ASSESSING THE EFFECTS OF COMPARTMENTALISATION OF DIKE-RING AREAS ON THE AMOUNT OF ECONOMICAL DAMAGE AND THE NUMBER OF CASUALTIES RELATED TO A FLOOD FOR ICWFM-2007

Dr. Jakolien K. LEENDERS – HKV CONSULTANTS, The Netherlands, j.k.leenders@hkv.nl
Susanne M. GROOT M.Sc. – HKV CONSULTANTS, The Netherlands
Ir. Bas KOLEN – HKV CONSULTANTS, The Netherlands
Ir. Henk VAN HEMERT – STOWA, The Netherlands

ABSTRACT
Dike-ring areas in the Netherlands are protected from the sea, large rivers and lakes by primary dikes. Often the dike-rings are unintentionally compartmentalised by historical dikes, levees, roads and railway embankments. The effect of unintended compartmentalisation on the risk of flooding has not been assessed. A method to determine the effect of compartmentalisation on the flooding pattern and the consequences on economical damage and number of casualties is presented. This method is consistent with the standardisation method for the primary dikes and should facilitate decision-making. The flooding pattern is studied by means of 1D2D flood modelling in situations with and without a compartmentalisation dike. Economical damage in the different scenarios is compared and a cost-benefit analysis is done to test the feasibility of improving the compartmentalisation dike. It can be concluded that the feasibility of improving the dike depends among others on the location of the breach and size of the considered compartments. The effect of a compartmentalisation dike on economical damage and number of casualties in case of a flood can be opposite, e.g. it can prevent damage and cause casualties.
Keywords: compartmentalisation, flood modelling, cost-benefit analysis

1. INTRODUCTION

Since the Middle Ages the Dutch have been building dikes to reclaim land and to protect the land from floods and erosion. Due to subsidence, compaction, sea level rise and climate change, flooding is an ongoing threat. High water levels due to storm surges on the North Sea as well as high river discharges can cause flooding. At present, about 25 percent of the Netherlands lies below mean sea level and more than 65 percent of its area is protected from flooding by dunes, dikes or storm surge barriers (Ven, 2004).

A large part of the Netherlands suffered from a flood disaster in 1953. Whole dike-ring areas (areas surrounded by dikes) were flooded, about 2000 people died and many more lost their livelihood. This event led to the foundation of the Delta Committee, assigned to formulate a plan to protect the Netherlands from disaster floods. The Committee proposed large construction works, which would offer safety levels along the coast (Delta Commissie, 1960). Safety levels for the major rivers Rhine and Meuse were formulated in 1970 (Kok et al., 2005a). The assigned safety level of a dike depends on the impact of a flood and the difficulty with which the flood can be predicted. The safety level is expressed in terms of the return period of a high water level. In the low-lying, densely populated areas bordering the sea (where the impact level is high and floods are difficult to predict) a safety level of 1/4,000 to 1/10,000 per year is imposed, meaning the dikes are able to retain floods with a return period of 4,000 to 10,000 year. Along the major rivers the safety level is 1/1,250 per year.

Dike-rings in the Netherlands are often (unintentionally) compartmentalised by historical dikes. Examples are former sea dikes in accretion zones of the coastal area that have no longer a primary protective function. Roads, railway embankments and levees can cause unintended compartmentalisation as well. The impact of these dikes on the risk of flooding is controversial; economical damage and number of casualties are reduced in the area protected by the compartmentalisation dike, but may increase in the flooded compartment (e.g. Theunissen et al., 2006; Groot et al., 2006). This increase is due to the reduction of the flooded area by compartmentalisation, leading to an increase in maximum water depth and a higher rate of rise in water level. The effectiveness of unintended compartmentalisation by dikes, embankments and levees on the risk of flooding has not been assessed. At present, provincial authorities are to decide about the function of such compartmentalisation dikes within flood protection and disaster mitigation. A decision about intended compartmentalisation requires an assessment of the impact of the compartmentalisation dike on the flood pattern and consequences in terms of damage and casualties. On an assignment by STOWA (the Dutch Foundation for Applied Water Research), a study was carried out to develop a method to gain insight in the function and effectiveness of compartmentalising (Geerse et al., 2006). This method is consistent with the standardisation method for the primary dikes and should facilitate decision-making.

