Integrated approach on the safety of dikes along the Great Dutch Lakes

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Abstract

Two great lakes of approximately 1000 km² exist in the Netherlands surrounded by low lying land. Under extreme events storm surges of 2-3 m can be expected with significant wave heights up to 3 m. The question to answer was to what extent, under extreme conditions, the situations around the two lakes are comparable with situations along the sea coast. And whether or not the dikes along these lakes should give similar safety against flooding. An integrated approach was followed based on risk analysis. The study contained the following parts: hydraulic boundary conditions, probabilistic calculations on required dike heights, cost estimates on possible dike improvements, damage due to flooding and risk analysis on inundation. The main conclusion is that the two lakes have a similar behaviour with respect to risk of flooding which is also comparable with estuaries and other areas along the sea coast.

Introduction

Dikes protect the hinterland from flooding by storm surges from the sea or by high river discharges. Both situations are well known in low-lying countries and safety in the Netherlands relies heavily on reliable, strong dikes. On the basis of risk analysis, including both the probability of failure and the effects of flooding, it has been decided that such dikes in The Netherlands must be strong enough to withstand very extreme events with return periods up to 1/10,000 years. Compared to breakwaters, for example, this is two orders of magnitude higher and such events are difficult to imagine.

A sea such as the North Sea, can create high storm surges and high waves against coastal defences. But large lakes can also generate storm surges and waves, particularly in the case of the extreme events already mentioned.

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Two great lakes exist in The Netherlands which both were part of the North Sea system before 1932. They were created at that time by closing the estuary with a dike (the Afsluit dike). Both lakes are only separated by a dam in between. The IJsselmeer ("meer" means lake) has a surface of about 1200 km^2 and the Markermeer about 750 km^2, see Figure 1.

Under extreme events, storm surges of 2-3 m can be expected with significant wave heights up to 3 m. Although not as severe as situations along the North Sea coast, it is comparable. Furthermore, some areas behind the dikes lie more than 4 m below the mean lake level. The differences between the two lakes are that a river flows into the IJsselmeer and that this lake can directly sluice water into the Norh Sea, which is not the case for the Markermeer.

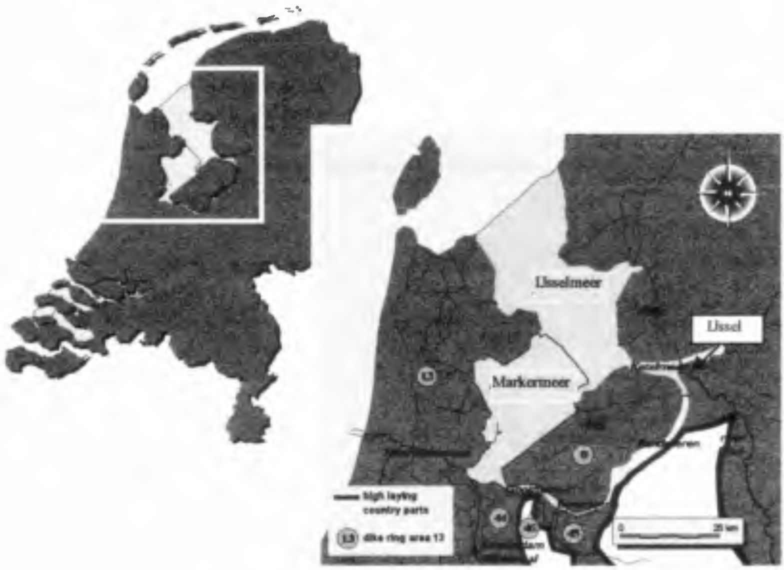

Figure 1. Study area

The question has arisen, both in Dutch Parliament and elsewhere, as to what extent the situations around the two great lakes under very extreme conditions are comparable with situations along the sea coast under similar conditions. And whether the dikes along these lakes should provide similar safety against flooding. An extensive study was performed by Delft Hydraulics, as an independent consultant, to give insight into the problem. An integrated approach was followed based on the concept of risk analysis. A full account of the study results is given in 15 reports by Delft Hydraulics, see the reference list. The study contained the following parts:

