River management and flood risk reduction using structural measures and disaster management for the Rhine river in the Netherlands

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ABSTRACT: Without flood defences much of the Netherlands would be flooded (from the sea or the river) on a regular basis. Along the full length of the Rhine branches and along parts of the river Meuse protection against river flooding is needed. These flood defences mainly consist of dikes. The Dutch government recently proposed to extend river management by flood disaster management strategies. Examples of flood disaster management are flood storage areas which can be used in case of extreme high water levels. The spatial planning of such areas has caused many discussions in society and the scientific community. The scientific discussions concentrate on the reduction the probability of flooding and the economic costs and benefits of these measures. In this paper we present a probabilistic method to assess the flood risk reduction of alternative flood disaster strategies. In this method we include the natural variability of water levels and wind generated waves, as well as knowledge uncertainties with respect to river behaviour and dike failure. The flood risk reduction of 8 alternative strategies is assessed. Using estimates of the economic flood damage, the expected yearly economic benefits are assessed. By comparing these benefits with the costs the strategies are ranked according to (i) their ability to reduce the expected flood risk and (ii) the benefit/cost ratio. In this ranking method we take into account the uncertainties of the impacts of the strategies.

1. INTRODUCTION

The Netherlands are situated in the delta of four rivers: the Rhine, the Meuse, the Scheldt and the Eems. As a result of this, the country has developed into an important, densely populated nation. But living in the Netherlands is not without risks. Large parts of the Netherlands are below mean sea level or below water levels, which may occur on the rivers Rhine and Meuse. High water levels due to storm surges on the North Sea, or due to high discharges of these rivers are a serious threat to the low-lying part of the Netherlands. Proper construction, management and maintenance of flood defenses are essential to the population and further development of the country. Without flood defenses much of the Netherlands would be flooded on a regular basis. The influence of the sea will mainly be felt in the West. The influence of the sea decreases where sea arms have been closed-off, or where flood defenses such as sea dikes or storm-surge barriers have been constructed. Along the full length of the Rhine and along parts of the Meuse protection against flooding is provided by dikes. For an overview of the current safety standards along the coast and major rivers, see for example Figure 2 (Brinkhuis-Jak et al, 2003).

2. FLOOD RISK MANAGEMENT

The current safety standards have been established after the 1953 flood disaster, where almost 2000 people died. After the flood, safety standards along the coast had been proposed by the Delta Committee (Delta Committee, 1960). The safety levels along the major rivers were introduced in 1970. The current water defenses are designed in such a way, that they can withstand water levels with an exceedance frequency of 1/1250 per year. In 1985 a method was devised to determine the required freeboard for wave run-up (TAW, 1985).

In figure 1 we show the area under consideration, with the rivers Rhine and Meuse. It can be clearly seen that the Dutch part of the river basin of the Rhine is studied. The dike-ring areas in the Netherlands are also shown.

