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a new graph-based approach used for real world applications

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Abstract

Flood prevention policy is of crucial importance to the Netherlands. We assess economical optimal flood prevention where multiple barrier dams and dikes protect the hinterland against sea level rise and peak river discharges. Current optimal flood prevention methods only consider dike rings with no dependencies between dikes. We propose a graph-based model for a cost-benefit analysis to determine optimal dike heights with multiple dependencies between dikes and barrier dams. Our model provides great flexibility towards the modelling of flood probabilities, damage costs and investments cost. Moreover, our model is easy to implement and can be solved quickly to proven optimality. Our model is developed for and applied to important policy decisions in the Netherlands for the Lake IJssel and Lake Marken region. Two barrier dams together with the dikes surrounding these two lakes protect a large part of the Netherlands. The area contains 17 dike ring areas, including the City of Amsterdam. Our model and application shows the importance of taking into account dependencies between dikes and barrier dams. The results of our model were used for major Dutch flood protection policy decisions, i.e. the decision how to control the water levels in Lake IJssel and Lake Marken and what economic efficient flood protection standards apply to barrier dams and dikes. Dependencies between barrier dams and dike rings have a large impact on economically optimal flood standards. On the basis of our model, the Dutch government decided not to increase the water level of Lake IJssel with up to 1,5 meter. This saved both the current landscape around Lake IJssel and billions of euros in coming decades.

Subject classifications: flood prevention; climate change adaptation; cost-benefit analysis; integer programming; graphs; economic optimization.
JEL classifications: C61; D61; H54; Q54.

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Dutch Abstract

Optimale waterveiligheid bij onderling afhankelijke dijken: toepassing op het IJsselmeergebied

Bescherming tegen stijgende zeespiegel en grotere rivierafvoeren is een belangrijk onderwerp wereldwijd én zeker ook in Nederland. Dit paper presenteert een nieuwe model om de optimale mate van waterveiligheid te bepalen. Met dit model is het mogelijk om rekening te houden met situaties waarin meerdere dijken of dammen gezamenlijk het achterland beschermen tegen zeespiegelstijging en piekafvoeren van rivieren. De huidige modellen om de optimale mate van waterveiligheid te bepalen konden tot nu toe alleen situaties berekenen waarbij er geen afhankelijkheden zijn tussen dijken en/of dammen. De afhankelijkheden tussen dijken en dammen in het IJsselmeergebied hebben een grote impact op de hoogte van de economisch optimale waterveiligheidsnormen.

Nederland is internationaal koploper bij het ontwikkelen van modellen om de optimale mate van waterveiligheid te bepalen[2]. Eerdere modellen en toepassingen zijn Van Dantzig (1954), Eijgenraam (2006), Brekelmans et al. (2012), Kind (2014), Eijgenraam et al. (2014), Eijgenraam et al. (2016) en Zwaneveld et al. (2018). Het model dat in dit paper wordt gepresenteerd, breidt dit vakgebied uit.

We stellen een op graventheorie gebaseerd model voor. Dit betreft een kosten-batenanalyse om daarmee de optimale dijkhoogten te bepalen voor situaties waarin meerdere dijken en dammen in onderlinge afhankelijkheid gezamenlijk de mate van waterveiligheid bepalen. Dit model is ontwikkeld voor en toegepast op belangrijke beleidsbeslissingen in Nederland en wel het gebied rond het IJsselmeer en het Markermeer. Twee dammen (de Afsluitdijk en de Houtribdijk) beschermen samen met de dijken rond beide meren een groot deel van Nederland. Het model en de toepassing ervan tonen aan dat het meenemen van de afhankelijkheden tussen dijken en dammen kwantitatief van groot belang is bij het bepalen van de optimale mate van waterveiligheid.

De resultaten van ons model zijn gebruikt voor belangrijke beslissingen om Nederland te beschermen tegen overstromingen. De besluiten betroffen de wijze waarop de waterstanden in het IJsselmeer en het Markermeer moesten worden beheerst en wat de economisch optimale waterveiligheidsnormen zijn van de dijken en dammen rond deze meren. Op basis van ons model heeft de Nederlandse regering besloten om het waterpeil van het IJsselmeer met pompen te beheersen en niet te verhogen met 1,5 meter. Hierdoor kan het huidige landschap behouden blijven. Ook heeft dit miljarden euro's in de komende decennia bespaard.

[2] Zie bijvoorbeeld: Koks, E., T. Husby. 2018. Suggesties voor de economische inschatting van optimale dijknormeringen, ESB Jaargang 103 (4759), pp. 108-111.

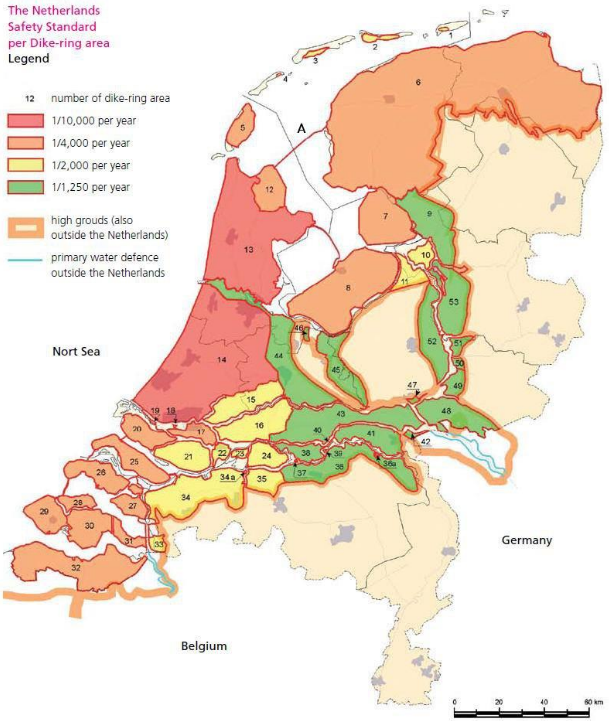
1. Introduction[3]

The Netherlands is exposed to the risk of large-scale flooding as over 50% of the country is susceptible to flood risk. The 1953 flood in the Netherlands is after almost 60 years still in the Dutch collective memory. The flood occurred in the night and resulted into the death of 1,835 people. Almost 200,000 hectares of land were flooded, 67 dike breaches arose and immense economic damage resulted (10% of Dutch GDP). The government rapidly appointed the so-called Delta Committee in order to design measures for preventing similar disasters in the future. The Delta Committee asked Van Dantzig (1956) to develop a mathematical approach to formulate and solve the economic cost-benefit decision model concerning the optimal dike height problem.

The work of the Delta Committee, including the work by Van Dantzig (1956), finally resulted in statutory minimal safety standards. Up to the year 2017, the safety standards against flooding are defined on the basis of dike ring areas, see Figure 1.

[3] We are very grateful to members of the Administrative Supervisory Commission and the Scientific Supervisory Commission for the CPB-project 'Economic Optimal water safety in Lake IJssel region'. We thank Carel Eijgenraam, Ruud Brekelmans, Stan van Hoesel and Dick den Hertog for their comments and suggestions. We are particularly grateful to Joost Beckers (Deltares), Nienke Kramer (Deltares), Koos Poot (Ministry of Infrastructure and the Environment), Robert Slomp (Rijkswaterstaat), Pieter Vermeer (Ministry of Infrastructure and the Environment) and André Wooning (Rijkswaterstaat) for their extensive support.

Figure 1: Dike ring areas and safety standards in the Netherlands up to the year 2017.



Note: 'A' indicates the location of the barrier dam 'Afsluitdijk', which protects the northern part of the Netherlands

A dike ring is an uninterrupted ring of water defences. In total, there are 53 dike ring areas, each having a certain minimal safety standard (i.e. maximum flood probability). The tightest (i.e. lowest) flood probability is 1/10,000 per year for the most populated part of the Netherlands. This number is derived from Van Dantzig (1956).

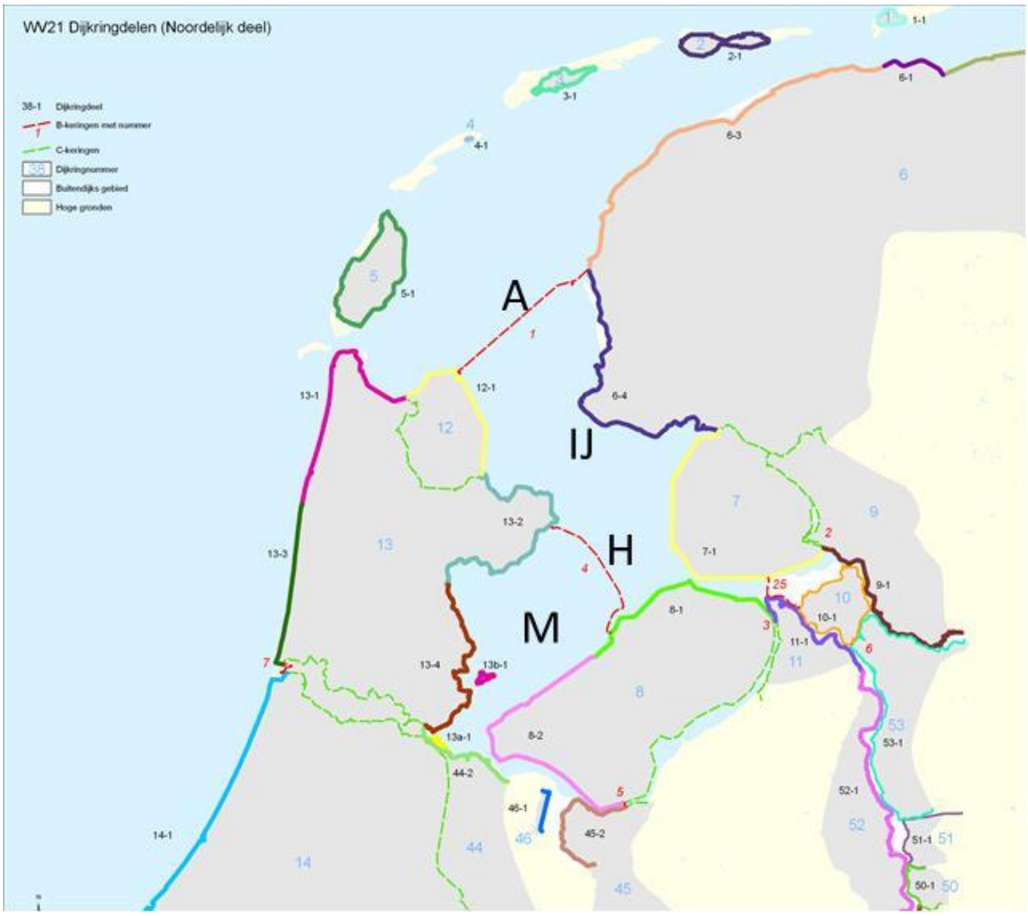
At present, protection against flooding is an important issue worldwide (Adikari and Yoshitania, 2009). Devastating floods occur each year somewhere in the world, e.g. in Bangladesh, Pakistan, Germany, United States. A well-known example is the serious flooding in and around New Orleans in 2005, which killed about 1,500 people and created enormous damage. In 2012, Hurricane Sandy severely affected New York: more than 230 people died and the economic losses across the United States alone were estimated to be at least 70 billion dollars (Eijgenraam et al., 2016).