2. AIM AND APPROACH

This paper presents a method to determine the function and effectiveness of compartmentalisation dikes or other flood defences (e.g. river dikes or storm surge barriers). The following questions are answered:

- What effect has a compartmentalisation dike on the flooding pattern?
- What effect does a compartmentalisation dike have on economical damage and casualties resulting of a flood?
- Can compartmentalising be cost-effective?

These questions are addressed by 1) modelling floods for several scenarios; 2) determining the effect of compartmentalisation dikes on economical damage and number of casualties resulting of these floods and 3) assessing the feasibility of improvement of the compartmentalisation dike (cost-benefit analysis). This is done for three cases in different parts of the Netherlands (river and coastal areas) (Groot et al., 2006; Groot and Kolen, 2006; Groot and Kolen, 2007), of which the last mentioned is presented here.

3. MATERIALS AND METHODS

The study is done for compartmentalisation dike the ‘Maasdijk’, located in the west of the Netherlands, in the province of Zuid-Holland (Figure 1). The effect of the Maasdijk on the economical damage and number of casualties as caused by a flood are studied in several settings. Four floods of different return period (and thus different magnitude) are modelled in four different dike scenarios.

3.1 Study-site

The Maasdijk is located in a dike-ring (Figure 1) with a safety standard of 1/10,000 per year, as registered by law by the Ministry of Transport, Public Works and Water Management (TAW, 1998). The area of the dike-ring is about 2200 km^2, with about 4 million inhabitants. The average altitude is 1.3 metres below mean sea level. The Maasdijk is located in the south of the dike-ring and has a length of 15 km with an average height of 5.3 m above the land surface. The Maasdijk divides the dike-ring in two parts: a southern part of about 25 km^2 and a much larger northern part (which will not be flooded completely in the modelled floods). The number of inhabitants in the area around the Maasdijk that would be affected in case of flooding near the Maasdijk comprises 1.7 million.

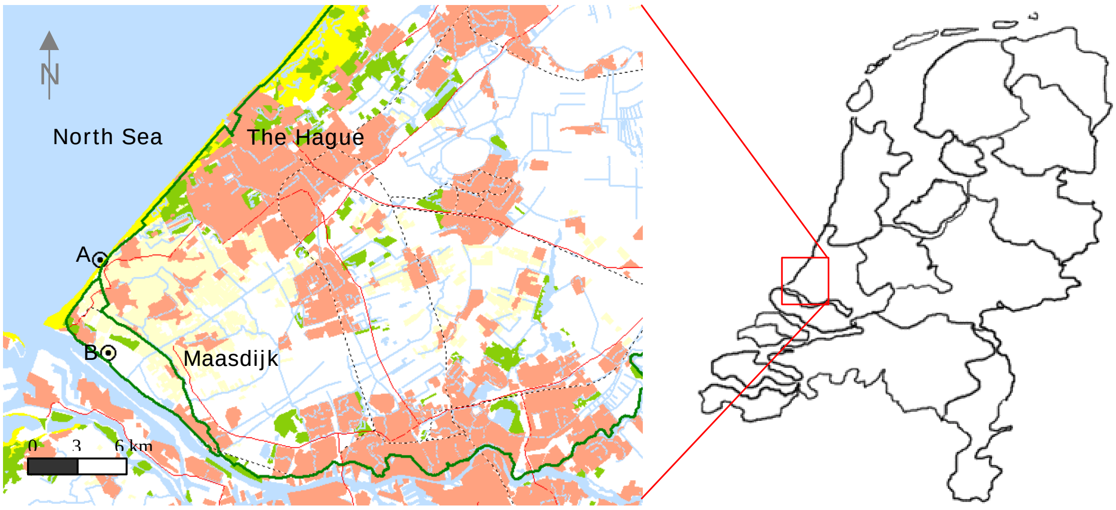


Figure 1 *Map of the part of the dike-ring in which the Maasdijk is located with the Maasdijk and the breach locations at which the primary dike is modelled to collapse (A and B) indicated*

