maximal when the river discharge is high at times of high water sea level. The northern and eastern dikes can fail after the water courses are fed by large incoming water volumes due to prior failure of water-retaining structures elsewhere, like storm surge barriers, sluices or primary dikes of other dike ring areas.

Three of the breach locations distinguished are at the coast, west of the dike ring area: Katwijk (northern breach location), Scheveningen (near The Hague) and Ter Heijde. With these breach locations, the attack from the sea has been researched, both through single-breach and through multiple-breach events. The multi-breach event is the same flood scenario as the so-called worst-case scenario considered by VNK (2005). Another breach location borders the river estuary in the south of the dike ring area, called Kralingen (near Rotterdam). In the north, the fifth breach location is at the North Sea Channel, near Haarlem. This breach will occur indirectly, after prior failure of the sluices of IJmuiden.

Sobek-rural of WL|Delft Hydraulics was used for the breach growth and 1D/2D flood calculation, together with the schematization of dike ring area 14 as applied in the study Flood Risk and Safety in the Netherlands (VNK, 2005). Seven flood scenarios (A–G) were formulated, based on the breach locations. Four of these scenarios have only one breach location. Two scenarios consist of, respectively, two and three breach locations. In the worst-case scenario of this research, the water runs into the dike ring area through all five of the breach locations. In the research, the breach conditions and the hydraulic preconditions remain the same for each flood scenario; only compartmentalization dikes are positioned in the dike ring area.

The number of victims, the number of casualties and the economic damage are calculated with the damage and victim module of the Flood Information System HIS-SSM (Kok *et al.*, 2005). In this article, we look at the victims, whereby a victim is a person who is present in the flooded area. The area is determined to be flooded by an inundation depth of 2 cm.

Elaboration of the three compartmentalization strategies

The three compartmentalization strategies have been elaborated using, whenever possible, existing line elements such as railway lines, roads, regional retaining structures and catch-water basins. These are present in the landscape, but have to be adapted for their new function as a compartmentalization dike. In order to perform a proper comparison between the strategies, we have assumed that the compartmentalization dikes are high and strong enough to retain the water. Given that an insight into the effects of various compartmentalization strategies was the objective of the research, no study has been carried out of economic and social feasibility.

The partition strategy was designed by positioning two dikes in the shape of a cross in the dike ring area (120 km altogether; see Table 1). The dike, constructed from east to west, consists of dikes along the Oude Rijn, which are currently being strengthened to function as a compartmentalization dike. For the double-hull strategy, line elements were sought that are situated as close as possible behind the primary retaining structures. The distance between the primary retaining structure and the compartmentalization dike differs and, at the same time, part of the dike runs through urban areas because some cities (such as The Hague and Rotterdam) are built directly up against the primary retaining structures. The length of the constructed dikes adds up to 194 km. For the value-protection strategy, it was chosen to provide extra protection for compact cities with about 100 000 inhabitants and Schiphol Airport as the

Table 1 Lengths of dikes to be constructed in the three compartmentalization strategies

	Partition	Double hull	Value protection
Total length of compartmentalization dikes (km)	120	200	250
Dike through urban area (km)	20	40	30
Adaptation of existing higher line elements (km)	100	110	100