Renewed interest in determining optimal dike heights in the Netherlands arose - again - after a near-flooding situation in 1995. Awareness grew in the Netherlands that the current safety levels against flooding were about 60 years old and in need of a thorough reconsideration. Since then, both the population size and the economic value of the protected land have increased significantly. Moreover, the knowledge about the causes of flooding has increased, as well as the portfolio of civil engineering and other measures to prevent flooding or reduce its consequences. And last but not least, the sea level and the discharge levels of the rivers during winter have risen during this period. Therefore, the Dutch Central Government initiated a safety programme as part of an overall new and permanent Delta Programme (Delta Programme Commissioner, 2012), with the aim of developing and setting down new water safety standards and implementing the EU Flood Risks Directive (EU, 2007). In 2017, the new standards were set down in the Water Act.

Several research projects were initiated to prepare these new standards and to determine optimal strategies for flood prevention. An economic cost-benefit analysis (CBA) was carried out by the hydraulic research and consultancy company Deltares (Kind, 2011). This CBA also resulted into several scientific papers, e.g. Brekelmans et al. (2012), Kind (2014) and Eijgenraam et al. (2016). These authors developed extensions of the earlier mathematical model by Van Dantzig (1956) and Eijgenraam (2006). Chahim et al. (2012) and Zwaneveld et al. (2018) present alternative solution approaches to these problems.

The most important characteristic of all presently available models is the fact that a dike ring is analysed in isolation. Hence, no dependencies between dike ring areas may occur. Or to state it differently, the failure probability of a dike ring is not allowed to depend on the strength of other dikes or barrier dams. This assumption is valid for many dike ring areas along the major Dutch rivers Rine and Meuse. However, this assumption is clearly not valid for many other dike ring areas in the Netherlands. Therefore, the Dutch ministry of Infrastructure and the Environment asked us to develop and apply a model capable to assess these situations. The most important situation of interest is the Lake IJssel and Lake Marken region in the northern part of the Netherlands (see Figure 1 and Figure 2).

Figure 2 Lake IJssel and Lake Marken region with dike rings.



Note: The numbers in this figure are explained in Table B1 in Appendix B.

The situation can be characterized as follows. A barrier dam called the Afsluitdijk ('Enclosure dam', see 'A' in Figure 2) protects Lake IJssel ('IJ') from north-western storm surges from the North Sea. Hence, the failure probability of a dike ring adjacent to Lake IJssel depends on its own strength as well as on the strength of the Afsluitdijk. The water in Lake IJssel is mainly supplied by the river IJssel, which stems from the river Rhine. The situation is even more complex around Lake Marken ('M'). This lake is separated from Lake IJssel by the barrier dam 'Houtribdijk' ('H'). Hence, the failure probability of a dike adjacent to Lake Marken depends on its own strength and on the strength of both the Afsluitdijk and the Houtribdijk.

The Lake IJssel and Lake Marken region is important for the Netherlands. The barrier dams and dikes surrounding Lake IJssel and Lake Marken protect in total 17 dike ring areas. In total 2.5 million people are protected against flooding including the City of Amsterdam. Thread of flooding of this region is still in the collective memory of the Netherlands. The decision to construct the Afsluitdijk to close off the former ‘Southern Sea’ to become ‘Lake IJssel’ was taken about a century ago after the 1916 flooding due to a storm surge (Bos and Zwaneveld, 2017).

Beside the assumed independency of dike rings, another crucial assumption of the previously mentioned models is not valid in many real world situations and particularly for the Lake IJssel region. The assumption is that all locations fail under identical circumstances. This not the case for many dike rings in the Lake IJssel region. For example, dike ring 13 (see Figure 1) is partly adjacent to Lake IJssel and partly adjacent to Lake Marken. Hence, they fail under different circumstances since the water level in both lakes are managed separately. Moreover, different parts of this dike ring fail by wind surges from divergent directions. This also holds for many other dike rings e.g. dike rings ‘6’ and ‘7’.

An important improvement to previous models is the greater flexibility of our model with respect to input parameters. Previous models use specific mathematical functions for investment costs and failure probabilities. For both aspects, these models used continuous exponential functions that only depend on the height of a dike. Hence, decreasing the flood probability of a dike can only be obtained by heightening this dike. This approach also only allows for assessing height-based failure mechanisms (‘overflow’) and doesn’t allow strength-based failure mechanisms, like piping or lack of structural quality of construction. In practice, there is a need to assess the optimal timing of anti-piping measures and renovations of constructions. This requires the use of discontinuous investment cost and failure probability functions. Currently, the overall flood probability of about half of all dike rings is to a large extent (>50%) determined by other failure mechanism than overflow (Kind, 2011). Hence, the ability to correctly model these other failure mechanisms is of utmost importance for real world applications.

In this paper we present the general framework, methodology and results of the cost-benefit analysis for analysing economical optimal flood prevention for a multi-level system of dikes and barrier dams with multiple interdependencies between dikes and barrier dams. We have applied our model to the actual situation of the Lake IJssel and Lake Marken region. Based upon our model and results policy decisions were made by the Dutch Cabinet.

We also discuss how to derive economically efficient flood protection standards from the optimal investment policy. These flood protection standards serve as the (legal) basis for daily decision making on whether to improve the protection level at specific locations.

Many situations similar to Lake IJssel exist in the Netherlands. Figure 1 shows that in the south-western part of the Netherlands several barrier dams protect a lake from the North Sea. In total 27 barrier dams exists in the Netherlands (Ministry of Infrastructure and the Environment, 2007). Moreover, our modelling approach is capable to asses all kind of dependencies between dikes, including dependencies between dikes along major rivers in Europe. Around the world, many river deltas exist for which multi-level flood prevention is appropriate. Syvitski et al. (2009) analyse 33 important deltas worldwide, finding that 85% of these deltas had experienced severe flooding in the past decade. Our model is already applied to the Galveston Bay area in Texas.

The contributions of this paper are the following.

1. We extend existing models to determine economic optimal flood prevention strategies. We show how to include flooding dependencies between dikes by using a graph-based modelling approach. Our approach is general applicable and can be adjusted to other situations.
2. The modelling approach provides maximum flexibility towards input parameters: flood probabilities, damage costs and investments cost. As a result, important non-linearities in costs and flood probabilities as a function of time and height, can be included. In addition, several made-to-measure and case specific aspects can also be taken into account. The discretization of both time and height enables the inclusion of these relevant aspects.
3. Our model is applied to real-life governmental decision problems, which ensures that the input data and the results are validated by field experts. Quantitative results from these real life applications are presented. These results show that dependencies between dikes are important.
4. Our model is easy to implement and can be solved quickly to proven optimality.
5. We present a novel approach to derive flood protection standards based upon the optimal investment policy. Our approach takes into account climate change and economic uncertainties.

This paper presents the methodological underpinning of the results of two policy oriented studies. These results were earlier reported in Dutch written reports and presented to policy makers and general Dutch media (Bos & Zwaneveld, 2012, Zwaneveld and Verweij, 2014a, Deltaprogramma IJsselmeergebied, 2014).

2. Cost-benefit model as an integer programming model

In this section, we present an integer programming (IP-model) formulation for optimal dike strengthening in a multi-level flood prevention situation. Our new modelling approach is used to determine the optimal timing and extent of dike heightening or strengthening, including protective barrier dams. We will use the terms heightening and strengthening interchangeably throughout this paper. The aim is to provide a model formulation with maximum flexibility.

In this section, we present the situation in which one barrier dam protects a fresh water lake from storm surges from the sea. Around this lake, dikes protect the hinterland. These dikes are subdivided into multiple dike rings. These dike rings are mutually independent. Hence, if one dike rings fails this has no consequences for other dike rings. If a dike ring fails at any point, the dike ring area is flooded. This characterization exactly captures the interdependencies between the barrier dam ‘Afsluitdijk’ and the dike rings adjacent to Lake IJssel (see Figure 2).