3.2 Modelling of the flood

A 1D2D-SOBEK flow model of the dike-ring (Melisie and Blanker, 2005) is applied to determine the effect of the Maasdijk on the flooding pattern. In this model a one-dimensional (1D) channel-flow model is combined with a two-dimensional (2D) overland flow model, using the SOBEK software package. The 1D-flow model solves the continuity and momentum equation of Saint-Venant for the main channel flow. The flow in two dimensions is described by three equations: the continuity equation, the momentum equation for the x-direction and the momentum equation for the y-direction (SOBEK help, 2006). The 2D-flow model uses a Digital Elevation Model (DEM, 100 x 100 m) and a roughness grid of 100 x 100 m for the routing of water. The roughness values are related to land use, with grass, cultivated area, forest, water, nature, main roads, railways, and built-up area as distinguished land use types. An advantage of using a combination of 1D2D-flood models over a 2D-model is that structures such as bridges and weirs can explicitly be incorporated in the main channel domain. Werner (2005) showed that the 1D2D-modelling approach gives better results compared to 1D or 2D models.

The mechanism of failure at the breach locations in the primary dike is considered to be overflow. Overflow is considered dominant in the probability of flooding in other studies as well (Kok et al., 2005a). In this study, flooding resulting from two breach locations is modelled: one to the north of the Maasdijk, from the North Sea (A) and one to the south, from the estuary (B) (Figure 1). When the water level at the breach location reaches the water level related to the safety level of the primary dike, a breach starts to grow. Breach growth is modelled with the formula of Verheij-van der Knaap (Verheij, 2002). The breach is modelled to deepen from crest level to surface level in ten minutes, after which it widens. The rate of widening and the maximum width of the breach depend on the material of the dike and the difference in water levels on both sides of the dike.

The water levels that are input in the model at breach locations A and B are generated using probabilistic computer models that combine tidal effects with a storm (Figure 2). The return periods of the resulting storm surges range from 10,000 to 1,000,000 year (Table 1) to cover a wide spectrum of possible events. The maximum water levels in the storm surges vary from 5.20 m to 6.70 m above mean sea level at breach location A and from 5.18 m to 6.64 m above mean sea level at breach location B (Table 2).

Each of these storm surges is combined with a Maasdijk-scenario:
1. Situation in which the Maasdijk is absent;
2. Situation in which the Maasdijk has its present height (5.3 m above the land surface) and overflows, without causing a breach;
3. Situation in which the Maasdijk retains the flood (modelled with the Maasdijk at 99 m above mean sea level).

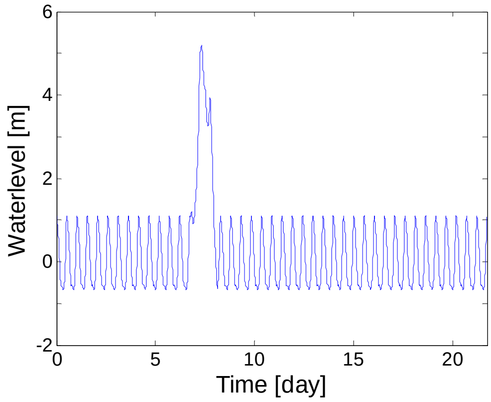


Figure 2 Water levels during a storm surge at breach location A, with a return period of 10,000 year

Storm surge	Return period (year)	Maximum water level at A (m +MSL)	Maximum water level at B (m +MSL)
1 (safety standard)	10,000	5.20	5.18
2	46,400	5.70	5.67
3	215,400	6.20	6.15
4	1,000,000	6.70	6.64

Table 1 Used storm surges, with their return period and maximum water level at breach locations A and B