- hydraulic boundary conditions
- cost estimates on possible dike improvements
- damage due to flooding
- risk analysis on inundation
- integration of technical and legal aspects

Only the hydraulic boundary conditions with effects on safety and dike heights, the damage due to flooding and the risk analysis are treated in this paper. The problem in more detail can be defined as follows:

- are IJsselmeer and Markermeer comparable with respect to safety?
    - what will be the influence of a better control on the lake level of the Markermeer (the river IJssel flows into the IJsselmeer which gives less control)
    - what will be the difference in flood damage if the same areas are flooded by IJsselmeer or Markermeer
    - what will be the difference in risk of flooding
- is risk of flooding from the lakes comparable to sea coast areas?

Hydraulic boundary conditions: lake levels

A run-off model was first made of the entire lake system, calibrated using 20 years of measurements. The free parameters in the calibration were the control parameters of the sluices. Therefore, the calibration was carried out on management of the two lakes, because this determines the lake levels. A longer period of measurements for calibration than 20 years was not possible as the dike that separates the Markermeer and IJsselmeer was constructed in 1976. Data before 1976 was available, but then for one large and not separated IJsselmeer. Actually, data from the closure of the northern Afsluit dike in 1932 and onwards was available, resulting in more than 60 years of measurements.

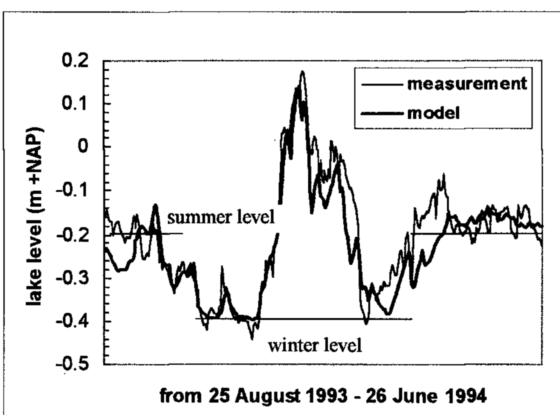

Figure 2. Example of calibration of the run-off model for the Markermeer for the winter of 1993-1994

A result of the calibration for the Markermeer is given in Figure 2 for the winter of 1993-1994. In that winter high lake levels occurred in December and January. The peak is fairly well predicted. In summer the lake level will be maintained at –0.2 m NAP and in winter the lake level is lowered to –0.4 m NAP. Here, NAP is a national level. It is, however, more difficult to control the level in winter than in summer, which can also be concluded from Figure 2. This is caused by heavier rainfall, storms and higher discharges of the river IJssel in winter than in summer. The peak in December 1993 was the highest in the 20 years of measurements.

After calibration, data before 1976 was used to run the model and to predict lake levels for the two lakes. The maxima were then used to determine a statistical distribution based on 60 years. These distributions were then extrapolated to give predictions for events with return periods up to 1 in 10,000 years, by statistical methods which are also used to predict extreme river run-off.

Similar calculations were made for various scenarios like sea level rise or climate change, increase of pump or sluice capacity into the North Sea, partly reclaiming the Markermeer and a modified control of the sluices between IJsselmeer and Markermeer. Finally, all calculations resulted in three possible lake level statistics for each of the two lakes. These statistics are shown in Figures 3 and 4. The middle curves give the present situation and the highest curves include climate change. The lowest curves give the effect of double pump or sluice capacity into the North Sea.