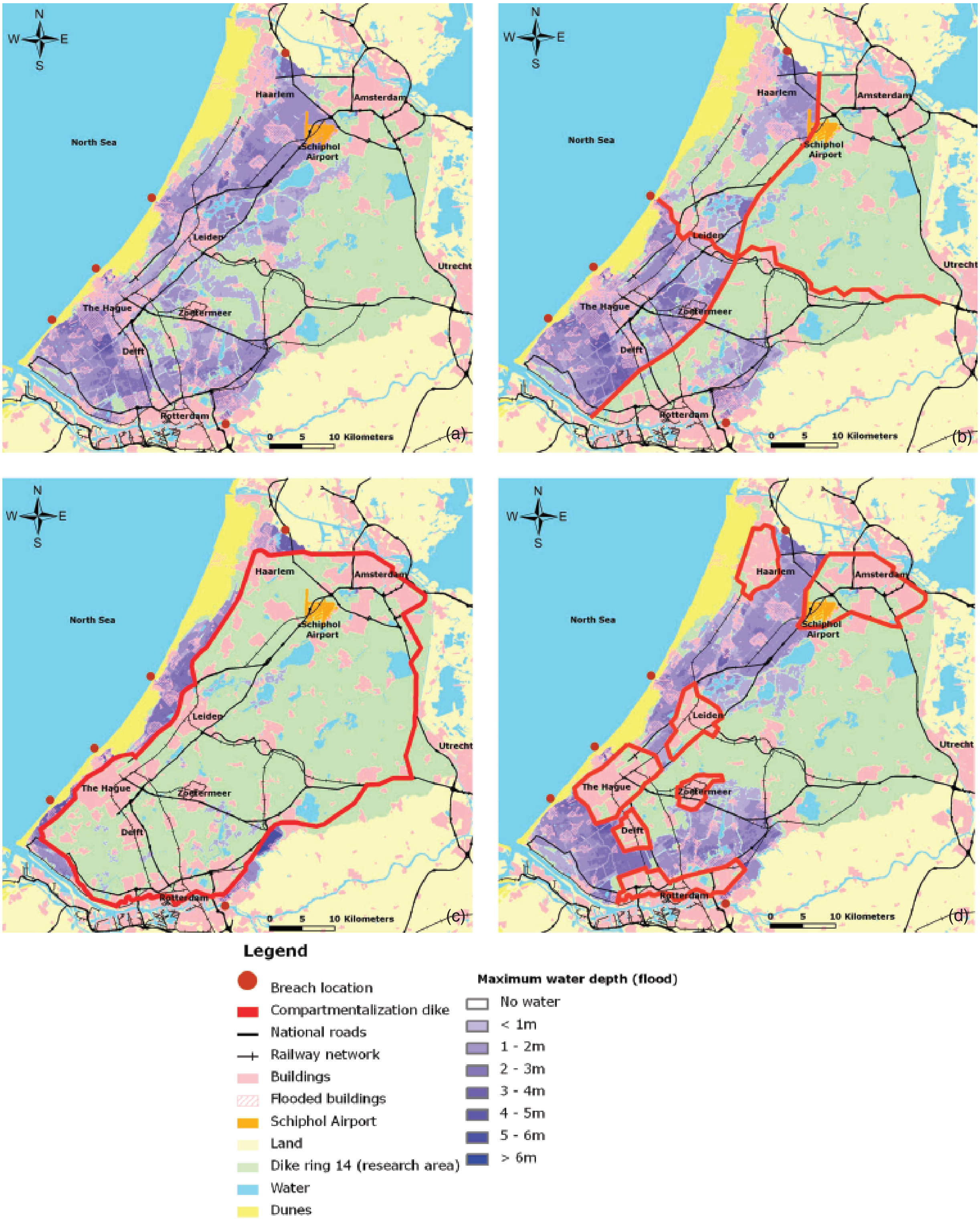

Figure 3 Maximum water depth in the worst-case scenario for the various compartmentalization strategies (red line); (a) the zero situation, (b) the partition strategy (c) the double-hull strategy and (d) the value protection strategy. The points show the breach locations.

Table 2 Total number of people affected in dike ring area 14 per flood scenario and compartmentalization strategy, with the percentages in regard to the zero situation

		Compartmentalization strategies (victims)			
Flood scenario	Breach location(s)	Zero situation	Partition	Double hull	Value protection
A	Scheveningen	207 000	208 000 (101%)	33 000 (16%)	33 000 (16%)
B	Kralingen	173 000	172 000 (99%)	62 000 (36%)	121 000 (70%)
C	Ter Heijde	664 000	498 000 (75%)	43 000 (7%)	251 000 (38%)
D	Haarlem	129 000	130 000 (101%)	70 000 (54%)	71 000 (55%)
E	Ter Heijde + Scheveningen + Katwijk	1 130 000	872 000 (77%)	168 000 (15%)	481 000 (43%)
F	Ter Heijde + Kralingen	791 000	682 000 (86%)	93 000 (12%)	311 000 (39%)
G	Ter Heijde + Scheveningen + Katwijk + Kralingen + Haarlem	1 372 000	1 171 000 (85%)	276 000 (20%)	565 000 (41%)

important economic centre. In the implementation of this strategy, dikes were positioned around urban areas, but some dikes also run through urban areas. For this strategy, a total of 247 km dike was constructed. This considerable length is also due to the fact that the people and economic value in dike ring area 14 are spread over a large number of centres, which resulted in many areas being ringed by a dike.

The costs of implementation are mainly dependent on the total length of the required compartmentalization dikes. The use of existing higher line elements in the landscape reduces the costs. Finally, dikes through urban areas are more costly than dikes through rural areas. The double-hull strategy relatively includes most dikes through urban areas (Table 1), due to the fact that many urban centres are built immediately behind the primary dike.

Results

The maps in Figure 3 show the maximum inundation depth per strategy in the worst-case scenario (scenario G). The flooded surface area differs per strategy. In the zero situation (without compartments), about 40% of the dike ring area is inundated. In the case of the partition and value-protection strategies, about 30% is inundated, while with the double-hull strategy, it amounts to only 10%.