3.3 Calculation of the economical damage and number of casualties

The results of the flood modelling are combined with data on land use and demography in HIS-SSM (Kok et al., 2005b) to study the effect of flooding on economical damage and number of casualties. The economical damage *S* (further referred to as damage) is calculated by:

$$S = \sum_{i=1}^{n} \alpha_i n_i S_i$$

where α_i is the 'damage factor' for category *i* , n_i the number of unities in category *i* and S_i the maximum damage per unity in category *i*. Each category (*i*) represents a land use type. The damage-factor α_i represents the effect of hydraulic conditions and is affected by the maximum water depth, rise in water level, flow velocity, a material factor and for built-up areas the type of buildings (Kok et al., 2005b). The maximum damage per unit in category *i* is derived from Briene et al. (2002). The discrepancy between the expected value of damage in HIS-SSM and the real damage is 10 – 20 % (Kok et al., 2005b).

The number of casualties is calculated by multiplying the number of inhabitants that is affected by the flood and cannot be saved by a factor. This factor depends on the maximum water depth, the rate of rise in water level and the flow velocity (Kok et al, 2005b). The possibility of evacuating people from the area that is being flooded or sheltering people in safe zones in the affected area, is not taken into account. Consequently, the number of casualties is overestimated and the analyses present worst-case scenarios.

The damage and number of casualties per storm surge are used to calculate a value of yearly expected damage and number of casualties. The yearly expected values result from risk calculations in which the amount of damage/number of casualties caused by a flood is related to the return period of that flood by:

$$YEV = \frac{1}{T_n} * S(T_n) + ... + \left(\frac{1}{T_2} - \frac{1}{T_1} \right) * \frac{S(T_2) + S(T_1)}{2}$$

in which *YEV* is the yearly expected value of damage or casualties, *T* the return period (in years) of the event and *S* either the damage or the number of casualties resulting of the flood with return period T_n.

3.4 Cost-benefit analysis

A cost-benefit analysis is done to study the cost-effectiveness of heightening the Maasdijk from its present height with 1 m. The latter situation is comparable to the situation of scenario 3. The costs in the analysis comprise the costs of heightening the Maasdijk with 1 m. These costs are calculated with a cost-module based on construction rates as provided by the Civil Engineering Division from the Directorate-General for Public Works and Water Management in the Netherlands. The benefits comprise the yearly expected damage that the heightened Maasdijk would prevent. The benefits are expressed as the difference between yearly expected damage of scenario 3, where the Maasdijk retains water, and scenario 2, where the Maasdijk overflows. This difference is expressed in present value over 50 years by correcting it for interest rate over a period of 50 years:

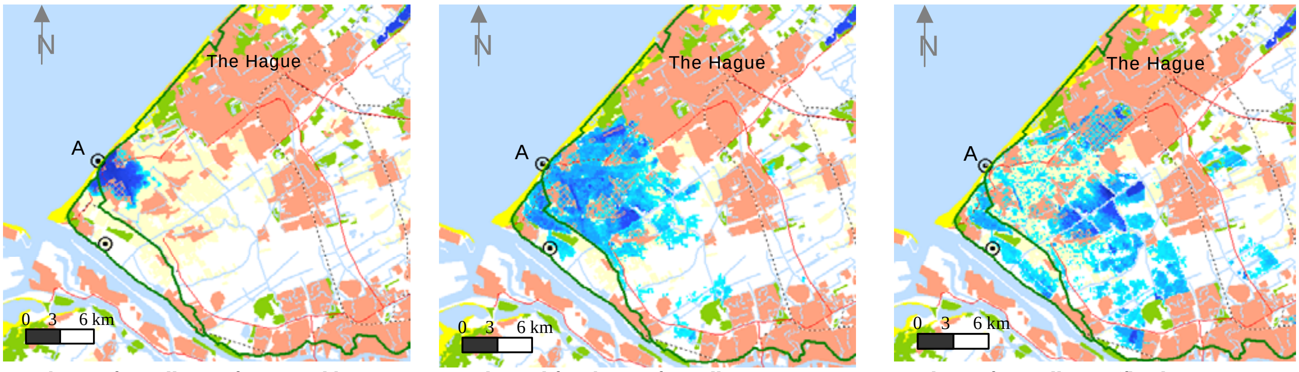
$$PV = V * \left(1 - \frac{1}{(1-r)^{50}} \right) * \frac{1}{r}$$

in which *PV* is the present value, V is the yearly expected value of damage and *r* is the interest rate (4 %).