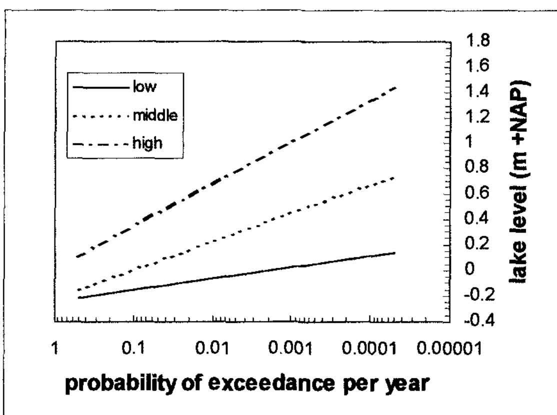

Figure 3. Three possible (extrapolated) lake level distributions for the Markermeer

A modified control of the sluices between IJsselmeer and Markermeer gives also the lowest line in Figure 3. This modified control means that, if due to the river IJssel the lake level in the IJsselmeer increases, the sluices to the Markermeer will be closed and that, therefore, the Markermeer will not be influenced by a high level in the IJsselmeer (which may increase the lake level in the IJsselmeer, however). The highest lines in Figures 3 and 4 are comparable. The lowest line in Figure 3 is much lower than the one in Figure 4.

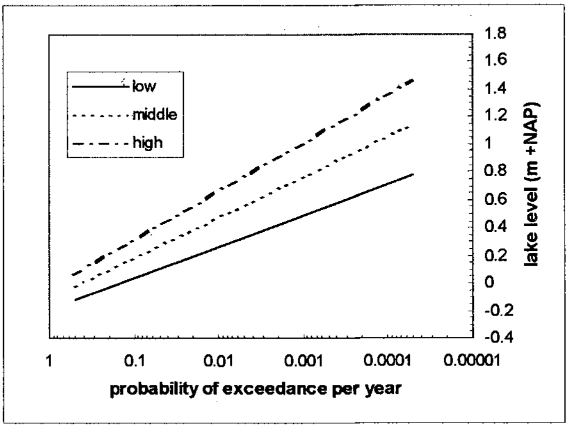

Figure 4. Three possible (extrapolated) lake level distributions for the IJsselmeer

Based on Figures 3 and 4 the following conclusions about extreme lake levels were derived:

- the river IJssel determines mainly the lake level of the IJsselmeer
- the sluice control between the IJsselmeer and Markermeer during high lake levels in the IJsselmeer determines the lake level in the Markermeer:
  - if the sluices stay open, the Markermeer level will follow the IJsselmeer level
  - if the sluices are closed, the Markermeer level will stay low

in principal the Markermeer level is better manageable than that of the IJsselmeer. But what will be the effect on safety of the dikes?

Hydraulic boundary conditions: extreme storms

Storms generate surges and waves and the dikes should withstand these conditions. Flow and wave height calculations were performed with DELFT-3D (in the 2DH mode), the integrated modelling system developed by Delft Hydraulics. These calculations result in storm surge levels and wave heights, periods and directions at more than 1000 locations along the lakes' dikes.

In total 216 calculations were performed covering the following conditions:

- lake levels of –0.4 m, +0.3 m and +1.3 m NAP
- 12 wind directions, each covering a sector of 30°
- 6 wind velocities, from 15 m/s up to 42 m/s

All data of the calculations and for the more than 1000 locations along the lakes' dikes was stored in a data management system and used for further analysis. Figure 5 gives an example of a calculation with DELFT-3D for the Markermeer. The condition given is a very extreme one: a lake level of +1.3 m NAP, combined with a wind velocity of 42 m/s from 330°. Figure 5 shows the storm surge levels. The highest levels occur in the south-east part where the levels may exceed +4 m NAP. The joint probability of this lake level and wind velocity is so small, however, that it is not a realistic situation for the Markermeer. These conditions were the upper boundary of the set of conditions given above.