The basic dilemma on when and how much to heighten dikes and barrier dams, is the trade-off between paying up the investment costs of strengthening dike rings and the barrier dam or accepting a higher probability of dike failure. Safety (i.e. lower failure probability) for the hinterland can be obtained from strengthening the barrier dam and/or the dike ring. The costs of flooding include damage costs, cost of evacuation, rescue costs and immaterial costs (e.g. victims, sufferings).

For clarity, we restrict the discussion in this section to one barrier dam and one lake. The actual situation in the Netherlands is more complex and includes two barrier dams and two lakes. The model for that situation is presented in Appendix A of this paper. This extension shows the flexibility and general applicability of our model approach.

2.1 IP-model for multi-level flood prevention

2.1.1 Notation

The (binary) decision variables represent the decision to heighten (or more generally spoken: strengthen) a dike ring in a particular year from height/safety level h_1 to safety level h_2. The set H represents all possible safety levels/heights of this dike ring. For example, one may consider heightening a dike ring with steps of 20 cm. From a practical point of view, steps smaller than 20 cm need not to be considered. Several uncertainties exist about the actual height/strength of a dike ring: the unknown settlement after heightening of a dike ring and uncertainties with respect to a-priori unknown thickness of the clay used for heightening. A safety level h_2 can also refer to specific actions to solve flooding due to mechanisms like piping and the quality problems of some structures. Hence, these safety levels provide the model its flexibility to fit real situations.

The set T represents all considered time periods. A time period $t \in T$ may represent one year, but can also represent a certain time period, say 5 or 10 years. In practice, the exact timing of a dike heightening cannot be planned with great precision due to legislation, consulting local authorities, communication and negotiation with land owners and inhabitants and planning uncertainties due to civil engineering works. For example, the construction of a higher dike takes at least five years. Year '0' and height '0' is used to represent the starting conditions of a dike ring. Without loss of generality, we can denote and order the different safety level/heights by $H = \{0, 1, 2, ..., |H| - 1\}$ and the time period/years by $T = \{0, 1, 2, ..., |T| - 1\}$. Not all safety levels may be available for all dike rings and the barrier dam. Hence, subsets of allowed safety levels are defined.

A dike ring $d \in D$ protects a certain area of land against water flooding from Lake IJssel. In total 10 dike rings are adjacent to Lake IJssel (including the adjacent river IJssel). All dike rings and the barrier dam can be heightened independently.

2.1.2 IP-model formulation

The decision variables are:

$CY(t, d, h_1, h_2) =$ 1, if dike ring d is updated in time period t from height/safety level h_1 up to height/safety level h_2. If $h_1 = h_2$ then this dike ring segment is not strengthened in period t and remains at its previous strength. This decision variable is used for bookkeeping investment (and maintenance) costs.

0, otherwise.

$DY(t,d,h_2,h_2^B) =$ 1, if dike ring *d* in time period *t* has height h_2 and the barrier dam has height h_2^B This decision variable is used for bookkeeping flood probabilities and related expected damage costs.

0, otherwise.

$B(t,h_1^B,h_2^B) =$ 1, if the barrier dam (i.e. the 'Afsluitdijk') is updated in time period *t* from height/safety level h_1^B up to h_2^B. If $h_1^B = h_2^B$ then the barrier dam is not strengthened in period *t* and remains at its previous strength. This decision variable is used for bookkeeping investment (and maintenance) costs, flood probabilities and related expected damage costs of the barrier dam.

0, otherwise.

The input-parameters are:

$Dcost\left(t,d,h_1,h_2\right)$ = costs for investment and maintenance, if dike ring *d* is strengthened in time period *t* from h_1 to h_2. If $h_1 = h_2$, the dike ring segment is not strengthened and these costs only represent maintenance costs.

$Dexpdam\left(t,d,h_2,h_2^B\right)$ = expected damage, i.e. $probability(t,d,h_2,h_2^B) \times damage(t,d,h_2,h_2^B)$, if the resulting height of dike ring *d* in period *t* equals h_2 and the barrier dam equals h_2^B.

$Bcost\left(t,d,h_1^B,h_2^B\right)$ = costs for investment and maintenance, if the barrier dam is strengthened in time period *t* from h_1^B to h_2^B. If $h_1^B = h_2^B$, the barrier dam is not strengthened and these costs only represent maintenance costs.

$Bexpdam\left(t,h_2^B\right)$ = expected damage, i.e. $probability(t,h_2^B) \times damage(t,h_2^B)$, if the resulting height of the barrier dam in period *t* equals h_2^B.

All input parameters are calculated in net present value of a certain year (i.e. 2015, which is the starting year for our calculations) and represent price levels in a certain year. In our calculations, we also presume that dike heightening takes place immediately at the start of the time period $t \in T$. The final time period $|T|-1$ includes the expected damage from this time period until infinity.

The model reads as follows:

$$
\begin{aligned}
Min \; & \sum_{t\in T}\sum_{d\in D}\sum_{h_1\in H^I}\sum_{h_2\ge h_1\in H^I} Dcost(t,d,h_1,h_2)\cdot CY(t,d,h_1,h_2) \\
& +\sum_{t\in T}\sum_{d\in D}\sum_{h_2\in H^d}\sum_{h_2^B\in H^B} Dexpdam(t,d,h_2,h_2^B)\cdot DY(t,d,h_2,h_2^B) \\
& +\sum_{t\in T}\sum_{h_1^B\in H^B}\sum_{h_2^B\ge h_1^B\in H^B}[Bcost(t,h_1^B,h_2^B)+Bexpdam(t,h_2^B)]\cdot B(t,h_1^B,h_2^B)
\end{aligned}
\tag{1}
$$

subject to

$$CY('0',d,'0','0')=1; CY('0',d,h_1,h_2)=0 \quad \forall d\in D; h_1,h_2\in H^d; h_2\ge h_1 \wedge h_2>'0' \tag{2}$$

$$\sum_{h_1\le h_2\in H^d} CY(t-1,d,h_1,h_2)=\sum_{h_3\ge h_2\in H^d} CY(t,d,h_2,h_3) \quad \forall t\in T/\{'0'\}, d\in D, h_2\in H^d \tag{3}$$

$$\sum_{h_1\le h_2\in H^d} CY(t,d,h_1,h_2)=\sum_{h_2^B\in H^B} DY(t,d,h_2,h_2^B) \quad \forall t\in T, d\in D, h_2\in H^d \tag{4}$$

$$B('0','0','0')=1; B('0',h_1^B,h_2^B)=0 \quad \forall h_1^B,h_2^B\in H^B; h_2^B\ge h_1^B \wedge h_2^B>'0' \tag{5}$$

$$\sum_{h_1^B\le h_2^B\in H^B} B(t-1,h_1^B,h_2^B)=\sum_{h_3^B\ge h_2^B\in H^B} B(t,h_2^B,h_3^B) \quad \forall t\in T, h_2^B\in H^B \tag{6}$$

$$\sum_{h_2\in H^d} DY(t,d,h_2,h_2^B)=\sum_{h_1^B\le h_2^B\in H^B} B(t,h_1^B,h_2^B) \quad \forall t\in T, d\in D, h_2^B\in H^B \tag{7}$$

$$CY(t,d,h_1,h_2)\in\{0,1\} \quad \forall t\in T, d\in D, h_1\in H^d, h_2\ge h_1\in H^d \tag{8}$$

$$DY(t,d,h_2,h_2^B)\in\{0,1\} \quad \forall t\in T, d\in D, h_2\in H^d, h_2^B\in H^B \tag{9}$$

$$B(t,h_1^B,h_2^B)\in\{0,1\} \quad \forall t\in T, h_2^B\ge h_1^B\in H^B \tag{10}$$

The objective function (1) minimizes the total cost for investments for all dike rings (first term) and expected damage in all dike rings (second term) and the total investment costs and expected damage of the barrier dam (third term). Constraints (2) define the starting condition for each dike ring *d* (i.e. its present height/strength). Constraints (3) ensure that the final height of each dike ring *d* in a period *t-1* equals the starting height of the dike ring in the consecutive period *t*. Constraints (4) ensure that the expected damage decision variables of each dike ring *d* in each period *t* correspond to the decision variables which determine the investment cost of each dike ring. If dike ring *d* obtains height h_2 in time period t, then decision variable $DY(j,t,h_2,h_2^B)$ has to obtain the same value (i.e. ‘1’). Constraints (5) define the starting condition for the barrier dam (i.e. its present height/strength). Constraints (6) ensure that the final height of the barrier dam in period *t-1* equals the starting height of the barrier dam in the consecutive period *t*. Constraints (7) ensure that the expected damage decision variables of each dike ring *d* in each period *t* correspond to the decision variables that determine the investment cost and expected damage of the barrier dam. If the barrier dam obtains height h_2^B in time period t, then decision variable $DY(j,t,h_2,h_2^B)$ has to obtain the same value (i.e. '1'). Constraints (8), (9) and (10) declare the decision variables as binary.