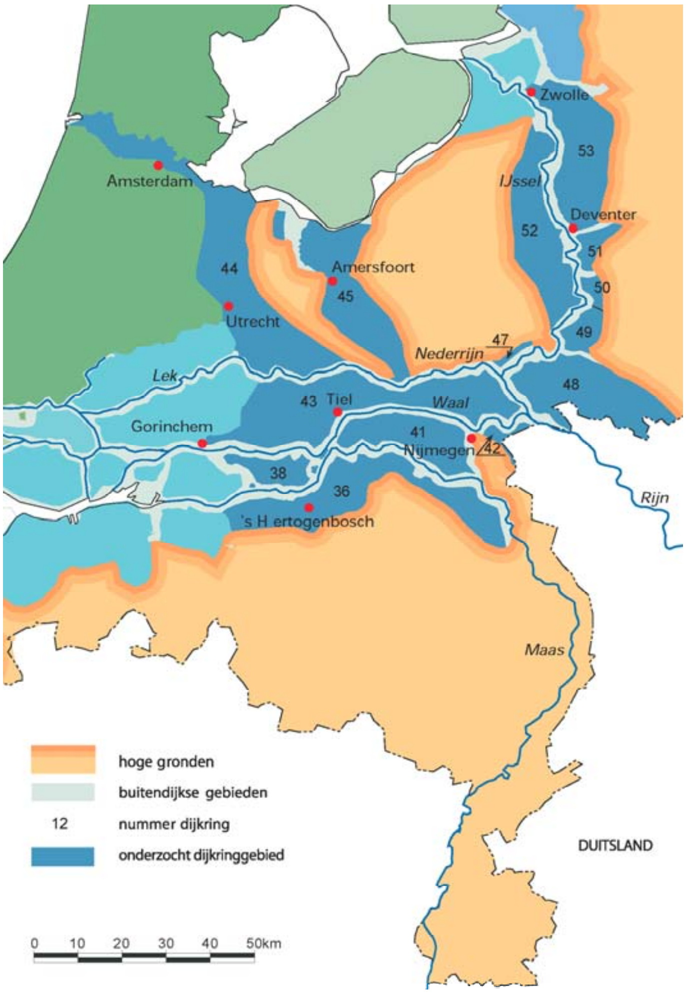

Figure 1. Overview of the study area (dark blue), and the dike-ring area areas. The safety standard of the investigated dike-ring areas is 1/1250 per year.

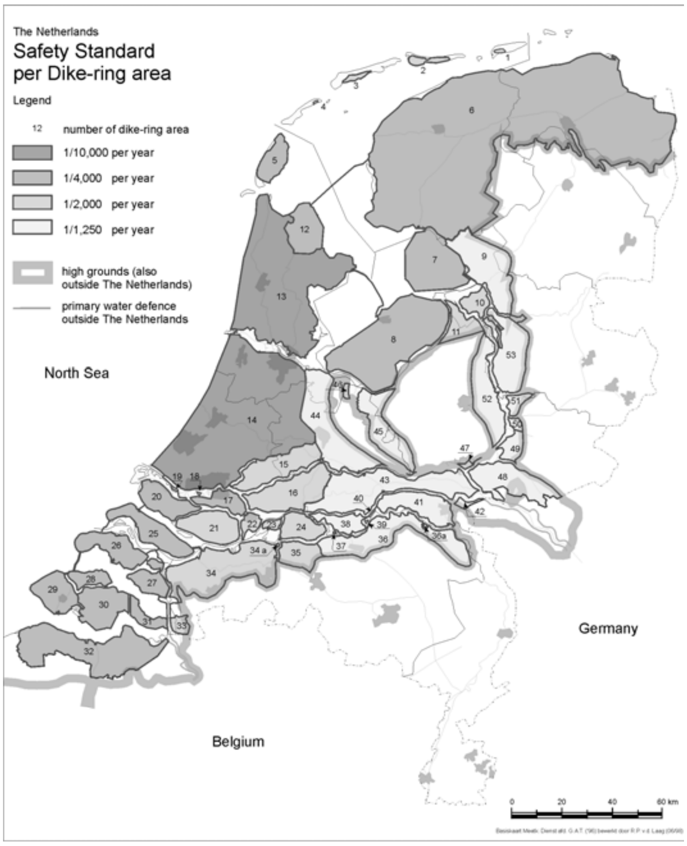

Figure 2. Dikering areas in the Netherlands

The definition of a dike-ring area is: the area that will be flooded after failure of a part of the dike-ring area. A dike-ring area can be small or big, and that is a result of the physical characteristics of the system and of decisions by the authorities (for example: new compartment dikes can be build to create new dike-ring areas). An overview of the dike-rings in the Netherlands is given in figure 2.

It is shown that the safety standards (the probability of exceeding the design water levels) are much smaller along the coast (1/4000 to 1/10000 per year) than along the major rivers (1/1250 per year). The reason is that floods along the coast have a higher impact and are more difficult to predict. The transition area's in between have an exceedance probability of 1/2000 per year, and are located along the rivers. These areas are threatened by high discharges, impeded drainage to the sea and storm surges which build up behind the storm surge barriers. These areas are not covered in this paper.