4. RESULTS

4.1 Flooding pattern

An example of flooding from breach location A with the Maasdijk at its present height (scenario 2) is given in Figure 3. Within four hours after the formation of the breach in the primary dike, nearby villages are flooded. In just over a day, the flood has reached the city of The Hague. In six days the flood has reached its maximum extend (120 km^2) and part of The Hague is flooded. The northwestern part of the Maasdijk overflows so the southern compartment is flooded as well. The southern compartment would however be flooded faster and to greater water depths when the Maasdijk would be absent.

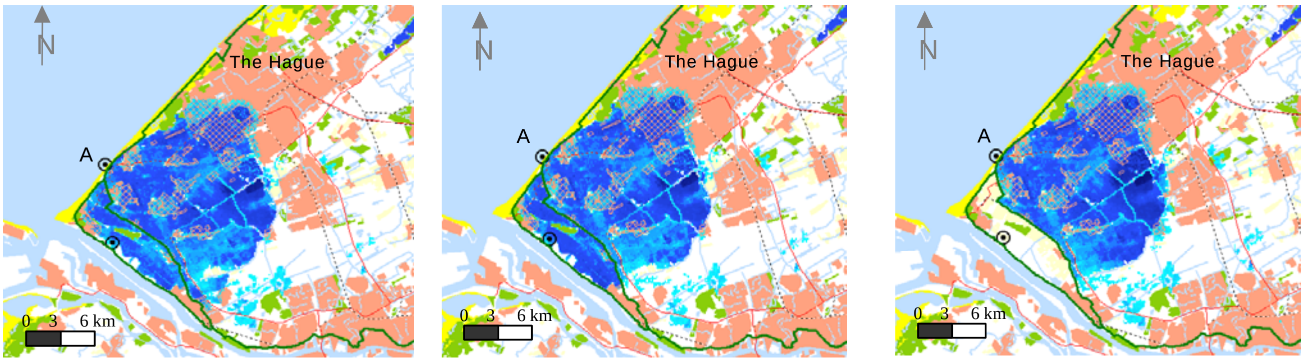


Four hours after collapse of primary dike | One day and four hours after collapse | Six days after collapse (flood at maximum extend)

water depth > 0.10 m
water depth = 1.50 m
water depth > 5.00 m

Figure 3 *Flooding scenario for a breach at location A with storm surge level 1 (Table 1). The Maasdijk scenario is scenario 2 (present height)*

In Figure 4 a flood from location A is shown in the scenario without the Maasdijk (scenario 1), the scenario with the Maasdijk at present height (scenario 2) and the scenario with the Maasdijk retaining the flood (scenario 3). Since the area is relatively flat, water can spread freely north and south of the breach when the Maasdijk is absent. In case the Maasdijk retains the flood, the water is forced to flow northwards in the direction of the city of The Hague. As can be seen in Figure 4, the differences in flooded area between the three scenarios are relatively small. The water depths however do differ; in scenario 1 the water depths are generally lower than in scenario 2 and 3.



Scenario 1 (without Maasdijk) | Scenario 2 (Maasdijk at present height) | Scenario 3 (Maasdijk retains the flood)

water depth > 0.10 m
water depth = 1.50 m
water depth > 5.00 m

Figure 4 *Flooding scenario one day after collapse of the primary dike in the three Maasdijk scenarios, for a breach at location A with storm surge level 4 (Table 1)*

As the return period of the storm surge increases the flooded area, the maximum water depth and the rate of water level rise, increase within each scenario (Figure 3 and 4). The flooding pattern for a breach at location A differs from the flooding pattern for a breach at location B, especially for the scenarios in which the Maasdijk is present (scenario 3 and 2). When the Maasdijk retains the flood (scenario 3), only the compartment in which the breach is located is flooded. Therefore the flooded area is much smaller for a breach at location B. When the Maasdijk is at its present height, a breach at location B will still result in a much smaller flooded area than a breach at location A, because only the northwestern part of the Maasdijk overflows.