An additional constraint that may be added to the model comes from the already mentioned fact that it takes a certain time period to construct a higher dike. Hence, a dike ring cannot be updated twice within a certain time period. We denote this minimum update period of dike ring *d* by *up(d)*. Hence, we can add the following constraints:

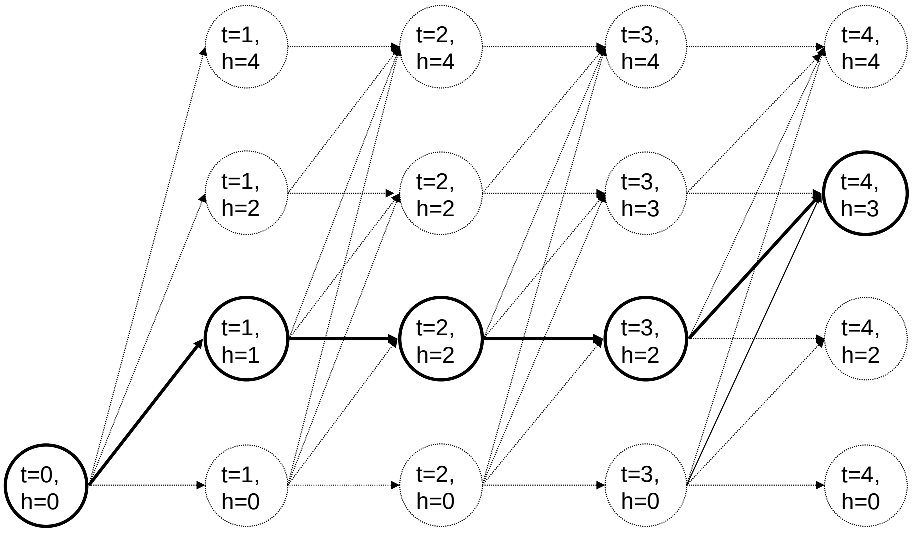
$$\sum_{t^*=t+1,\dots,t+up(d)} \sum_{h_1 \in H^d} \sum_{h_2 > h_1 \in H^d} CY(t^*,d,h_1,h_2) \le 1 \qquad \forall d \in D, t = 0,\dots,|T| - up(d) \tag{11}$$

Similar constraints can be added for the barrier dam. Other constraints can be easily added to the model as well (Zwaneveld and Verweij, 2014a). Another real-world example of an additional constraint is the obligation that a segment must be updated before a certain year. This is due to the fact, that certain segments wore out and need to be thoroughly reconstructed at a certain point in time. A policy relevant side constraint that could be relevant is a maximum (e.g. yearly) budget for total investment costs for both dike ring and barrier dams.

A careful investigation of the model and especially equations (3) and (6), show that a large part of the model satisfies the most fundamental of all network flow problems (Ahuja et al., 1993), namely the minimum cost flow model (or a shortest path problem). See Figure 3 for an illustration of this graph-based representation: the nodes *{t, h}* in this network are represented by a specific choice of time period *t* and dike height *h*. Constraints (3) and (6) can be seen as *flow* or *mass balance constraints*. Hence, the model can be presented as a graph with vertices and edges and solved by using graph based solution procedures as discussed in Zwaneveld and Verweij (2014a) and Zwaneveld et al. (2018; Appendix A). Standard graph-based solution procedures like dynamic programming or shortest path algorithms are not usable in many cases. For complex problems - like we are discussing here - the state space explodes and this approach becomes infeasible. For example, the corresponding graph $G = (V, E)$

involves $|H^B| \cdot |H^d|^{|D|} \cdot |T|$ vertices. Solving this graph using the Dijkstra algorithm requires $O(|V|^2) = O(|H^B|^2 \cdot |H^d|^{2 \cdot |D|} \cdot |T|^2)$ computing time. In addition, using a dynamic programming or a graph based solution approach would also require substantially more programming efforts than using our IP-model.

Figure 3 Graph representation for a dike ring for five time periods and four heights: minimal cost flow or a shortest path



Note that if an investment strategy (i.e. when and how much to strengthen a dike or barrier dam) is given for the barrier dam (or for all dike rings), our IP-model reduces to several independent *shortest paths* or *minimal cost flow problems* which can easily be solved in polynomial time (Zwaneveld and Verweij, 2014a). Future research may use this property to solve very large problem instances heuristically.

We have implemented the model in GAMS and used CPLEX to solve models to proven optimality by using branch-and-cut. Given the model formulation, optimal integer solutions to that IP-model can be easily found by solving its LP-relaxation and searching few branch-and-bound branches (Zwaneveld & Verweij, 2014a). The addition of side -constraints such as (11) doesn't influence this solution procedure. Solving the full model to proven optimality with all 17 dike rings in the Lake IJssel and Lake Marken area and the two barrier dams, requires twenty to thirty seconds.

Our modelling and solution approach requires minimal programming efforts and guarantees optimal solutions. Easy and inexpensive implementation is of crucial importance for practical use and dissemination of our results. This holds for the Netherlands and probably even more for less wealthy countries that are at risk of flooding. Therefore, we deliberately use standard and easily available software (GAMS and CPLEX). Similar and free modelling software can be used as well (e.g. Python, C++, MatLab).

The model requires discretization of time period and heights/safety levels, see also Zwaneveld et al. (2018). The model results with respect to the near future, say 20 to 30 years from now, are being used in practice. It is this still important to take time periods in the distant future into consideration. Possible dike heightening in the distant future may influence dike heightening decisions in the first few decades. These considerations led to the following discretization scheme. Five year period are used until the year 2100. Next, ten-year periods are used up to the year 2300. For each of the two barrier dams, 13 safety levels are used: each represents a 50 cm height increase. Additional safety levels are added to include specific measures or potential cost-effective measures. For all 17 dike ring areas, at least 13 safety levels are used. In addition to the starting safety level, the first six safety levels represent a 20 cm height increase. The next six safety levels represent a 75 cm height increase. If appropriate, an additional safety level is introduced to model specific measures to solve piping and structural problems.

2.2 Input parameters

The basic dilemma on when to heighten the dikes and barrier dams is the trade-off between paying up the investments costs of heightening/strengthening a dike ring or a barrier dam or accepting a (higher) probability of dike failure with all associated damage costs of flooding. Therefore, information on damage costs, flood probabilities and investment costs is required in order to make economically optimal investment decisions. Information on these parameters will be provided in the next subparagraphs.

2.2.1 Damage costs

The costs of flooding include damage costs (including repair), cost of evacuation, rescue costs and immaterial costs (e.g. victims, sufferings). Damage and immaterial costs for each dike ring are based upon extensive simulations by engineers of hydrological consultancy firm

Deltares using the information system HIS-SSM. This work is commissioned by Rijkswaterstaat. Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management and responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands. Repair costs are based on works by Deltares, Rijkswaterstaat and CPB. See Zwaneveld and Verweij (2014a) for a detailed discussion and further references.

2.2.2 Flood probabilities

Flood probabilities are a crucial element of our approach. Flood probabilities of the barrier dams and all (parts of the) dike ring areas were determined by joint work of Deltares (Kramer and Beckers, 2012) and CPB (Zwaneveld and Verweij, 2014a) with the help of Rijkswaterstaat.

The flood probability of the barrier dam is determined as follows. The barrier dam consists of three components, namely outlet sluices, locks and the body of the dike. Its weakest component determines the overall flood probability of the barrier dam. For the first two components, specific flood probability assessments are available (Zwaneveld and Verweij, 2014a). The flood probability of the body the barrier dam is based upon the original 'exponential' probability function used by Van Dantzig (1956):

$$P^B(h_2^B,t) = P_0 e^{\alpha^B t} e^{-\beta^B [hh(h_2^B) - hh('0')]}$$

Here, $P^B(h_2^B,t)$ is the flood probability in time *t* of the body of barrier dam B that is strengthened to safety level h_2^B. Function *hh* returns absolute height (above sea level) of safety level h_2^B. Given a certain (climate, social-economic and policy) scenario, which includes among other a yearly sea level rise and yearly rain and storm characteristics, the flood probability of the body was determined by detailed storm and wave simulation using the statutory required hydrological model Hydra-K. This flood probability was determined for several heights of the body of the barrier dam. The estimation (by ordinary least squares) of the probability function parameters is based upon these simulated values. This provided a near perfect fit (R^2 of about 99%).

Dike rings around Lake IJssel can fail due to water overtopping the crown of a dike which causes a breach in the dike. For this failure mechanism three distinct flood probabilities are identified, namely P1, P2 and P3. Each of these flood probabilities is modelled as an 'exponential' probability function and estimated using a similar procedure as described above. Again, a near-perfect fit was obtained (R^2 of about 99%). The hydrological model Hydra-Zoet was used for detailed storm, wave and rain simulations to assess dike failure ('flooding') of a dike ring.

Flood probability P1 refers to the flood probability of a dike ring adjacent to Lake IJssel given a well-functioning barrier dam. The barrier dam ('Afsluitdijk') is assumed to be absolutely fool proof. Hence, this flood probability is– by definition – independent of the flood probability of the barrier dam. P1 primarily depends on the height and strength of the dikes surrounding the dike ring area, wind speed and wind direction, sea levels, river discharges (from the river IJssel into Lake IJssel) and the methods used for controlling the water level in Lake IJssel (e.g. discharging using outlet sluices or pumping). Flood probability P1 is standard output from the hydrological model Hydra-Zoet. This model is used by many Dutch hydrological consultancy firms.

Flood probability P2 is the flood probability of a certain dike ring during the *same* storm surge in which the barrier dam fails. In this case, sea water overtops the barrier dam during a storm surge. This additional water into Lake IJssel increases the hydrological load onto the dikes, which may cause flooding of the dike ring. A storm surge can also cause a breach in the barrier dam. During a storm surge, a breach starts small and will expand. This allows additional sea water to enter Lake IJssel. Again, this additional water increases the hydrological load on all dikes. Hence, P2 depends on the strength/height of the barrier dam and the strength /height of the dike ring area. The Hydra-Zoet hydrological model was used to asses P2 by including the surge dependent additional water into Lake IJssel. This flood probability was determined for several combinations of heights of the body of the barrier dam and heights of all dike rings.

Flood probability P3 is the flood probability due to a follow up storm surge in the six month that a breach (or 'gap') in the barrier dam has not been repaired. This six month period is the estimated repair time for a barrier dam (see Zwaneveld and Verweij, 2014a).This breach creates an open connection between the North Sea and Lake IJssel. This raises the water level in Lake IJssel which increases the hydrological load onto the dikes. P3 does not depend on the strength/height of the barrier dam *after* the gap is formed. The Hydra-Zoet hydrological model was used to asses P3 by adjusting the water level statistics of Lake IJssel. Flood probabilities P3 are determined for several heights of all dike ring. .