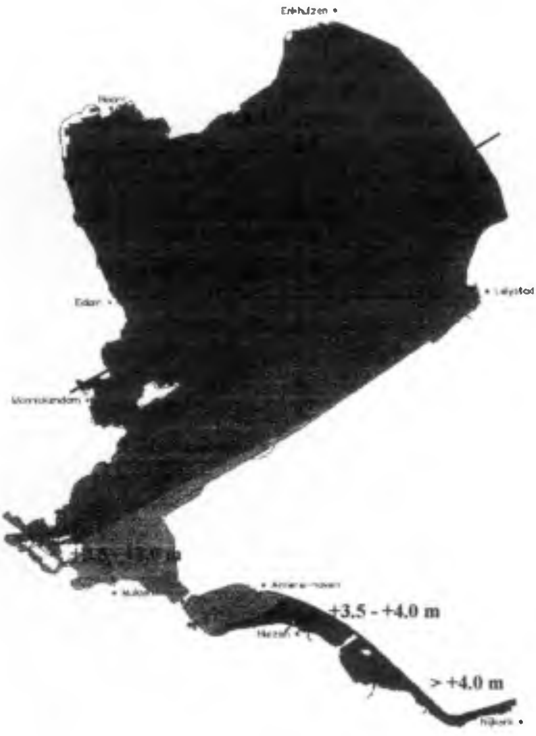

Figure 5. Calculation of storm surge levels in the Markermeer for a lake level +1.3 m NAP and a wind velocity of 42 m/s from 330°

<u>Probabilistic calculations on required dike heights</u>

The long-term statistics of the water levels (Figures 3 and 4) and the data management system on storm surge levels and waves were input for full probabilistic calculations of expected wave run-up or wave overtopping. The model includes also the long-term wind statistics (and through the data management system its effects in surges and waves).

The locations with the hydraulic boundary conditions from the data management system, however, were chosen about 400 m from the dike. Very often the foreshore leads to shallower water at the toe of the dike. And the wave conditions at this toe are required to make the right calculations on required dike height. If the water depth at the toe was different from the location from the data management system, calculations were performed to establish the required conditions.

With these boundary conditions, calculations on wave run-up or wave overtopping were performed according to Van der Meer and Janssen (1995). All these calculations were integrated in the full probabilistic model. With the long-term lake level and wind statistics, the conditions from the data management system, the geometry of the foreshore and the dike itself, a Riemann integration was performed to give the required dike height for a given safety level of say 1 in 10,000 years.

Comparison of the two lakes

Calculations with the full probabilistic model were performed to compare required and existing dike heights and to establish necessary improvements. Other calculations were made in order to compare the IJsselmeer with the Markermeer and to investigate possible essential differences. Figure 6 shows in each of the lakes 15 locations. Locations with the same numbers (for example M01 in the Markermeer and IJ01 in the IJsselmeer) have more or less a similar location in the lake and have also the same orientation of the dike.

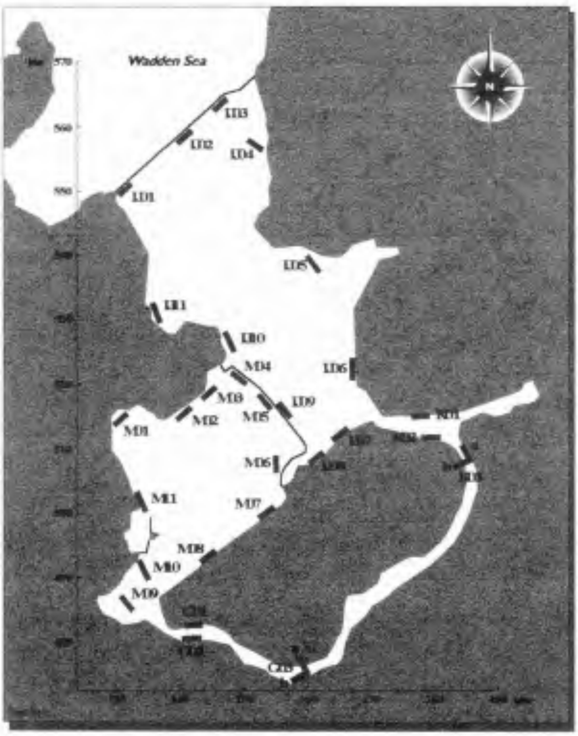

Figure 6. IJsselmeer and Markermeer with similar locations for comparison

Calculations were made for a “standard” dike with a smooth slope of 1:4 and without a foreshore. The required dike heights at all locations were determined for the 2%-wave run-up level as governing condition and for a safety level of 1 in 10,000 years. These calculations were performed for all three lake level statistics given in

Figures 3 and 4. The results are shown in Figures 7 and 8 for Markermeer and IJsselmeer, respectively. The low, middle and high points of the legend correspond with the curves in Figures 3 and 4.