4.2 Economical damage and number of casualties

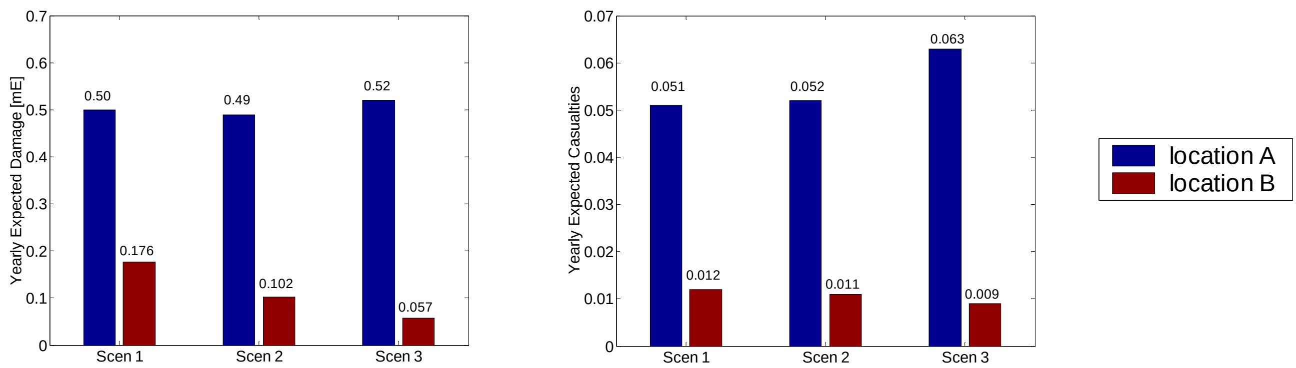
The damage and number of casualties increase as the return period of the storm surge increases. This is because the flooded area is larger, the maximum water depth is larger and the rise in water level increases faster. The effect on the number of casualties is stronger than the effect on damage (Table 2), i.e. an increase in flooded area, maximum water depth and rise of the water level have a stronger effect on the number of casualties than on the damage. In the northern compartment the maximum damage and number of casualties is much larger than in the southern compartment (up to 10 times as large). This is related to the large size of the northern compartment (Figure 1), where water can flow and spread broadly.

Breach location	Return period (per year)	Damage (millions of Euro)			Number of casualties (persons)		
		North	South	Total	North	South	Total
A	10,000	3,247	0	3,247	303	0	303
A	46,416	5,760	0	5,760	654	0	654
A	215,443	8,101	0	8,101	1,315	0	1,315
A	1,000,000	11,270	0	11,270	2,459	0	2,459
B	10,000	0	378	378	0	18	18
B	46,416	0	637	637	0	68	68
B	215,443	0	825	825	0	276	276
B	1,000,000	0	1,156	1,156	0	962	962

Table 2 *Damage and number of casualties for four storm surges for the Maasdijk which retains the flood (scenario 3)*

The total yearly expected values of damage and casualties for both breach locations are shown in Figure 5. The total yearly expected values of damage and number of casualties are higher for a breach at location A than for a breach at location B. For a breach at location A the damage and number of casualties are highest when the Maasdijk retains the flood (scenario 3). The damage is lowest when the Maasdijk is at present height (scenario 2); the number of casualties is lowest when the Maasdijk is absent (scenario 1). For a breach at location B this is different: the economical damage and number of casualties are highest when the Maasdijk is absent and lowest when the Maasdijk retains the flood.

For a breach at location B the flooded area is limited when the Maasdijk is present, resulting in less damage and number of casualties compared to a breach at location A. When the Maasdijk is present, for a breach at location A the water depth in the city of The Hague is larger than in case the Maasdijk is absent (Figure 4). Consequently, the damage that results in the city is higher when the Maasdijk is present.