The Rhine and Meuse rivers have different characteristics. We name the important ones:

1. The design discharge of the Rhine (16000 m^3/s) is much higher than the design discharge of the Meuse (3800 m^3/s). The exceedance probability of the design discharge is 1/1250 per year;
2. There are more changes to the (shape of the) flood wave along the Meuse than along the river Rhine. This is caused by lateral inflows and large flood plains. The shape of the peak of the flood wave also depends on the duration of the flood. This means that, given the design discharge, the relative uncertainty along the Meuse is much higher than the along the Rhine;
3. The water levels on the Meuse are affected heavily by rainfall river and therefore reacts much faster than the Rhine. This also means there is a shorter lead time for flood warnings (about 12 hours).

The Northern Rhine Branch, the IJssel, is somewhat similar to the Meuse. It is characterized by large lateral inflows and a relatively large flood plain.

A typical cross section of the Rhine is given in Figure 3.

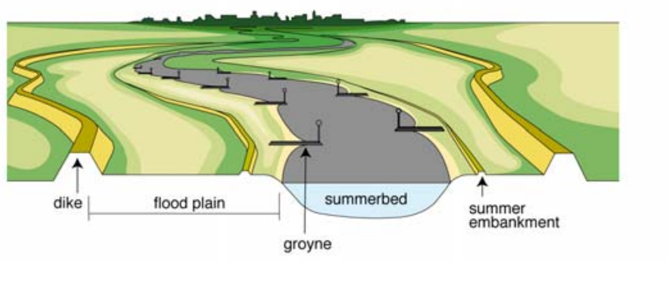

Figure 3. Typical cross section of the Dutch rivers

3. OBJECTIVE OF THE STUDY

The objective of this study is to assess the impact of disaster management strategies and structural measures strategies which aim to reduce the flood risks along the Dutch rivers.

Examples of measures in a disaster management strategy are the use of sandbags or flood retention areas ("controlled flooding" instead of "uncontrolled flooding").

In this paper we will follow the standard approach in decision analysis. This means that the relevant impacts of strategies are assessed, such as the economic costs and benefits. We make a distinction between

a. "disaster management" measures which aim to reduce the impact of flooding, and
b. "structural' measures which aim to increase the safety against flooding with structural measures.

Because of the differences between the Meuse and the Rhine, and differences between the various Rhine Branches there may be differences in the "optimal" mix of structural and disaster management measures.

More details about the background and results of the research are given in (Kok et al, 2003).

4. METHODOLOGY

The methodology is described in (Stijnen et al, 2002) and (Kok et al, 2003). The core of the approach is the calculation of the probability of flooding of the dike-ring areas. The calculation of this probability is not an easy problem, since a dike-ring area has many sections (which might be interdependent) and many structures. Moreover, a dike-ring area may fail due to one of many failure mechanisms (such as overtopping of the flood defense, piping, loss of stability, etc). For an overview of the methods to compute the flooding probability we refer to (Vrouwenvelder et al, 1998). In our research we used a simplified method to calculate the flooding probability (Stijnen et al, 2002; Kok et al, 2003).

1. We investigated only one failure mechanism: overflow and wave overtopping. Other mechanisms (for example sliding of the inner slope, piping and micro instability, see TAW, 1998) are not included. These mechanisms may be important, but in the study (TAW, 2001) it is concluded that overflow and wave overtopping is the dominant mechanism in the probability of flooding, assuming that the possible "weak spots" are strengthened;
2. In the assessment of flood defenses it is useful to distinguish between failure and collapse of a structure. Failure is defined as not fulfilling one or more water defense functions (the crest of part of the flood defense is too low, for example). Collapse means the loss of cohesion or large deformations in geometry. In this paper we only handle failure of the water defense.
3. The state (failure) function Z of the failure mechanism wave overtopping is: $Z = q_c - Q(H_s, h)$ where q_c stands for the critical overtopping discharge (which may be stochastic, but in this paper we will assume that it has a deterministic value of 0.001 $m^3/s/m$, which is equivalent to 1 l/s/m), H_s is the wave height and h is the water level.