The conclusion on the influence of the long-term lake level statistics on required dike heights becomes very clear from Figures 7 and 8. There is hardly any influence as most of the three lake level statistics give the same required dike height, except for a few, more sheltered, locations.

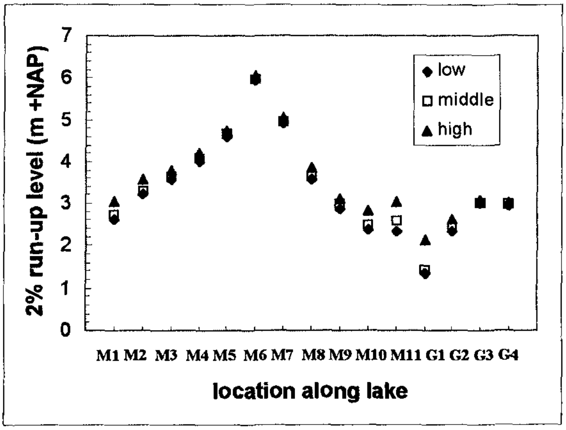

Figure 7. Required dike heights for locations in the Markermeer given in Figure 6 and for 3 long-term lake level statistics given in Figure 3

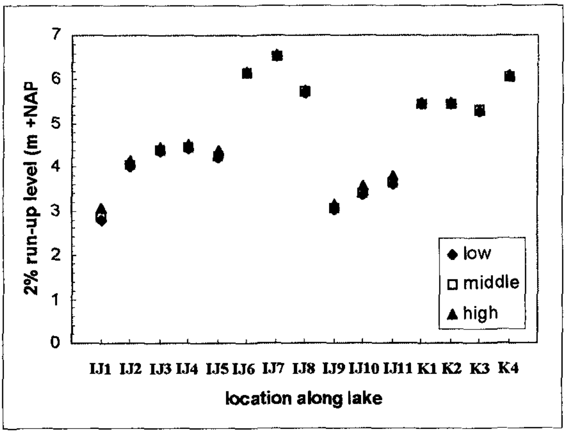

Figure 8. Required dike heights for locations in the IJselmeer given in Figure 6 and for 3 long-term lake level statistics given in Figure 4

The reason why the long-term lake level statistics have hardly influence on required dikes heights, is that extreme lake levels and extreme storms are independent events. A (very) strong wind with a level close to the winter level of –0.4 m NAP has a larger probability of occurrence, than a less strong wind with a much higher lake level to give the same required dike height. In fact very strong wind governs the required dike height and not the long-term lake level statistics. This means also that the lake level control of the Markermeer has no or only marginal influence on dike safety. From that point of view the Markermeer and IJsselmeer are comparable.

Possible damage due to flooding

There are two areas that can be flooded by both the IJsselmeer and the Markermeer, see Figure 9. One area is just north of the separating dike and the other just south. An in-depth study was made of the expected damage in the two areas. The main goal was to investigate the influence that the difference in lake size has on damage. The areas were divided in smaller areas with similar bottom levels. With a simple inundation model the maximum water depth after flooding was calculated for each of these areas.

Figure 9. Two areas that can be flooded by both lakes

A large number of damage categories were used to calculate the total damage. Each category had a given relationship between inundation depth and damage. A few of the damage categories were: agriculture, cattle breeding, horticulture, urban area, recreation, roads, houses, transport, etc. Also a category victims due to drowning was used. The expected damage and the expected number of victims for the southern area (Flevoland) is given in Table 1. Flevoland is one of the polders reclaimed from the lake and the depth is more or less equal to the old bottom of the IJsselmeer which is about –4 m NAP.