I II

Figure 5 *Yearly expected damage (I) and number of casualties (II) for a breach at location A and B.*

The results show the importance of the breach location for the determination of the effectiveness of the Maasdijk with respect to economical damage and number of casualties resulting of a flood. Figure 5 clearly shows the positive effect on damage and casualties the Maasdijk has for a breach at location B, and the negative effect it has for a breach at location A.

4.3 Cost-benefit analysis

For a breach at location A and a Maasdijk retaining the flood (scenario 3), the yearly expected damage is 0.52 m€. For the Maasdijk in its present state (scenario 2) the yearly expected damage is 0.49 m€ (Figure 5). As such, heightening of the Maasdijk is not feasible for a breach at location A.

For a breach at location B the Maasdijk does prevent damage in case it is higher than present, the yearly expected damage is

- 0.057 (PV = 1.2 m€) in scenario 3
- 0.102 (PV = 2.2 m€) in scenario 2

When expressing this in a present value (PV) over 50 years, the benefits of the higher Maasdijk comprise 1 million €.

When the Maasdijk is heightened 1 m over its full length the function of the Maasdijk is equivalent to that in scenario 3. The costs for heightening the Maasdijk with 1 m are 22 million €. This means that heightening the Maasdijk 1m is not feasible (costs > benefits).

5. DISCUSSION AND CONCLUSIONS

In this study it is shown that a compartmentalisation dike can have a significant effect on the area that is being flooded and consequently on the damage and number of casualties that result of a flood. Whether the effect is positive or negative depends among others on the breach location, the size of the compartment in which the breach is located and the land use of the flooded area. Factors like heights of other dikes, height of the hinterland and slope of the dike-ring are also important for the flooding pattern (and consequently the damage and number of casualties). For example, when the compartmentalisation dike is higher than the primary dike, the lower primary dike marginalises the effects of the compartmentalisation; water will overflow the primary dike before it overflows the compartmentalisation dike. Or, when the area slopes away from the compartmentalisation dike, the load on the dike will not be severe, as the water will flow away from the dike (Groot et al., 2006)

The effects of a compartmentalisation dike on damage and number of casualties as a result of flooding can either be positive or negative. Due to the presence of a compartmentalisation dike the damage and number of casualties can be diminished (e.g. this study, breach at location B). However, a compartmentalisation dike can also increase damage and number of casualties (e.g. this study, breach at location A) or diminish damage and at the same time increase number of casualties (Groot and Kolen, 2007).

For the simulations of the Maasdijk the effect of compartmentalisation is especially visible for a breach at location B. The effect on damage and number of casualties for a breach at location A is relatively small, because of the flooding of the city of The Hague. When the Maasdijk is at its present height, the damage and number of casualties is even higher than if the Maasdijk is absent. The presence of the Maasdijk results in a larger water depth in the city of The Hague. Consequently the damage and number of casualties in the city of The Hague increase compared to the situation where the Maasdijk is absent. To protect the city of The Hague from a flood, it is advisable to construct an extra compartmentalisation dike just south of The Hague. It can be concluded that the presence of built-up areas and the population density in the flooded compartment are important for the effect of the compartmentalisation dike on the total damage and number of casualties in case of flooding.

The cost-benefit analysis for the Maasdijk showed that the costs of heightening the Maasdijk outweigh the benefits of prevented damage. This is partly related to the high safety level of the primary dike (1/10,000 per year), meaning high water levels when it overflows. In situations with lower safety levels (1/4,000 per year), compartmentalisation is more feasible. Especially in coastal areas, where the restricted duration of the storm surge results in less extreme hydraulic boundary conditions (waterlevel and wave height) within the compartment, the costs and benefits are more in balance (e.g Groot and Kolen, 2007). In these situations, a relatively low compartmentalisation dike can withstand the flood. A coastal defence strategy based on compartmentalisation has been applied in the Netherlands in the past, and is applied at present in vulnerable areas in northern Vietnam (Hemert, 2003). However, although a compartmentalisation can be cost-effective, the number of casualties resulting from a flood can increase because of the presence of the compartmentalisation dike (Theunissen et al., 2006; Groot and Kolen, 2007). This contradiction demands carefully balanced decisions on measures such as compartmentalisation, on a case-by-case basis.