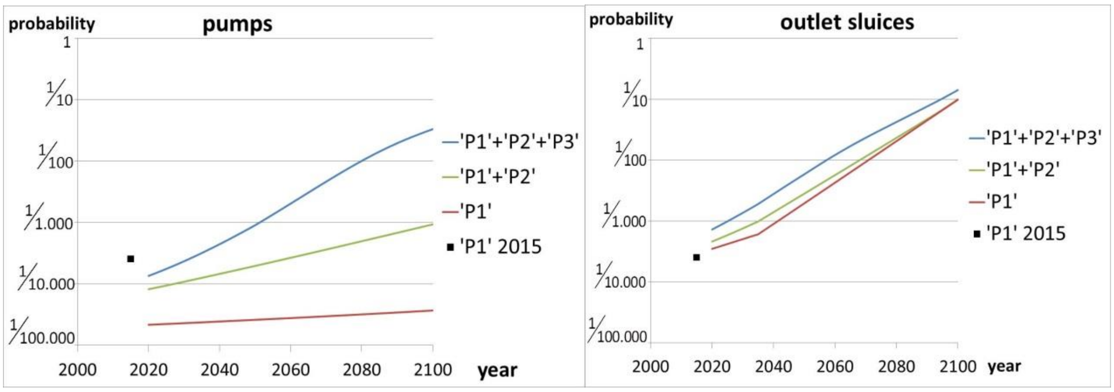
In order to calculate the total failure probability due to water overtopping, the three flood probabilities P1, P2 and P3 are redefined and recalculated as the additional, disjoint probabilities 'P1', 'P2'and 'P3'[4]. By definition `P1'equals P1. `P2'defines the probability of failure additional to the probability of events that were already subsumed under P1. Not correcting these events would result in double counting of events that occur under both P1 and P2. Similarly, the `P3' identifies the failure probability additional to P1 and P2. Then, the total probability of failure P can be calculated as the sum of probabilities 'P1', 'P2'and 'P3'.

Besides dike failure due to water overtopping the crown of a dike and causing a breach, two other failure mechanism were identifies that may cause flooding: the dike may fail due to piping (hollowing due to percolating water, which causes dikes to collapse) and slope instability. Heightening a dike reduces the probability of water overtopping. Flood probability due to overtopping are determined using previously mentioned hydrological models. Specific piping and slope instability assessment are available for all dike rings (Kind, 2011) allow adjusting previously determined flood probabilities 'P1', 'P2'and 'P3' to include these additional two failure mechanism. Specific measures are identified to solve these other two failure mechanisms (de Grave and Baarse, 2011). These specific measures are represented by corresponding safety levels for these dike ring areas. More discussion can be found in Appendix B.

Figure 4 presents flood probabilities 'P1', 'P2' and 'P3' of dike ring 'Zuid West Friesland' (indicated by 6-4 in Figure 2). In the leftmost panel, pumps are used to manage the water level in Lake IJssel. In the rightmost panel, outlet sluices are used to discharge water from Lake IJssel into the North Sea. All dikes and the Afsluitdijk are maintained at their present height/strength and the moderate pessimistic climate scenario W+ for the Netherlands (KNMI, 2006) is assumed.

[4] See Kramer and Beckers (2012) and Zwaneveld and Verweij (2014a) for more details.

Figure 4 ***Flood probabilities 'P1', 'P2', 'P3' for dike ring 'Zuid-West Friesland', using pumps (left) and outlet sluices (right)***



Note: 'P1' 2015 represents the flood probability 'P1' in the year 2015.

The figure shows the significant impact of assessing multi-level flood probabilities. The dependent multi-level flood probabilities 'P2' and 'P3' contribute significantly to the overall flood probability for this dike ring. If outlet sluices are used, the water level of Lake IJssel must be raised together with the sea level rise. Therefore, the flood probabilities 'P1' is substantial higher. Hence, Figure 4 also shows the substantial safety advantages of using pumps instead of outlet sluices to manage the water level of Lake IJssel[5].

2.2.3 Cost of heightening/strengthening

Investment costs of heightening a dike $d \in D$ depends on realised height $hh(h_2, d)$, previous height $hh(h_1, d)$ and starting height $hh('0', d)$. Deltares (de Grave and Baarse, 2011) assessed all dike rings in the Netherlands and derived the following 'exponential' investment cost function for each dike ring *d*:

$$I(d, h_1, h_2) = [a_d + b_d\{hh(h_2, d) - hh(h_1, d)\}]e^{\lambda_d[hh(h_2,d) - hh('0',d)]} \text{ if } hh(h_2, d) > hh(h_1, d).$$

Parameters $a_d, b_d, \lambda_d > 0$ are suitably chosen for dike ring *d*. These cost functions are widely used in the Netherlands. Moreover, detailed case-specific costs assessments are available for measures to solve piping and slope instability problems for all dike rings. These costs are used to include these measures into our model.

[5] To the best of our knowledge, we are the first to quantitatively assess these multi-level flood probabilities for the Netherlands and the safety benefits of pumps in comparison with outlet sluices.

For the barrier dams, specific cost functions are derived for each of the three components, namely outlet sluices, locks and the body of the dike. Strengthening the first two elements means rebuilding them. This involves fixed costs for about 80% of the total costs for a typical strengthening. The remaining 20% depends linearly on the height above 3m of these outlet sluices and locks.

$$I(h_2^B) = a_B + b_B[hh(h_2^B) - 3.00] \text{ if } hh(h_2^B) > hh(h_1^B) .$$

The costs for heightening the body of the barrier dam are fitted in the following 'quadratic' investment cost function.

$$I^B(h_1^B, h_2^B) = a[hh(h_1^B) / hh('0')] + b[hh(h_2^B) - hh(h_1^B)] + c[hh(h_2^B) - hh(h_1^B)]^2$$

$$\text{if } hh(h_2^B) > hh(h_1^B)$$

Parameters $a, b, c > 0$ are suitably chosen. The quadratic term follows from the fact that the amount of clay that is needed to heightening the body of the dike grows quadratically in its height.

The individual cost function of all three elements, i.e. outlet sluices, locks and the body of the dike, are combined into an overall cost function for strengthening the barrier dams.

3. Applications and results

The IP model, called the CPB Diqe-Opt model, was developed by request from the Ministry of Infrastructure and Water Management. The model[6] was used to assess two important policy questions:

1. Decision on flood protection measures and fresh water options for the Lake IJssel and Lake Marken region.
2. New legal flood protection standards for all dikes rings and barrier dams in the Lake IJssel and Lake Marken region for the year 2050.

Our (Dutch) reports to the Dutch government with our answers to these two questions are Bos and Zwaneveld (2012) and Zwaneveld and Verweij (2014a). Both reports were used by the, so called, Delta programme (Delta Programme Commissioner. 2012). This - permanent -

[6] As a prove of the flexibility of our modeling approach, a first version of the Diqe-Opt model was built in Microsoft Excel to asses several option to renovate the Afsluitdijk. This model was capable of performing 'what-if' analysis only. See Zwaneveld et al. (2012) and Grevers and Zwaneveld (2011).

programme was a reaction to recommendation in 2008 by the Second Delta Committee to raise the level of Lake IJssel by 1.5 m in the year 2050 and to increasing legal flood protection standards at least tenfold to compensate for population and economic growth. The former would cost several billion euro and would substantially change the landscape around Lake IJssel due to required dike heightening and the substantial water level increase. The latter would require investments of well over 10 billion euro (Eijgenraam et al., 2014).

3.1 Cost-benefit analyses of flood protection measures and fresh water option for the Lake IJssel region

The main question (Bos and Zwaneveld, 2012) is how to manage the water level in Lake IJssel and Lake Marken until the year 2100 and when and how much should all dikes and barrier dams be heightened. This study also assesses to what extent the fresh water supply should be enlarged before the year 2025[7]. Total investment cost and remaining expected flood damage are crucial policy information. The Diqe-Opt model was used to determine for each water management alternative the optimal costs of dike heightening and remaining expected flood damage costs. For each alternative, the optimal timing and extent of dike heightening were determined for all 17 dike rings and the two barrier dams. Additional cost and benefits[8] were also assessed, e.g. the effects of changing water levels for the natural environment, shipping, agriculture and historic monuments.

The main question for long term water management was assessed by analyzing the following two alternatives:

1. Install large *pumps* at the Afsluitdijk and maintain the present water level for both Lake IJssel and Lake Marken

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[7] The Diqe-Opt model was also used to assess safety risks and required investments for enlarging the fresh water supply in Lake IJssel. Fresh water supply can be enlarged – especially in the summer - by raising the water level in Lake IJssel. This induces additional safety risks. By using the Diqe-Opt model, an option to double the fresh water supply in the summer was identified which requires an investment of only 10 million euro. Tripling the present fresh water supply would require an additional 16 million euro. This would be sufficient for the next decades for all foreseeable future climate scenarios.

[8] The effects were incorporated by several approaches. The main approach was to estimates the costs to prevent environmental damage as much as possible, see Table 3.1. Other approaches were to assess to which extent legal environmental protection standards were met and to measure effects on biodiversity by using expert based ordinal 'biodiversity point' (Bos and Zwaneveld, 2012).

2. Raise the water level of Lake IJssel in accordance with the sea level rising. Use discharge *sluices* to transport excess water from Lake IJssel to the North Sea

The main result of the cost benefit analyses is summarized in Table 3.1.