Flevoland	flooding from Markermeer	flooding from IJsselmeer	ratio IJM/MM
economic damage (billions guilders)	5.8	6.9	1.2
victims (number)	119	355	3.0

Table 1. Expected economic damage and number of victims by flooding of Flevoland

The damage by flooding from the IJsselmeer is a little larger than from the Markermeer. The reason is that the Markermeer in size is about 2/3 of the IJsselmeer, giving inundation depths that are approximately 0.5 m smaller. Inundation depths in average will be about 2.2 m to 3.3 m. Although the figures for the Markemeer are a little lower, the order of magnitude is the same. A similar conclusion was drawn for the northern area in Figure 9. This means that also from the point of view of damage due to flooding, both lakes are comparable.

Risk analysis on inundation

Dikes in the Netherlands are currently designed and examined on a prescribed load, given as an event with a certain return period (between 1/1,000 and 1/10,000 years). A dike must be capable of withstanding such an event. In future, rather than considering each dike section individually, a total area surrounded by dikes or other forms of protection must have a certain safety level. This should it make possible to describe the circumstances under which dikes really do breach and how a breach develops.

A further step will be to describe safety in terms of risk. Risk is then described as the combination of probability on flooding and the consequences in terms of loss of material (economic damage) and human lives (risk = probability * effect). It is currently not possible to perform a quantitative risk analysis in full detail as described above, but a first attempt was made in this study, using recent studies of the TAW (Technical Advisory Committee on Water Defences in the Netherlands).

In these studies existing dike ring areas were taken and all data on dikes and hydraulic boundary conditions were gathered. A probabilistic computer model was made that includes all possible failure mechanisms of a dike and that is able to calculate the probability of flooding by breaching of one of the dike sections. The description to the actual failure mechanism is still preliminary and needs more research in future (what overtopping discharge can a dike really withstand?).

Each dike section was designed for a prescribed load with a certain return period. The outcome of the probabilistic calculation was the probability of flooding of the whole dike ring area. In total six different dike ring areas were treated by the TAW. The main results are given in Figure 10.

A preliminary conclusion is that the probability of flooding of a dike ring area is similar to the probability of the prescribed load under which conditions the dike should be capable of withstanding this event. This conclusion needs further research for confirmation, but for the present study it was used for a complete risk analysis.

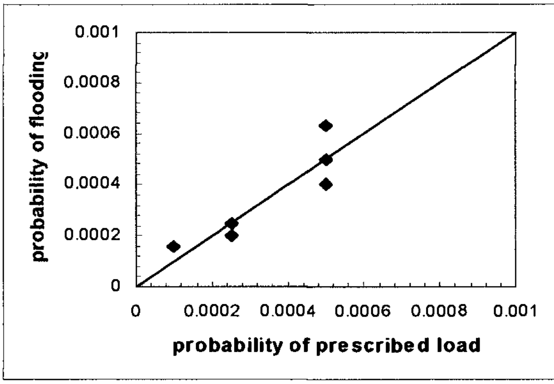

Figure 10. Relationship between a dike section designed for a prescribed load and the probability of flooding of the dike ring area, according to TAW-studies

The probabilities of occurrence of the prescribed loads of each of the dike sections around IJsselmeer and Markermeer have been given by law. These probabilities vary from 1/1,250 to 1/10,000 years. With above conclusion, the probability of flooding of each dike ring area was given the same value. The economic damage of two areas had already been calculated, see Figure 9 and Table 1. In a similar, but slightly simplified way, damage caused by flooding was calculated for all dike ring areas around the both lakes. Together with the probability of flooding it was then possible to calculate the risk of flooding for each dike ring area, by multiplying the probability of flooding with the economic damage.