In the computations we used the following random variables and distributions:

1. The discharge, with actual statistics from the exceedance frequency line of the discharge peak according to (Parmet et al, 2002).
2. The wind direction, with actual statistics for the measurement station of Schiphol Airport (Geerse et al, 2002).
3. The wind speed, with actual exceedance probabilities for the measurement station of Schiphol Airport (Geerse et al, 2002).
4. Water levels, where a normal distribution is assumed. This is a result from uncertainties around the river bifurcation points, the geometry, hydraulic roughness and lateral inflow (Stijnen et al, 2002). In Figure 4 an example is given of the uncertainties in measured water levels, given the discharge at Lobith (where the river Rhine enters the Netherlands).
5. For each dike-ring area a number of "critical" locations has been selected, largely based on wind fetches. The number depends on the length of the dike-ring area. On average, 8 to 10 locations were selected. Data for each location was selected, using among others a GIS-information of the Dutch rivers. The flooding probability of the dike-ring area is equal to the maximum of the probabilities of each location.

The computations to solve the failure function can be made with numerical integration, FORM, SORM, crude Monte Carlo or Directional Sampling. Detailed information about these methods can be found in (Vrouwenvelder, 2001) and (Vrijling & Van Gelder, 2002). In the current research we have a limited number of random variables and we used Numerical Integration as the technique to calculate the probabilities (Stijnen et al, 2002).

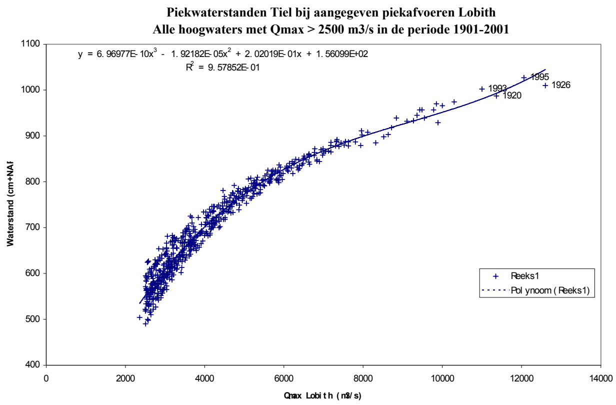

Figure 4. Example of uncertainty in QH-relation: measured water levels and measured discharge (source: Van Vuren, 2003).

The flood damage was calculated using a flood damage assessment model. In this model we assumed a simple hydrodynamic scenario: the breach is situated at the most upstream part of the dike-ring area area and the maximum water level is bounded by the lowest dike section in the area. It is verified that there is enough water available to flood the complete dike-ring area area. In the economic assessment model the materialistic damage and the economic damage of companies has been included. Results of the approach are given in Table 1.

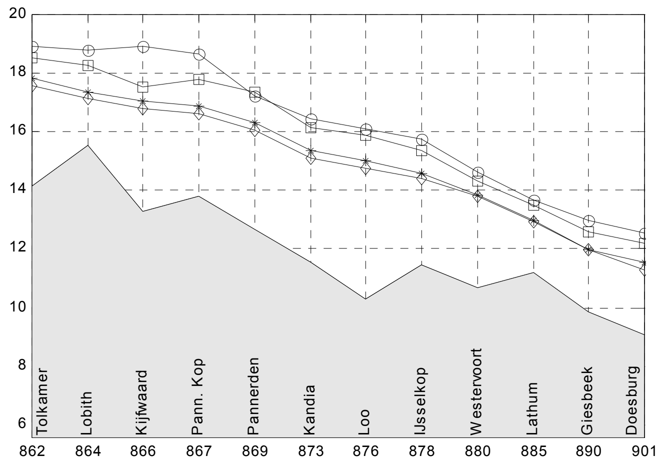

Figure 5. Graphical overview of selection of available data in dike-ring area 48. The Design Water Levels are also shown for two different years. It can be seen that these levels have increased for 2006.