This study shows that flood modelling using a 1D2D modelling approach in a dike ring and combining it with HIS-SSM and a cost-benefit analysis is applicable to determine the function and effectiveness of compartmentalisation dikes. The method provides policy makers with a tool to consider the economical effects of heightening a dike. Costs and benefits can be considered separately and can be balanced with the investments in safety. As such the method facilitates decision-making. The presented method can be applied for other flood defences (e.g. river dikes or storm surge barriers) as well. It can also be applied to determine the optimal locations and dimensions for compartmentalisation dikes or other flood defences (as is illustrated for The Hague). For areas where the availability of records on land use and topography is limited, remote-sensing images can be used to obtain the height and land use information needed as input for the 2D model and HIS-SSM.

The method is concluded to be valid for the purpose of study. There are, however, a number of opportunities for improvement. In our simulation one mechanism of failure is considered, whereas in reality many other mechanisms are possible as well (Kok et al, 2005a). Incorporating this in the flood model expands the possibilities and enlarges the representation of reality. Evacuation strategies can be taken into account in determining the number of casualties.

7. REFERENCES

Briene, M., Koppert, S., Koopman, A., Verkennis, A.,(2002). Financiële onderbouwing kengetallen hoogwaterschade. NEI, Rotterdam, The Netherland, 77 pp.

Delta Commissie (1960). Rapport van de Delta Commissie, Deel 1. The Hague, the Netherlands, 176 pp.

Geerse, C., Stijnen, J., Kolen, B. (2006). Leidraad normering compartimneteringdijken –Eerste aanzet. HKV Lijn in water, Lelystad, the Netherlands, 25 pp.

Groot, S., Kolen, B., Leenders, J. (2006). Uitwerking showcase bovenrivieren, Meidijk. HKV lijn in water, Lelystad, the Netherlands, 29 pp.

Groot, S., Kolen, B. (2006). Uitwerking showcase benedenrivieren, Maasdijk. HKV lijn in water, Lelystad, the Netherlands, 21 pp.

Groot, S., Kolen, B. (2007). Uitwerking showcase kust, Middeldijk. HKV lijn in water, Lelystad, the Netherlands, 27 pp.

Hemert, H. van (2003). Vietnam Netherlands Integrated Coastal Zone Management -project, final report Nam Dinh pilot project. Dutch Min. of Foreign Affairs., Nam Dinh City, Vietnam, 92 pp.

Kok M., Silva, W., Slomp, R., Stijnen, J.W. (2005a). River management and flood risk reduction using structural measures and disaster management for the Rhine river in the Netherlands. Proceedings of the International symposium on stochstic hydraulics 2005. Nijmegen, the Netherlands.

Kok, M., Huizinga, H.J., Vrouwenvelder, A.C.W.M., Braak, W.E.W., van den (2005b) Standaard methode 2005, Schade en Slachtoffers als gevolg van overstromingen. HKV Lijn in water, Lelystad, the Netherlands, 53 pp.

Melisie, E.J., Blanker, J.P.G., (2006). Veiligheid Nederland in Kaart, Risico-case dijkring 14 Zuid-Holland, berekening van het overstromingsscenario. Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands, 94 pp.

TAW, Technische Adviescommissie voor de Waterkeringen (1998). Grondslagen voor Waterkeren, Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands, 169 pp.

Theunissen, R., Kok, M., Vrijling. H. (2006). Compartimentering van dijkringen: niet altijd dé oplossing. H_2O, Vol. 21, 29-31.

SOBEK help (2006), SOBEK-RURAL version 2.10.003

Ven, G.P. van de (ED) (2004). Man-made lowlands, History of water management and land reclamation in the Netherlands. International commission on irrigation and drainage (ICID). Utrecht, the Netherlands, 432 pp.

Verheij, H.J. (2002): Modification breach growth model in HIS-OM; WL | Delft Hydraulics, Q3299, November 2002 (in Dutch).

Werner, M. (2005). Spatial flood extent modelling – a performance based comparison. PhD-thesis, Delft University Press, Delft, The Netherlands, 176 pp.