The main question to consider, however, was the comparison of both lakes with each other and with areas situated along the sea coast. A lake or a sea is not a dike ring area, but a *threat* to the dikes. Therefore, the definition of risk is not applicable to the hydraulic system and a modified definition had to be established. The term *risk profile* was invented for these threats or hydraulic systems:

risk of flooding = probability of flooding of a dike ring area * damage due to flooding

risk profile = the cumulative flooding risks of all dike ring areas along the threat

In this way the risk profile of each hydraulic system like a lake, sea or estuary can be calculated and compared. Both risk and risk profiles are given in value per year, say in million Dutch guilders per year (one US dollar is about two guilder). Figure 11 gives the risk profiles of 5 hydraulic systems in the Netherlands. Two of them are of course the IJsselmeer and Markermeer. They have similar risk profiles of 4.5 and 4.2 million guilders per year.

Although the Markermeer gives lower inundation levels, and therefore lower damage compared to the IJsselmeer, the risk profile is the similar. The main reason for this is that more people live in the dike ring areas around the Markermeer than around the IJsselmeer (Amsterdam is situated on the Markermeer).

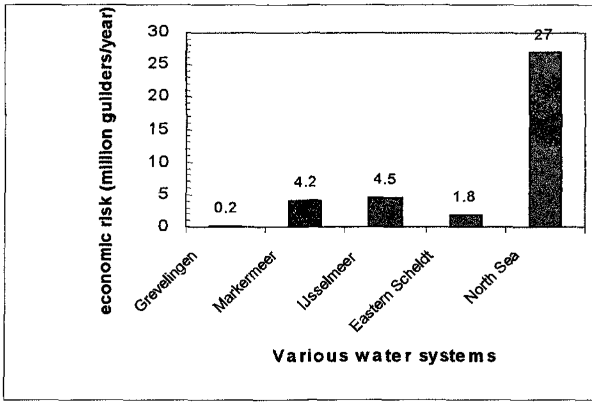

Figure 11. Risk profiles of various hydraulic systems in the Netherlands

The above system analysis leads to the first overall conclusion of the study:

- with respect to safety the two lakes do not show significant differences and should be treated in the same way.

Three other hydraulic systems are given in Figure 11. The Grevelingen is also a lake and after the Markermeer the largest in size in the country. There is more than an order of magnitude difference with the Markermeer and this lake should not be considered like the IJsselmeer or Markermeer or like estuaries or seas.

The last two hydraulic systems are the Eastern Scheldt and the North Sea which directly attacks the rest of the Netherlands. The Eastern Scheldt is an estuary which is closed by the well-known Eastern Scheldt barrier if the storm surge reaches a level of +3 m NAP. From that moment on the estuary becomes a closed lake. The risk profile for this estuary is smaller than for the IJsselmeer and Markermeer, but still comparable. The North Sea threats a large part of the Netherlands and gives of course the largest risk profile. There is, however, less than an order of magnitude difference with the two lakes. Comparing the two lakes with the two salt water systems gives the final conclusion:

- large lakes like the IJsselmeer and Markermeer give similar risk profiles as for areas along the sea coast and should, with respect to safety, be treated in the same way.

Conclusions

A system analysis of the threat that hydraulic systems, such as large lakes, estuaries and seas, can form for the safety of dike ring areas around these systems, gives a good insight into the physical aspects. Together with a risk analysis, finally leading to the description of the risk profiles of hydraulic systems, it makes it possible to compare the various hydraulic systems from the point of view of safety. To that aspect the IJsselmeer and Markermeer should be treated in a similar way as estuaries and the North Sea.

Lake level control has hardly any influence on required dike heights, or safety, as the dike heights in most situations are determined by very strong wind, high storm surges and high waves. Flood damages from IJsselmeer and Markermeer are comparable, although the damage due to the Markermeer will be a little smaller as the lake is also smaller (the inundation depths, therefore, are a little smaller).

Acknowledgement

The authors wish to thank all those who have actively participated in the extensive technical, legal and managerial discussions, which have formed the basis for this study. During the 1½ year study representatives from the Netherlands' Ministry of Transport, Public Works and Watermanagement, several Provinces and Waterboards worked together with the research staff of Delft Hydraulics, the Technical University of Delft and the University of Utrecht. The outcome of this work underlines that a technical study, set in the context of a political and managerial debate, can indeed lead to consensus on the management steps to be taken and the legal changes that are necessary to make this happen.

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