In the analysis we calculated for each dike-ring area i the expected yearly economic damage d_i by calculating the economic damage D_i with the flooding probability of dike-ring area p_i:

$$d_i = p_i * D_i \,.$$

In order to compare the expected annual economic damage with investment costs we calculate the Present Value. We use the symbol □ to denote the yearly discount factor and γ the yearly economic growth. The Present Value PV_i of the expected yearly economic damage of dike-ring area area i is:

$$PV_i = \sum_{t=1}^{T} d_i (1+\gamma)^t \Big/ (1+\delta)^t$$

In this equation T is the planning horizon. If $T = \infty$ we have the following expression for PV (assuming that $\gamma < \delta$):

$$PV_i = d_i \Big/ (\delta - \gamma)$$

We assume that $\delta = 0,04$ and $\gamma = 0,02$. With $T = \infty$ we find:

$$PV_i = 50 * d_i$$

The benefits of an alternative is the reduction in the present value of the alternative compared to the reference alternative.

Dike-ring area area (number and name)	Damage (10^9 €)
36 Land van Heusden / Maaskant	17.6
38 Bommelerwaard	2.5
41 Land van Maas en Waal	7.9
42 Ooij en Millingen	0.9
43 Betuwe/ Tieler en Culemborgerwaarden	16.4
44 Kromme Rijn	30.8
45 Gelderse Vallei	8.2
47 Arnhemse en Velpsebroek	0.9
48 Rijn en IJssel	5.5
49 Ijsselland	0.7
50 Zutphen	1.7
51 Gorssel	0.5
52 Oost-Veluwe	3.1
53 Salland	7.9
Total	104.6

Table 1. Overview of economic damage (in prices 2001). The number of the dike-ring area areas are given in figures 1 and 2. (source: Holterman, 2003)

In Table 1 we present the damage of the individual dike-ring areas. However, if we want to assess the benefits of measures we have to take into account the dependencies between the dike-ring areas. If for example, there is a breach in one of the dike-ring areas, the probability is decreased that one of the other dike-ring area areas downstream will be flooded as well. This is a difficult probabilistic problem, and it was not possible to solve this problem in a scientific way within the current research project. Therefore, we followed a more pragmatic approach, which was also be followed by (Walker et al, 1995). We add the benefits of all the individual dike areas, which gives us an “upper bound” for the benefits. The “lower bound” is given by the benefits of one of the dike-ring areas, because it might be argued that if one of these dike-ring areas is flooded all others might be saved (because the water levels will decrease downstream of the breach). For pragmatic reasons we will assume the 'lowerbound' to be 10% of the sum of the benefits. As 'upperbound' we use 50% of the sum of the damages. As 'middle value' we use 25% of the sum of all the individual dike-ring areas. By doing this we obtain an interval of possible benefits of the alternatives.

The costs of the measures are assessed by a global design of the measure and default cost per unit (length, m^3, m^2, …).

In the study we assessed the qualitative impact of the alternatives on spatial quality, potential victims, social acceptance and flexibility. These impacts are assessed by subjective judgments, and are not shown in this paper. We refer again to (Kok et al, 2003).

5. SET OF MEASURES

Many measures are possible to reduce the flood risks. An overview of structural measures is given in Figure 6. The measures can be spatially tuned: in some parts of the river system the floodplains can be lowered, and in other parts it may be better to widen the floodplain. This depends on the decision criteria, for example the costs and the benefits (for example the impact on nature and landscape).

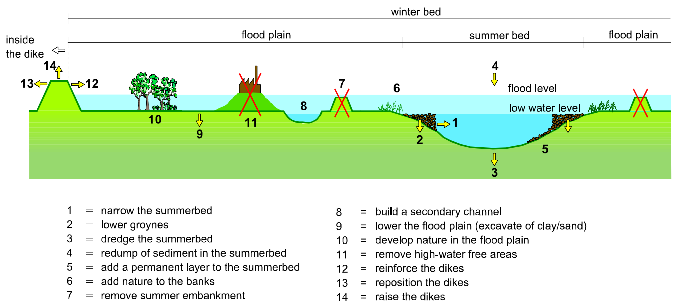

Figure 6. Set of possible measures

In this study we assessed the impact of the following alternatives:

1	Reference alternative
Disaster	*management*
2A	Retention areas according to report of Committee (with protection measures to protect the villages)
2B	Retention areas without protection measures and without inlet
2C	Flood Retention areas with a simple inlet
2D	Maximal use of sand bags and other emergency measures
2E	Real time control barrier at the bifurcation points in the Rhine branches (Arnold et al, 2005)
Structural	*measures*
3A.	Room for the River. In (Kok et al, 2003) four alternatives are assessed (minimal costs, spatial measures according to preferences of province Gelderland, maximal spatial quality and changed discharge distribution at the bifurcation points. In this paper we present the results of the alternative with 'minimal costs'.
3B	Dike heightening. In (Kok et al, 2003) an alternative is given with changed discharge distribution at the bifurcation points.
3C	Part of the flood defenses designed as overflow flood defense
3D	Compartmentalization of dike-ring area 43 (along the Amsterdam-Rhine Canal)

In (Kok et al, 2003) "combination alternatives" are investigated as well, but the impacts of these alternatives are not presented in this paper.

6. RESULTS

The flood probabilities for the reference alternative are given in Table 2. The reference situation is not the present situation, but it is assumed that the flood defenses follow the standards as set by the Flood Defense Law (see figure 2). These standards are exceedance probabilities of water levels, and not flooding probabilities. Flooding probabilities can be higher than these exceedance probabilities, because of the uncertainties of for example water levels used in the calculation of flood probabilities. However, flooding frequencies might also be lower than the safety standards, because the flood defenses are designed with certain 'safety factors'. For example, the flood defense is designed with a minimal freeboard of at least 0,5 m than the Design Water Level at the base of the dike, or with a freeboard equal to the wave run-up height calculated at design wind speeds.

Dike-ring area	**Flooding probability**

Dijkring 48: Rijn en IJssel	1 / 1100
Dijkring 42: Ooij en Millingen	1 / 1700
Dijkring 41: Land van Maas en Waal	1 / 1500
Dijkring 43: Betuwe, Tieler- en Culemborgerw	1 / 1100
Dijkring 38: Bommelerwaard	1 / 1700
Dijkring 44: Kromme Rijn	1 / 1400
Dijkring 45: Gelderse Vallei	1 / 1600
Dijkring 47: Arnhemse- en Velpsebroek	1 / 1150
Dijkring 49: IJsselland	1 / 900
Dijkring 50: Zutphen	1 / 1000
Dijkring 51: Gorssel	1 / 1000
Dijkring 52: Oost-Veluwe	1 / 700
Dijkring 53: Salland	1 / 850

Table 2. Overview of flooding probability in the reference alternative.

The benefits of the alternatives are given in Table 2. These benefits are given for all investigated dike-ring areas are given in Table 3. Because of the interdependencies between the dike-ring areas we cannot add the benefits of each dike-ring area separately. As explained in section 4 we present a "lower bound", "upper bound" and the "middle value".

The Present Value of the expected flood damage in the reference alternative is equal to $1.120\square10^6$ € (middle value, the lower bound is: $450\square10^6$ € and the upper bound is $2.240\square10^6$ €). From an economical point of view these amounts are the maximum investment and maintenance costs which can be justified, if the flood risk would be zero after the investment. This is practically not possible (there will always be a flood probability > 0). In the calculations for the risk *reduction* of the flood damage in the alternatives we use the flood damage in the reference alternative as reference.

The results show that in alternative 2B "Retention areas without protection measures and without inlet" the Present Value of the flood damage increases compared to the reference alternative. This is because the uncontrolled inflow will result in a lot of damage downstream. This damage is higher than the damage in the reference alternative because (1) retention areas are used more frequently than "uncontrolled" flood events, and (2) the retention areas are quite small and they are sloped, so that downstream dike areas will be flooded as well. From the table it can be concluded that the disaster management alternatives can reduce the flood risk, but the reduction is 10-20% of the total risk. The structural measures "Room for the river" and "Dike heightening" can reduce 70-80% of the total flood risks, and the other investigated structural measures, such as construction of dikes or dike sections resistant to overtopping and overflow and compartmentalization along the Amsterdam-Rhine Canal, reduce the expected damage with 30% and 10% respectively.