Table 3.1 Cost-benefit overview of two main alternatives for the years 2020-2100

	Pumps	**Sluices**
	million euro	
Investment costs pumps/sluices	1.000	700
Energy costs pumps/sluices	154	1
Maintenance costs pump/sluices	2.600	1.790
Costs (optimal) dike heightening	3.815	8.452
Additional costs for nature, shipping, agriculture, etc	28	1.218
Subtotal (expenditure)	*7.597*	*12.161*
Expected flood damage costs	5.238	6.934
Total	**12.835**	**19.095**
Fresh water buffer (in million m^3)	600	1.000

Note: KNMI W+ climate scenario (i.e.+ 4°C worldwide temperature in 2100). Costs (in euro 2009) are non-discounted.

Table 3.1 clearly shows the large cost advantage of pumps. This is primarily due to the safety benefits of pumps (see Figure 4). Installation of these pumps greatly reduces the need for dike heightening around Lake IJssel and Lake Marken. In addition, fewer compensation measures are needed to avoid damage to nature, shipping and agriculture. Raising the water level in Lake IJssel does increase the fresh water to 1.000 m^3.Using pumps results in a 600 m3 fresh water buffer. However, a 600 m^3 fresh water supply already triples the present water supply in the region: more than enough for the foreseeable future.

A closer look at the sluices alternative in Table 3.1 shows, that besides the higher costs for dike heightening, the remaining expected flood damage costs are also higher. Hence the additional safety risk of using sluices is only partly mitigated by increasing dikes in the optimal heightening scheme for this situation. In additional to Table 3.1, other alternatives and (climate) scenarios were assessed in Bos and Zwaneveld (2012). All showed very substantial cost advantages of using pumps over sluices of several billion euro.

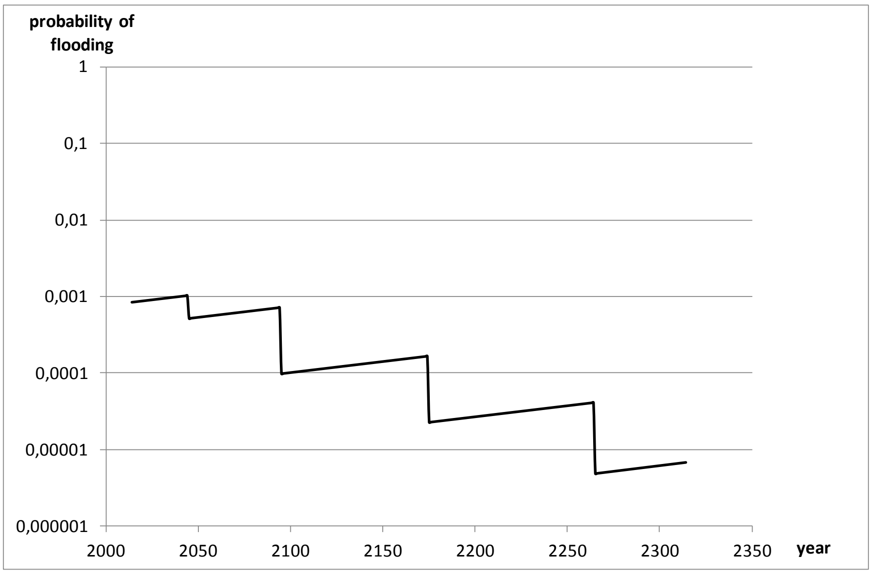
Due to the expenditure benefit of about 5,5 billion euro in Table 3.1, the Dutch government (Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, 2014; Deltaprogramma IJsselmeergebied, 2014) decided in 2015 - fully in line with our analysis - to install pumps at the Afsluitdijk and to triple the fresh water buffer. Hence, the previous advice to raise the water level of Lake IJssel by 1.5 meter was laid aside.

3.2 Economic efficient flood protection standards for the Lake IJssel region

Decision making on flood protection in the Netherlands and many other countries is based on legal flood protection standards. Legal standards work as conditional test standards: when the standard is (expected to be) exceeded in any year, an action for improvement must start. The Dutch government searches for new legal standard for following decades. The year 2050 was selected as 'target year'. New legal test standard must be realized in the year 2050. In this section, we present the legal safety standards and the way they can be derived from the optimal investments from the Diqe-Opt model . We present the results of our multi-level approach and compare them with the legal standards at that time of our analysis.

The link between the optimal investment pattern and a proposed legal standard can best be explained by using Figure 5. Typically, flood probability follows a saw tooth pattern. Due to climate change and soil subsistance, the flood probability gradually increases. The flood probability drops considerably after an investment, which occurs among others in the years 2045 and 2095. Figure 5 also shows that flood probabilities just prior to a heightening decrease over time. Due to economic and population growth, it is optimal to increase protection levels against flooding, i.e. flood probabilities become smaller.

Figure 5 Typical saw tooth pattern: flood probabilities according to an optimal investment strategy.



To calculate a legal flood protection standard[9], we propose the so-called 15years flood probability. Given a certain generally agreed-upon base case scenario for economic growth and climate change, we calculate the optimal investment strategy for a dike ring. We also determine the first heightening of this dike ring after the year 2050. Hence, this is the year 2095 in Figure 3.1. Our proposed legal flood standard is the flood probability 15 years prior to this year, i.e. the flood probability in the year 2080. These 15 years follow from the fact that it takes on average 15 years to strengthen a dike ring. This 15 year 'lead time' is needed for the decision making process of Dutch government, all legal Dutch requirements and the actual construction of a dike ring upgrade.

[9] The literature provide only one alternative legal test standard. This test standard is called the so-called middle flood probability. This was first introduced by Eijgenraam (2006). The middle flood probability is calculated as follows for the year 2050 (see also Eijgenraam et al., 2016). Given a certain generally agreed –upon base case scenario for economic growth and climate change, the optimal investment strategy for a dike ring is determined. Then, the first heightening of this dike ring after the year 2050 must be identified. Hence, this is the year 2095 in Figure 5. Next, the expected flood risk just before and just after this heightening is determined. Following that, the logarithmic mean of both values must be determined. This logarithmic mean is divided by the damage costs in the year 2050 in case a flooding occurs. This approach is also used in Brekelmans et al. (2012) and Kind (2011, 2014).

The next question is: provides the 15year flood probability a good and robust signaling when to start a process of upgrading a dike ring. Our approach is as follows [10]. We assessed whether this flood standard definition is robust to *uncertain* future climate change and economic developments. To test this, we have determined for 50 different climate and economic scenarios (see Zwaneveld and Verweij, 2014a), the optimal investment strategy for all 17 dike ring areas. Given the obtained value of the middle flood probability and the 15 year probability for the base case scenario, we checked whether each of these two probabilities would provide the correct signal of starting a decision-making process to upgrade a dike ring in each of these 50 scenarios. We checked the first dike strengthening of each dike ring after the year 2050. The 15year flood probability[11] provided a correct signal in 95% of these all these 17*50=850 cases.

Table 3.2 summarizes the proposed flood protection standard as follows from the Diqe-Opt model. We report standards based upon the total flood probability (i.e. ‘P1’+ ‘P2’+ ‘P3’) as well as flood probability ‘P1’ only. The latter can be regarded as the total flood probability if all barrier dams are infinity strong. Following the results from paragraph 3.1, we assume that large pumps are used to manage the water levels in Lake IJssel and Lake Marken. In additional, the legal standards at the time of our analysis are presented in column 5 as well. The value of these standard should be compared to our ‘P1’-based flood protection standard, since they assumed that the barrier dams were infinity strong. The proposed legal standards (indicated by WV21) are also presented which followed from the model by Brekelmans et al. (2012) as used by Kind (2011, 2014). As mentioned earlier, this model is not capable of

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[10] Eijgenraam et al. (2016) and Kind (2014) use only the ‘middle flood probability’. Both present a Monte Carlo simulation to check how this probability depends on the input parameters. They do not discuss whether the middle flood probability is can be regarded as ‘good’ or ‘robust’. Brekelmans et al. (2012) present ‘robust optimization results’. They search for a <u>fixed</u> a priori determined investment scheme of when and how much to strengthen a dike ring given certain, equally likely or more sophistically weighted scenarios. This approach is not optimal at all in practice. We will explain this as follows. Given this a priori investment scheme a dike must be heightened in a certain year by a certain amount. If flood probabilities hasn’t risen as fast as (on average) assumed, there is of course no need to actually execute this a priori investment scheme. The dike ring is safe enough and the investment can be postponed. For this reason, these robust optimization results are not used in practice.

[11] We also tested the robustness of the middle flood probability. The middle flood probability provided a correct signal in 70% of these cases. For many cases, the 15year flood probabilities and the middle flood probability turned out to be almost identical.

assessing flooding dependencies between dikes and barrier dams. Hence, Kind (2011, 2014) had to assume that the barrier dams are infinitely strong.

Table 3.2 Flood protection standards around Lake IJssel: Diqe-Opt results (total and 'P1'-flood standards), WV21-results and (former) legal norm

Barrier dams	**Total flood probability**	**'P1' flood probability**	**WV21 flood probability**	**Legal norm**
Afsluitdijk	1/9,400	n.a.	n.a.	1/10,000
Houtribdijk	1/60	n.a.	n.a.	1/10,000
Dike rings				
1. Zuid-West Friesland	1/1,300	1/17,000	1/400	1/4,000
2. Noordoostpolder	1/1,600	1/2,800	1/3,000	1/4,000
3. Flevoland-Noordoost	1/3,000	1/5,200	1/5,200	1/4,000
4. West-Friesland (NH)	1/15,000	1/87,000	1/4,000	1/10,000
5. Wieringen IJsselmeer	1/42,000	1/190,000	1/2,300	1/4,000
6. IJsseldelta	1/700	1/900	1/1,400	1/2,000
7. Mastenbroek	1/1,000	1/1,100	1/1,600	1/2,000
8. Vollenhoven	1/3,700	1/4,200	1/1,700	1/1,250
9. Salland	1/2,000	1/2,200	1/2,900	1/1,250
10. Oost Veluwe	1/500	1/500	1/1,000	1/1,250

Note: n.a. =not available. Numbers represent yearly flood probabilities. Column 5 (norm) presents legally binding norms at the time of our analysis. The location of the dike rings can be found in the appendix.