The largest inundation depths are found in the old land reclamation sites: Haarlemmermeerpolder, Zuidplaspolder and Alexanderpolder. Water that enters at the breach in Katwijk or the North Sea Channel (near Haarlem) flows in the direction of the Haarlemmermeerpolder. Water that enters through the breaches in the southern part of the dike ring area flows towards the low-lying part near Rotterdam, which results in a stream running from the coast, from west to east. The inundation depths in the older (inner) cities, such as Haarlem, Delft and Leiden, remain relatively shallow and this also applies to parts of Amsterdam and Rotterdam. Because one of the breach locations is in The Hague, larger inundation depths occur locally but those in other parts of the city remain relatively shallow.

In the zero situation, the water spreads over a large section of the dike ring area, while in the double-hull strategy, the flooded surface is limited to the area directly behind the breach locations. This strategy shows the largest reduction of the flooded surface. The partition strategy shows a comparable flooded area as the value-protection strategy, but both strategies lead to a reduced flooded surface compared with the zero situation.

In the double-hull strategy, less water enters the area. Furthermore, in the partition strategy, it can be seen that the overland flow from the coast to the polders near Rotterdam is stopped. In the zero situation and the value-protection strategy, the water continues to flow into and through the dike ring area for > 10 days. In the double-hull strategy, the water stops flowing after about half a day, because the water level in the inundated area rises quickly. With this strategy relatively large water depths occur in the flooded area.

Table 2 provides an overview of the victims per compartmentalization strategy for each of the seven flood scenarios. The double-hull strategy results in the largest reduction: 46–93% (depending on the scenario) in relation to the zero situation. The value-protection strategy yields a reduction of 30–84%. The partition strategy is the least effective, with a reduction of at most 25% with respect to the zero situation. In the scenarios with multiple-breach locations (E–G), all compartmentalization strategies result in a decrease in the number of victims (Oost and Hoekstra, 2007).

It is interesting that the new compartmentalization dikes provide new elevations in the area, which result in new evacuation routes that could boost evacuation. The dikes also obstruct the water and more time is gained for the evacuation. However, at some place the water will rise quicker, which increases the probability of drowning.

Conclusions

In the research, three different compartmentalization strategies were introduced based on alternative dike configurations. Each strategy has its own effect on the overland water flow and the number of victims. The spatial layout of the area and the length of the compartmentalization dikes codetermine the effectiveness of the strategy.

For dike ring area 14, the double-hull strategy (constructing a second dike behind the primary dikes) is the compartmentalization strategy that mostly cushions the consequences of a flood in terms of victims. The value-protection strategy is less effective in decreasing the number of victims due to the widespread urbanization in the dike ring, which means that there are still many potential victims outside the protected most urbanized areas. Compared with the double-hull strategy, the value-protection strategy is also more costly in terms of the length of compartmentalization dikes to be constructed. However, the value-protection strategy could be an effective solution for dike ring areas with a highly concentrated value. The partition strategy is not really effective in a situation where the water can enter the dike ring area from all sides and whereby the water can still reach undesirable places. The positive side of the strategy, compared with the other two strategies, is that the dikes can be better fitted in the landscape.

An interesting follow-up research could be to determine the effect of a combination of compartmentalization strategies in a dike ring area. A combination could include the positive effects of the separate strategies. In the end, each dike ring area has its own characteristics and the compartmentalization strategy has to be adapted accordingly. A possible combination that has not been considered but that could be functional under certain conditions is a low secondary dike behind the primary dike plus lower partition or value-protection dikes in the landscape; the water will pass the lower dike, but it will take more time and the resulting water levels behind the secondary dike will probably be less.

Ultimately, the investment in compartmentalization dikes will have to be weighed against the long-term benefits, like shown by Leenders *et al.* (2007). In addition, comparisons will have to be made with other safety strategies such as investment in primary retaining structures, improved large-scale disaster and evacuation plans, local self-protection strategies, (partly) raising the land and the reallocation of investments to less vulnerable parts of the country.

A final observation is that the historical developments with respect to flood risk management strongly influence the attractiveness of various flood-risk mitigation options in the future. Wesselink (2007) describes the existing system of flood risk control in the Netherlands as a situation of technological and political lock-in, which means that it is difficult to deviate from the chosen focus on flood-probability control through primary dikes. Implementing a new, broader risk control strategy, including the concept of compartmentalization and possibly other options aimed at the reduction of flood damage rather than flood probability, will be difficult, because it requires large initial investments. Feasibility can be increased by aiming at a phased introduction over a few decades, so that the construction of new infrastructure can be included in regular spatial developments.

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