	Alternative	Flood risk reduction [10^6 €]

		L	M	U
1	Reference alternative			
	Disaster management			
2A	Retention areas according to report of Committee (with protection measures to protect the villages)	70	170	350
2B	Retention areas without protection measures and without inlet	-560	-90	-690
2C	Retention areas with a simple inlet	30	130	310
2D	Maximal use of sand bags and other emergency measures	-	-	-
2E	Real time control barrier at the bifurcation points in the Rhine branches (Arnold et al, 2005)	60	130	270
	Structural measures			
3A	Room for the River. Alternative with 'minimal costs'.	350	870	1740
3B	Dike heightening.	300	750	1510
3C	Part of the flood defenses designed as overflow flood defense	140	350	690
3D	Compartmentalization of dike-ring area 43 (along the Amsterdam-Rijn Canal)	40	100	190

Table 3. Present Value of flood risk reduction of the alternatives compared with the reference alternative. L: Lower bound; M: Middle value; U: Upper bound.

The costs of the alternatives are given in Table 4. These cost are rough estimates but they indicate the order of magnitude.

In Table 4 we also included the benefit-cost ratio. If this ratio is bigger than 1, than the benefits are higher than the costs. If it is lower than 1, than the costs are lower than the benefits. From this table we can conclude that most of the alternatives are attractive from an economical point of view.

From Table 4 we see that Room for the River has by far the highest costs. Even though the benefits are the largest of all alternatives, the benefit/cost ratio of this alternative is not very high. Dike heightening and the alternative of retention areas according to the report of the Committee are also very costly. Retention areas with a simple inlet on the other hand are not very expensive, and still have considerable effect on the flooding probabilities. The benefit/cost ratio in this case is the largest of all alternatives. The other alternatives are in between.

	Alternative	Costs 10^6 €	Benefit/cost ratio

1	Reference alternative		
	Disaster management		
2A	Retention areas according to report of Committee (with protection measures for the villages)	440	0,4
2B	Retention areas without protection measures and without inlet	0	
2C	Retention areas with a simple inlet	2	65
2D	Maximal use of sand bags and other emergency measures	85	
2E	Real time control barrier at the bifurcation points in the Rhine branches (Arnold et al, 2005)	60	2,1
	Structural measures		
3A.	Room for the River. Alternative with 'minimal costs'.	2870	0,3
3B	Dike heightening.	610	1,2
3C	Part of the flood defenses designed as overflow flood defense	90	4,9
3D	Compartmentalization of dike-ring area 43 (along the Amsterdam-Rijn Canal)	70	1,4

Table 4. Cost estimates of the alternatives and cost/benefit ratio (using the middle value of the flood risk reduction)

7. SENSITIVITY ANALYSIS

In this study many assumptions were made. We carried out a sensitivity analysis in order to investigate the influence of the most critical assumptions

Sensitivity	Average flood probability	Present value of flood risk 10^6 €
Reference	1/1000	1120
Wave overtopping discharge of 10 l/m/s	1/1500	700
Actual dike height	1/2200	480
Only half the freeboard is used to turn water levels	1/750	1380
Exceedance frequencies of water levels	1/1250	870
Reduction in uncertainty water levels	1/1200	940
Uncertainty cost estimates: upper-bound	1/1000	2240
Uncertainty cost estimates: lower-bound	1/1000	450

Table 5. Summary of results of the sensitivity analysis

In this project we choose the following variables:

a. Critical wave overtopping discharge of 10 l/m/s in stead of 1 l/m/s
b. Actual dike height in stead of design dikes
c. The freeboard may not be used to turn all water levels
d. Exceedance frequencies of water levels instead of flood probabilities
e. Uncertainties in water levels
f. Uncertainties in cost estimates and flood damage

In Table 5 we show the impact of the sensitivities in the average flooding probability and in the Present value of the expected flood risk. In Figures 7 and 8 we show the results of both the percentage of risk reduction as well as the benefit/cost ratio for each of the alternatives.