For the first time, the flood risk standard for barrier dams (column 2) is derived from a multi-level economic model. The (former) legal norm for the Afsluitdijk turned out to be almost optimal. The legal norm for the Houtribdijk may however become much lower from an economical perspective.

Our results also show, that the dependencies between a barrier dam and a dike ring have a considerable impact on economically optimal flood standards. This is the case when the total flood probability (column 2) is substantially higher than the 'P1'-flood probability (column 3); see for example dike ring Zuid-West Friesland. Hence, ignoring dependencies (see column 4) would results in economically too high (i.e. unsafe) flood standards. Differences between our results and the WV21–results are not only due to including dependencies. We also used updated cost estimates for dike strengthening and assumed large pumps at the Afsluitdijk (instead of sluices as in de WV21 study).

Table 3.1 also shows an increase of legal flood protection standards by at least tenfold is not needed in general from an economically perspective, but is in some case applicable[12].

4. Concluding remarks

This paper presents a novel approach to the dike height optimization problem with multilevel flood defences. We present for the first time a modelling approach to take dependencies between dikes and barrier dams into account. Our graph-based modelling approach is easy to implement, is very flexible to include all kind of situation specific aspects and can be solved quickly to proven optimality. Major policy decisions are based upon our model results.

The problem and our modelling approach are relevant for many other situations in the Netherlands and other deltas in the world. For example, we were contacted (see Huizinga, 2012) while working on our model by the governor of Texas due to similarities between the Lake IJssel region and the Galveston Bay area. Also researchers from Rice University (Texas) and Jackson State University (Mississippi) have visited us to learn about our approach. Researchers from Maastricht University, Delft University of Technology, University of Amsterdam, the Dutch national research institute for mathematics and computer science and Deltares used our graph-based modelling approach and our model as a workhorse for their research (Yüceoğlu, 2015; Dupuits et al, 2017a; Dupuits et al, 2017b; Abiad et al, 2018).

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[12] The Ministry of Infrastructure and Environment had to be sure about the quality of the Diqe-Opt model and the resulting policy recommendations. Therefore, they commissioned a committee of four professors at Dutch Universities for a second opinion. This second opinion was published and has been presented to the Dutch House of Representatives (Ierland et al., 2014). A non-published second opinion of our report (Bos and Zwaneveld, 2012) was written by another committee (see Donders et al. 2013).

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Appendix A: IP-model for the multi-level flood protection with two barrier dams

The model presented in Section 2 includes the dependency of one barrier dam only. As explained in Section 1, the actual situation we assess in the Diqe-Opt model includes two barrier dams. The flood probability of dike rings adjacent to Lake Marken depend on the strength of barrier dam number 1 (i.e. 'Afsluitdijk') and barrier dam number 2 (i.e. 'Houtribdijk'). It is a straightforward exercise to expand the model to include dependencies on two barrier dams for dike rings $d \in D2$ around Lake Marken.

The following additional decision variables have to be defined:

$DY2(t,d,h_2,h_2^B,h_2^{B2}) =$ 1, if dike ring $d \in D2$ in time period t has height h_2 and barrier dam number 1 has height h_2^B and barrier dam number 2 has height h_2^{B2}. This decision variable is used for bookkeeping flood probabilities and related expected damage costs.
0, otherwise.

$B2(t,h_1^{B2},h_2^{B2}) =$ 1, if the barrier dam number 2 is updated in time period t from height/safety level h_1^{B2} up to h_2^{B2}. If $h_1^{B2} = h_2^{B2}$ then the barrier dam is not strengthened in period t and remains at its previous strength. This decision variable is used for bookkeeping investment (and maintenance) costs, flood probabilities and related expected damage costs of barrier dam number 2.
0, otherwise.

$DB2(t,h_2^{B2},h_2^B) =$ 1, if in time period t barrier dam number 2 has height h_2^{B2} and barrier dam number 1 has height h_2^B. This decision variable is used for bookkeeping flood probabilities and related expected damage costs for barrier dam number 2 only.
0, otherwise.

These additional decision variables are included in the objective function and additional restrictions have to be included to link all decision variables to obtain feasible solutions. Corresponding input parameters are defined and included as well. The extended model reads as follows.

$$
\begin{aligned}
Min \; & \sum_{t\in T}\sum_{d\in D\cup D2}\sum_{h_1\in H^l}\sum_{h_2\ge h_1\in H^l} Dcost(t,d,h_1,h_2)\cdot CY(t,d,h_1,h_2) \\
& +\sum_{t\in T}\sum_{d\in D}\sum_{h_2\in H^d}\sum_{h_2^B\in H^B} Dexpdam(t,d,h_2,h_2^B)\cdot DY(t,d,h_2,h_2^B) \\
& +\sum_{t\in T}\sum_{d\in D2}\sum_{h_2\in H^d}\sum_{h_2^B\in H^B}\sum_{h_2^{B2}\in H^{B2}} D2expdam(t,d,h_2,h_2^B,h_2^{B2})\cdot DY(t,d,h_2,h_2^B,h_2^{B2}) \\
& +\sum_{t\in T}\sum_{h_1^B\in H^B}\sum_{h_2^B\ge h_1^B\in H^B} [Bcost(t,h_1^B,h_2^B)+Bexpdam(t,h_2^B)]\cdot B(t,h_1^B,h_2^B) \qquad \text{(A1)} \\
& +\sum_{t\in T}\sum_{h_1^{B2}\in H^{B2}}\sum_{h_2^{B2}\ge h_1^{B2}\in H^{B2}} B2cost(t,h_1^{B2},h_2^{B2})\cdot B2(t,h_1^{B2},h_2^{B2}) \\
& +\sum_{t\in T}\sum_{h_2^B\in H^B}\sum_{h_2^{B2}\in H^{B2}} B2expdam(t,h_2^B,h_2^{B2})\cdot DB2(t,h_2^B,h_2^{B2})
\end{aligned}
$$

subject to

$$CY('0',d,'0','0')=1; CY('0',d,h_1,h_2)=0 \quad \forall d\in D\cup D2; h_1,h_2\in H^d; h_2\ge h_1\wedge h_2>'0' \qquad \text{(A2)}$$

$$\sum_{h_1\le h_2\in H^d} CY(t-1,d,h_1,h_2)=\sum_{h_3\ge h_2\in H^d} CY(t,d,h_2,h_3) \quad \forall t\in T/\{'0'\}, d\in D\cup D2, h_2\in H^d \qquad \text{(A3)}$$

$$\sum_{h_1\le h_2\in H^d} CY(t,d,h_1,h_2)=\sum_{h_2^B\in H^d} DY(t,d,h_2,h_2^B) \quad \forall t\in T, d\in D, h_2\in H^d \qquad \text{(A4)}$$

$$\sum_{h_1\le h_2\in H^d} CY(t,d,h_1,h_2)=\sum_{h_2^B\in H^B}\sum_{h_2^{B2}\in H^{B2}} DY2(t,d,h_2,h_2^B,h_2^{B2}) \quad \forall t\in T, d\in D2, h_2\in H^d \qquad \text{(A4a)}$$

$$B('0','0','0')=1; B('0',h_1^B,h_2^B)=0 \quad \forall h_1^B,h_2^B\in H^B; h_2^B\ge h_1^B\wedge h_2^B>'0' \qquad \text{(A5)}$$

$$\sum_{h_1^B\le h_2^B\in H^B} B(t-1,h_1^B,h_2^B)=\sum_{h_3^B\ge h_2^B\in H^B} B(t,h_2^B,h_3^B) \quad \forall t\in T, h_2^B\in H^B \qquad \text{(A6)}$$

$$\sum_{h_2\in H^d} DY(t,d,h_2,h_2^B)=\sum_{h_1^B\le h_2^B\in H^B} B(t,h_1^B,h_2^B) \quad \forall t\in T, d\in D, h_2^B\in H^B \qquad \text{(A7)}$$

$$\sum_{h_2\in H^d}\sum_{h_2^{B2}\in H^{B2}} DY2(t,d,h_2,h_2^B,h_2^{B2})=\sum_{h_1^B\le h_2^B\in H^B} B(t,h_1^B,h_2^B) \quad \forall t\in T, d\in D2, h_2^B\in H^B \qquad \text{(A7a)}$$

$$B2('0','0','0')=1; B2('0',h_1^{B2},h_2^{B2})=0 \quad \forall h_1^{B2},h_2^{B2}\in H^{B2}; h_2^{B2}\ge h_1^{B2}\wedge h_2^{B2}>'0' \qquad \text{(A8)}$$

$$\sum_{h_1^{B2}\le h_2^{B2}\in H^{B2}} B2(t-1,h_1^{B2},h_2^{B2})=\sum_{h_3^{B2}\ge h_2^{B2}\in H^{B2}} B2(t,h_2^{B2},h_3^{B2}) \quad \forall t\in T, h_2^{B2}\in H^{B2} \qquad \text{(A9)}$$

$$\sum_{h_2\in H^d}\sum_{h_2^B\in H^B} DY2(t,d,h_2,h_2^B,h_2^{B2})=\sum_{h_1^{B2}\le h_2^{B2}\in H^{B2}} B2(t,h_1^B,h_2^B) \quad \forall t\in T, d\in D2, h_2^{B2}\in H^{B2} \qquad \text{(A10)}$$

$$\sum_{h_2^B\in H^B} DB2(t,h_2^{B2},h_2^B)=\sum_{h_1^{B2}\le h_2^{B2}\in H^{B2}} B2(t,h_1^{B2},h_2^{B2}) \quad \forall t\in T, h_2^{B2}\in H^{B2} \qquad \text{(A11)}$$

$$\sum_{h_2^{B2}\in H^{B2}} DB2(t,h_2^{B2},h_2^B)=\sum_{h_1^B\le h_2^B\in H^B} B(t,h_1^B,h_2^B) \quad \forall t\in T, h_2^B\in H^B \qquad \text{(A11a)}$$

$$CY(t,d,h_1,h_2)\in\{0,1\} \quad \forall t\in T, d\in D\cup D2, h_1\in H^d, h_2\ge h_1\in H^d \qquad \text{(A12)}$$

$$DY(t,d,h_2,h_2^B)\in\{0,1\} \quad \forall t\in T, d\in D, h_2\in H^d, h_2^B\in H^B \tag{A13}$$

$$DY2(t,d,h_2,h_2^B,h_2^{B2})\in\{0,1\} \quad \forall t\in T, d\in D2, h_2\in H^d, h_2^B\in H^B, h_2^{B2}\in H^{B2} \tag{A14}$$

$$B(t,h_1^B,h_2^B)\in\{0,1\} \quad \forall t\in T, h_2^B\geq h_1^B\in H^B \tag{A15}$$

$$B2(t,h_1^{B2},h_2^{B2})\in\{0,1\} \quad \forall t\in T, h_2^{B2}\geq h_1^{B2}\in H^{B2} \tag{A16}$$

$$DB2(t,h_2^{B2},h_2^B)\in\{0,1\} \quad \forall t\in T, h_2^{B2}\in H^{B2}, h_2^B\in H^B \tag{A17}$$

The objective function (A1) minimizes the total cost for investments for all dike rings (first term) and expected damage in all dike rings (second and third term) and the total cost of investment and expected damage of the barrier dam number 1(fourth term) and number 2 (fifth and sixth term). Constraints (A2) define the starting condition for each dike ring *d* (i.e. its present height/strength). Constraints (A3) ensure that the final height of each dike ring *d* in a period *t-1* equals the starting height of the dike ring in the consecutive period *t*. Constraints (A4 and A4a) ensure that the expected damage decision variables of each dike ring *d* in each period *t* correspond to the decision variables which determine the investment cost of each dike ring. Constraints (A5) define the starting condition for the barrier dam number 1 (i.e. its present height/strength). Constraints (A6) ensure that the final height of this barrier dam in period *t-1* equals the starting height of the barrier dam in the consecutive period *t*. Constraints (A7 and A7a) ensure that the expected damage decision variables of each dike ring *d* in each period *t* correspond to the decision variables which determine the investment cost of barrier dam number 1. Constraints (A8) define the starting condition for the barrier dam number 2. Constraints (A9) ensure that the final height of this barrier dam in period *t-1* equals the starting height of the barrier dam in the consecutive period *t*. Constraints (A10) ensure that the expected damage decision variables of each dike ring *d* in each period *t* correspond to the decision variables which determine the investment cost of barrier dam number 2. Constraints (A11) and (A11a) ensure that the expected damage decision variables of barrier dam number 2 correspond to the decision variables which determine the investment cost of barrier dam number 2 and 1, respectively. Constraints (A12) to (A17) declare the decision variables as binary.

Appendix B: Flood probabilities of dike rings

Flood probabilities of all dike rings are assessed by the hydrological model Hydra-Zoet. To perform all flood probability calculations, one or more representative locations must be selected for each dike ring (and the barrier dam ‘Houtribdijk’). All locations were selected by Deltares in cooperation with CPB after consulting hydrological experts from both Deltares and Rijkswaterstaat (Kramer and Beckers, 2012; Zwaneveld and Verweij, 2014a). Figure B1 provides an overview of all selected locations. For most dike rings, one representative location is sufficient. This location determines the flood probability of this dike ring. For several dike rings two or more representative location were selected. These multiple locations fail under different circumstances (e.g. different wind directions). Hence, the sum of the flood probabilities over all representative locations defines the flood probability of the dike ring. Table B1 provides an overview of representative locations for all dike rings and the ‘Houtribdijk’.

Figure B1 Selected representative locations around Lake IJssel and Lake Marken

Table B1 Representative locations

Dike ring	Representative locations		
Lake IJssel	1	2	3
Zuid-West Friesland (6-4)	F100	F280	F425
Noordoostpolder (7-1)	N223	N375	
Flevoland-Noordoost (8-1)	F095	F235	
West-Friesland (NH) noord (13-2-1)	06A	04A	
Wieringen IJsselmeer (12-1)	01B		
IJsseldelta (11-1)	Kampen		
Mastenbroek (10-1)	Wilsum		
Vollenhove (9-1)	Zwartsluis	Hessenpoort	
Salland (53-1)	Langenholte		
Oost Veluwe (52-1)	Hattem		
Lake Marken			
Flevoland-Zuidwest (8-2))	hm19.0		
West-Friesland (NH) zuid (13-2-2)	06A		
Noord-Holland Waterland (13-4)	30		
Marken (13b-1)	45B		
Gooi en Vechtstreek (44-2)	gav7		
Eempolder (46-1)	dp17.6		
Gelderse Vallei-Meren (45-2)	dp7.3		
Barrier dam			
Houtribdijk (4)	H-IJM 144		

Note: The number between bracket, e.g. (6-4) for dike ring Zuid-West Friesland refer to the number in Figure 2

As explained in Section 2, three flood probabilities were assessed for all dike rings around Lake IJssel. For dike rings around Lake Marken, the following seven flood probabilities were assessed.

$P1^M$ refers to the flood probability given the well-functioning of both barrier dams (i.e. barrier dam 1 ‘Afsluitdijk’ and barrier dam 2 ‘Houtribdijk’). This flood probability is identical to P1 in Section 2.

$P2^M$ is the flood probability during a storm in which barrier dam 1 fails and barrier dam 2 remains intact. Additional water in Lake IJssel due to a breach in barrier dam 1 may cause problems in discharging water from Lake Marken to Lake IJssel during this storm. Since we assumed at barrier dam number 2 in all instances a pump in addition to the present discharge sluices, water can be transfered from Lake Marken to Lake IJssel during this storm surge. Hence, $P2^M$ was always equal to zero.

$P3^M$ is the flood probability in the period after barrier dam 1 failed and barrier dam 2 remained intact. The repair time for a barrier dam is estimated to be six month. This breach creates an open connection between the North Sea and Lake IJssel. This raises the water level in Lake IJssel which increases the hydrological load onto the dikes. Note that $P3^M$ does not depend on the strength/height of the barrier dam 1 *after* a breach is formed. Additional water in Lake IJssel due to a breach in barrier dam 1 may cause problems in discharging water from Lake Marken to Lake IJssel during this six month period. This may increase flood probabilities. Since we assumed a substantial pump at barrier dam 2, $P3^M$ is always equal to zero.

$P4^M$ is the flood probability during a storm in which barrier dam 2 fails. Barrier dam 1 remains intact during this storm. Flood probabilities increase due to additional water that overtops barrier dam 2 and additional water that enters Lake Marken via the newly formed breach in barrier dam 2.

$P5^M$ is due to a follow-up storm surge in the period after barrier dam 2 failed due to an earlier storm. Barrier dam 1 remains intact. Due to a breach in barrier dam 2, the water level in Lake Marken can be higher which results in higher flood probabilities.

$P6^M$ is the flood probability during a storm in which barrier dam 2 fails. Barrier dam 1 failed during an earlier storm surge.

$P7^M$ is the flood probability in a follow-up storm in the period after both barrier dams failed during earlier storm surges. Breaches in both barrier dams result in a (much) higher water level in Lake Marken due to the open connection to the North Sea. The situation in which both barrier dams fail during the same storm surge is also included in $P7^M$.

In order to calculate the total failure probability due to water overtopping, the flood probabilities $P1^M$ to $P7^M$ are redefined and recalculated as the additional, disjoint probabilities '$P1^M$' to '$P7^M$'[13]. By definition `$P1^M$' equals P1. As an example, `$P6^M$' defines the probability of failure events additional to the probability of events that were already

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[13] See Kramer and Beckers (2012) and Zwaneveld and Verweij (2014a). Details on the used equations are available upon request from the authors. for more details about the flood probability calculations.

subsumed under P1 to P5. The total flood probability of a dike ring is then defined by the sum over all disjoint flood probabilities, i.e. ‘$P1^M$’+‘$P2^M$’+$P3^M$’+‘$P4^M$’+‘$P5^M$’+‘$P6^M$’+‘$P7^M$’. Our results show that only ‘$P1^M$’, ‘$P5^M$’, and ‘$P7^M$’ represent substantial flood probabilities.

All flood probabilities from available hydrological models refer to failure mechanism ‘overtopping’, i.e. the situation in which water overtops the crest of the dike in such amount that a breach occurs. Research in the years prior to our study revealed two additional failure mechanisms, namely piping and slope instability. Deltares (Kind, 2011) provide multiplication factors per dike ring to obtain total flood probabilities on the basis of these overtopping flood probabilities. These multiplication factors range from 1 to 5, with a medium value of 2. Hence, the total flood probability is twice the ‘overtopping’ flood probability for the median dike ring. See Kind (2011) and Zwaneveld and Verweij (2014a) for more details.

Detailed information about the calculation of flood probabilities with the use of mentioned hydrological models can be found in Kramer and Beckers (2012) and Zwaneveld and Verweij (2014a). All hydrological calculations were checked according to internal quality procedures at Deltares by two non-involved experts. In addition, two hydrological experts of Rijkswaterstaat checked flood probability calculations.

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