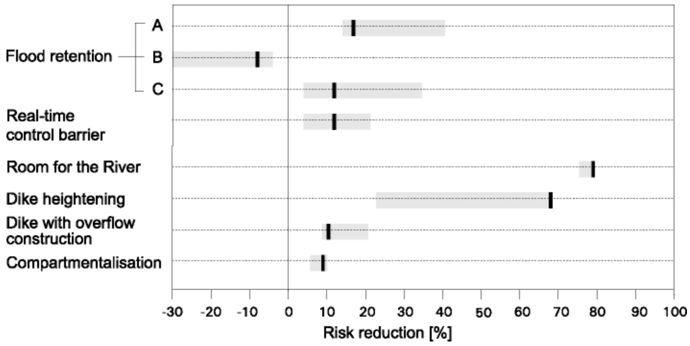

Figure 7. Overview of risk reduction per alternative

The results in Figure 7 are a graphical representation of the results of Tables 4 and 5. The black vertical bars represent the values as presented in Table 4, based on the middle value of the flood risk reduction. The gray bars indicate the sensitivity of each alternative to the assumptions that were made. As long as the risk reduction remains positive, the alternative has a positive effect on the flooding probability. This means that based on the assumptions, the black vertical bar may shift anywhere within the bounds of the gray bar.

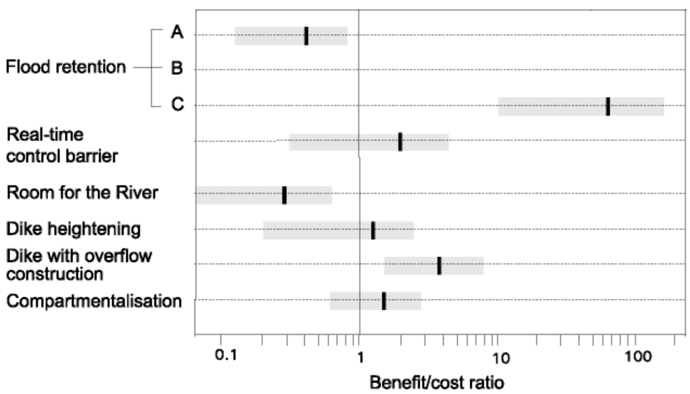

Figure 8 Overview of benefit-cost ratio per alternative

Again, the black vertical bars represent the values as presented in Table 4 and 5, based on the middle value of the flood risk reduction. The gray bars indicate the sensitivity of each alternative to the assumptions that were made. When the benefit/cost ratio is equal to one, the benefit and costs are balanced.

When the ration is larger than one, the benefits outweigh the cost.

CONCLUSIONS

In this study alternatives for flood disaster management have been evaluated based on their effectiveness (in the light of the other relevant design conditions), as well as a cost-benefit analysis (based on costs versus avoided damage). Results are presented in terms of risk reduction factors and cost-benefit ratios, both based on reductions in flooding probabilities.

The main conclusions from the study are the following:

1. Without exception we can say that strategies that increase the discharge capacity of the river system, such as heightening of the dikes, or enlargement of the floodplain, score very high in terms of flood-risk reduction. In comparison, the use of emergency flood-retention reservoirs scores much lower, with (A in Figures 4 and 5) or without (B/C in Figures 4 and 5) possible protection measures or inlet structures.
2. When looking at the benefit-cost ratio on the other hand, it is obvious that structural measures are characterized by high costs (ratios around or even below 1), while emergency flood retention areas with a simple enhancement such as an inlet construction, or some protective dikes, score very well.
3. It would seem beneficial to use the positive effects of the structural measures on a more local scale, specifically in combination with other disaster management strategies. Combinations of alternatives could prove to be both efficient and cost effective. This is currently being investigated in an ongoing research project, in which costs are considered in much more detail as well.
4. Other alternatives to emergency flood storage, such as the reduction of damage potential through the construction of compartments, or a real-time control barrier near the bifurcation points in the Rhine river, show positive results both in terms of flood risk reduction and in terms of benefit-cost ratios.

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